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THE INTEGRATED FARM SYSTEM MODEL

Reference Manual
Version 4.7

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EXECUTIVE SUMMARY

With tighter profit margins and increasing environmental constraints, strategic planning of farm production systems is becoming both more important and more difficult. This is especially true for dairy and beef production. Livestock production is complex with a number of interacting processes that include crop and pasture production, crop harvest, feed storage, grazing, feeding, and manure handling. Computer simulation provides a useful procedure for integrating these processes to predict the long-term performance, environmental impact, and economics of production systems.

Development of a simulation model of the dairy forage system began in the early 1980's. This model, known as the Dairy Forage System Model or DAFOSYM, linked alfalfa and corn production models with a dairy animal intake model to predict feed production and disappearance on the farm. This model was expanded with additional components for simulating feed storage and animal performance. Manure handling, tillage, and planting operations were then added to extend the model to a simulation of the full dairy farm. The dairy farm model was broadened further by adding components for simulating grass, small grain, and soybean growth, harvest, and storage. Through a major revision, a beef animal component was added along with a crop farm option (no animals) to form the Integrated Farm System Model or IFSM. This model has continued to grow as components were added to simulate environmental impacts including gas emissions, nitrate leaching, and phosphorus runoff and a life cycle assessment to determine the carbon footprint of production systems.

Unlike most farm models, IFSM simulates all major farm components on a process level. This enables the integration and linking of components in a manner that adequately represents the major interactions among the many biological and physical processes on the farm. This provides a robust research and teaching tool for exploring the whole farm impact of changes in management and technology. Process level simulation remains an important goal as additional components are developed and added.

In an IFSM simulation, crop production, feed use, and the return of manure nutrients back to the land are simulated over many years of weather. Growth and development of alfalfa, grass, corn, soybean, and small grain crops are predicted on a daily time step based upon soil water and N availability, ambient temperature, and solar radiation. Performance and resource use in manure handling, tillage, planting, and harvest operations are functions of the size and type of machines used and daily weather. Field drying rate, harvest losses, and nutritive changes in crops are related to the weather, crop conditions, and machinery operations used. Losses and nutritive changes during storage are influenced by the characteristics of the harvested crop and the type and size of storage facility used.

Feed allocation and animal response are related to the nutritive value of available feeds and the nutrient requirements of up to six animal groups making up either dairy or beef herds. Diets for each group are formulated using a cost-minimizing linear programming approach, which makes the best use of homegrown feeds and purchased supplements. Protein and energy requirements are determined for each animal group based upon the characteristics of the average animal in the group. One or two protein supplements are used to balance rations. These can include both high and low rumen degradable protein feeds. Feed characteristics can be defined to describe essentially any supplement of each type including blended feeds. Supplemental P and K fed, if needed, is the difference between the requirement of each animal group and the sum of that contained in the feeds consumed.

Nutrient flows through the farm are modeled to predict potential nutrient accumulation in the soil and loss to the environment. The quantity and nutrient content of the manure produced is a function of the quantity and nutrient content of the feeds consumed. Ammonia, hydrogen sulfide and volatile organic compound emissions occur in the barn, during manure storage, following field application, and during grazing. Denitrification and leaching losses from the soil are related to the rate of moisture movement and drainage from the soil profile as influenced by soil properties, rainfall, and the amount and timing of manure and fertilizer applications. Erosion of sediment is predicted as a function of daily runoff depth, peak runoff rate, field area, soil erodibility, slope, and soil cover. Phosphorus transformation and movement is simulated among surface and subsurface soil pools of organic and inorganic P. Edge-of-field runoff losses of sediment-bound P and soluble P are predicted as influenced by manure and tillage management as well as daily soil and weather conditions. The net emission of greenhouse gases includes the net exchange of carbon dioxide and the loss of nitrous oxide during the production of feed crops, the emission of methane from enteric fermentation in animals, and the losses of all three gases from manure on the barn floor, during storage, and following land application. Following the prediction of losses, whole-farm balances of N, P, K, and C are determined as the sum of all nutrient imports in feed, fertilizer, deposition, and legume fixation minus the exports in milk, excess feed, animals, manure, and losses leaving the farm.

Simulated performance is used to determine production costs, incomes, and economic return for each year of weather. A whole-farm budget is used, which includes fixed and variable production costs. Annual fixed costs for equipment and structures are the product of their initial cost and a capital recovery factor where this factor is a function of an assigned economic life and real interest or discount rate. The resulting annual fixed costs are summed with predicted annual expenditures for labor, resources, and products used to obtain a total production cost. Labor cost accounts for all field, feeding, milking, and animal handling operations including charges for unpaid operator labor. This total cost is subtracted from the total income received for milk, animal, and excess feed sales to determine a net return to the herd and management.

By comparing simulation results for different production systems, the effects of system differences are determined, including resource use, production efficiency, environmental impact, production costs, and net return. Production systems are simulated over a 25 year sample of recent historical weather. All farm parameters, including prices, are held constant throughout the simulation so that the only source of variation among years is the effect of weather. Distribution of the annual values obtained describes possible performance outcomes as weather varies. Inter-year dynamics are not considered; initial conditions such as soil nutrient concentrations and feed inventories are reset each year. Therefore, the simulated data indicate the range of variation in economic and environmental performance that can occur given the variation in weather at the farm location, i.e. the distribution of simulated annual values indicates weather-related risk experienced by the simulated production system. A wide distribution in annual values implies a greater degree of risk.

The Integrated Farm System Model functions on all recent Windows operating systems. Input information is supplied to the program through three parameter files. The farm parameter file contains data describing the farm such as crop areas, soil type, equipment and structures used, numbers of animals at various ages, harvest, tillage, and manure handling strategies, and prices for various farm inputs and outputs. The machinery file includes parameters for each machine available for use on a simulated farm. These parameters include machine size, initial cost, operating parameters, and repair factors. Most farm and machinery parameters are modified quickly and conveniently through dialog boxes in the user interface of the program. Many of these files can be created to store parameters for different farms and machinery sets for later use in other simulations. The weather file contains daily weather data for many years at a particular location. The daily data include the date, incident solar radiation, maximum and minimum temperatures, and precipitation.

Simulation output is available in four files, which contain summary tables, report tables, optional tables, and parameter tables. The summary tables provide average performance, environmental impact, costs, and returns for the years simulated. These values consist of crop yields, feeds produced, feeds bought and sold, manure produced, nutrient losses to the environment, production costs, income from products sold, and the net return or profitability of the farm. Values are provided for the average and standard deviation of each over all simulated years. The report tables provide extensive output information including all the data given in the summary tables. In these tables, values are given for each simulated year of weather as well as the mean and variance over all simulated years. Optional tables are available for a closer inspection of how the components of the full simulation are functioning. These tables include very detailed data, often on a daily basis. Parameter tables summarize the input parameters specified for a given simulation. These tables provide a convenient method of documenting the parameter settings for specific simulations.

INTRODUCTION

Dairy and beef production in the United States are facing two major challenges in order to remain viable industries. The first is an economic challenge: inflation-adjusted milk prices have remained stable or declined for many years, while the costs of most production inputs have increased. As farm profits continue to decrease, production systems must become more efficient. One of the most effective ways of improving efficiency has been to increase the number of animals per unit of cropland (i.e., intensification). This trend has contributed to the development of the second challenge: the farm's impact on the environment.

Livestock farms, particularly dairy farms, have grown more dependent upon the use of commercial fertilizers and the import of supplemental feeds. Their use has increased crop yields and animal production, which have improved the efficiency and profitability of the dairy and beef industries. With heavy import of nutrients, however, there is greater opportunity for buildup of nutrients in the soil and the loss of excess nutrients to ground and surface waters.

For more sustainable dairy and beef industries, improved production systems are needed that increase the profitability of farms while maintaining or reducing long-term negative impacts on the environment. Many alternative technologies and management strategies are available to today's farmers. These include choices in the number and type of animals, land area, crop mix, equipment, feed-storage facilities, animal facilities, manure-handling options, and much more. Changes in one component of the farm often affect other components, and this interaction can cause changes in the performance, environmental impact, and profitability of the farm that are not obvious or easily understood.

Quantifying and comparing the benefits and costs of alternative technologies and management strategies in farming is not easy. A production system that performs well under one set of crop and weather conditions may not perform well under other conditions. Long-term studies are needed to quantify the benefits and costs over a wide range of conditions. Field studies of this type are costly, impractical, and perhaps impossible. Another approach is to use computer simulation. Process-based models developed and validated with limited field experimental work can be used to study system performance over many years of weather.

The need for a research tool that integrates the many physical and biological processes on a farm has led to the development of the Integrated Farm System Model (*IFSM*). The model has been used to evaluate a wide variety of technologies and management strategies, and these analyses have been reported in the scientific and farm-trade literature. Systems research in dairy and beef production remains as the primary purpose for this tool, but the model also provides an effective teaching aid. With the model, students gain a better appreciation for the complexity of livestock forage systems. They learn how small changes affect many parts of the system, causing unanticipated results. They may also use the model to develop a more optimum food production system. When used in extension-type teaching, producers can learn more about their farms and obtain information useful in strategic planning. By testing and comparing different options with the model, those offering the greatest economic benefit with acceptable environmental impact can be found.

History of Model Development

The current farm model is the product of over 25 years of systems research and modeling work. The USDA's Agricultural Research Service has carried a major role in this effort. With the beginning of the U.S. Dairy Forage Research Center (*USDFRC*) in the late 1970s, a portion of the Center's first funding was provided to Michigan State University for development of a simulation model of dairy forage production. An integrated model of alfalfa growth, harvest, and feeding was created through the cooperative effort of two graduate students and several of the university's faculty (**Savoie et al., 1985**). The model, known as *DAFOSYM*, was written in FORTRAN for use on a mainframe computer. This version was relatively crude, but it provided a structure for further development. Development and application of the model continued with *USDA* support after the East Lansing Cluster program of the *USDFRC* was staffed in 1981.

During the early 1980s, most of the modeling effort was given to refining the relationships used to describe field curing and harvest losses in forage production (**Rotz, 1985**). In 1985, the model was converted to function on personal computers. Development continued toward making the model more convenient to use and more adaptable to other technology and locations.

In the late 1980s, a major effort was undertaken to upgrade the storage and animal submodels of *DAFOSYM*. With the help of others in the *USDFRC* and cooperators in the NE-132 Regional Research Project, the hay and silo storage and the animal component submodels were completed (**Buckmaster et al., 1989a, 1989b; Rotz et al., 1989**). For the next five years, emphasis was directed toward the application of the model to evaluate alternative forage systems. Benefits and costs of various technologies for hay conditioning, swath manipulation, hay drying, and preservation were analyzed with the model. The model was also used for making management decisions such as machine and silo selection and sizing.

In 1991, the user interface was upgraded to allow the model to be used as a teaching aid. This DOS version of the model used overlaying menus for editing model parameters and a plotting package for high-quality graphical output. Copies of this package were distributed upon request, with the primary audience being forage extension and teaching faculty in the U.S. and Canada.

In the early 1990s, development of the model continued as submodels for manure handling, tillage, and planting were added (**Borton et al., 1995 and Harrigan et al., 1996**). This expansion enabled the modeling of nitrogen losses and the farm balance of phosphorus and potassium, providing a new environmental aspect to the model. The expanded model was used to compare various manure-handling and tillage systems on dairy farms.

In the mid 1990s, *DAFOSYM* was converted to a Windows® operating system. A new user interface was developed to provide a more user-oriented model. This conversion allowed further expansion of the model to include animal facilities and essentially all costs incurred on typical dairy farms, making it a more complete dairy-farm model. This version of the model was placed on the Internet for national and international distribution.

Late in the 1990s, a new corn-growth submodel was added based upon the CERES-maize model. Other crop-production submodels were also added for grass, small grain, and soybean crops. The harvest, storage, feeding, and economic submodels were expanded to incorporate these new feeds on the farm (**Rotz et al., 2001**). Grazing of forage and a wide variety of possible feed supplements were also added (**Rotz et al., 1999b and Rotz et al., 1999c**). This expanded model was used to study the effects of crop rotation and feed supplementation on farm performance, profit, and nutrient loss to the environment. Beef and cropping options were added to the model, and the name was changed to the Integrated Farm System Model.

In the past several years, an improved pasture submodel was incorporated, allowing evaluation and comparison of pastures with multiple-plant species (**Corson et al., 2007b**) or warm-season grasses (**Corson et al., 2007a**). Routines were also added to predict nitrogen volatilization occurring in the barn, during manure storage, following field application, and during grazing (**Rotz and**

Oenema, 2006). Denitrification and leaching losses from the soil were related to the rate of moisture movement and drainage from the soil profile as influenced by soil properties, rainfall, and the amount and timing of manure and fertilizer applications. The soil submodel was extended to include a detailed simulation of soil phosphorus dynamics and losses. Erosion of sediment was predicted using a version of the Modified Universal Soil Loss Equation (*MUSLE*), and phosphorus transformation and movement was simulated among surface and subsurface soil pools of organic and inorganic phosphorus (**Sedorovich et al., 2007**). Edge-of-field runoff losses of sediment-bound and soluble phosphorus were predicted as influenced by manure and tillage management as well as daily soil and weather conditions.

Application as a Research Tool

The primary goal in the development of the farm model was to create a research tool for comprehensive evaluation and comparison of dairy-production systems. Many different technologies and strategies for dairy farms have been compared using this model and the results are published in scientific journals and conference proceedings.

The earliest simulation studies were conducted to evaluate the feasibility and economic benefits of new technologies in haymaking. Chemical conditioning of alfalfa was introduced in the late 1970s. Field experiments conducted to develop a practical system for hay producers provided the necessary equipment parameters and data to develop and validate the field curing submodels (**Rotz, 1985**). Simulations on representative farms in the Midwest and Eastern United States indicated that the chemical conditioning process reduced field curing time an average of 12 h on first cutting and 24 h on later cuttings. This resulted in more high-quality hay, which reduced feed costs on the dairy farm. With a treatment cost near $5/t DM of hay, the technique returned the cost of the treatment and provided a small economic gain for producers through improved hay quality.

Mat drying of hay was an experimental technology where forage was shredded and pressed into a mat that was laid back on the field for rapid drying. The matted forage dried to baling moisture in about one day with minimal loss even in humid climates. Shredding also improved the digestibility of the forage. Experimental work quantified the drying rates, losses, and machinery requirements for modeling the process, and farm level simulations showed that the new technology could be quite economical (**Rotz et al., 1990**). The proposed equipment was costly, but the model predicted that in the Midwest the process could provide a return of up to $4 for each dollar spent on increased equipment costs through improved hay quality.

Chemical and biological agents are often used to preserve high-moisture hay. By baling damp hay, field losses are reduced, but storage losses are increased. Hypothetical treatments with a wide range of effectiveness in preserving high-moisture hay using several strategies were simulated to determine potential break even treatment costs. Actual treatment costs were considerably greater than the break even costs determined through simulation, which indicated an economic loss with current treatments (**Rotz et al., 1992**). These simulation results provided preservative manufacturers with guidelines on effectiveness versus cost for future product development.

Large round hay bales can be stored using a variety of methods. The long-term performance, costs, and return above feed costs for six storage methods, three bale sizes, two feeding methods, and two milk-production levels were compared on 60- and 400-cow dairy farms (**Harrigan et al., 1994**). The value of bale protection was influenced by bale size, amount of hay in the diet, level of milk production, and feeding method. Shed storage was usually, but not always, more profitable than unprotected storage. The greatest economic return from bale protection occurred when small-diameter bales were fed to high-producing cows with all alfalfa fed as dry hay. Compared to unprotected hay, annual net return increased as much as $155/cow with shed storage and $143/cow with tarp-covered stacks. The lowest benefit from bale protection was realized when large-diameter bales were chopped and fed as a small amount of a total mixed ration. With this system, annual net return was within $8/cow for all storage systems indicating little benefit for protected storage.

The technique of ensiling direct cut alfalfa has long been of interest in humid climates to eliminate field wilting losses. Simulation was used to compare the long-term performance and the economics of conventional wilted silage systems to a direct-cut alfalfa harvest and storage system that used a treatment such as formic acid to enhance preservation (**Rotz et al., 1993**). Reduced harvest losses with direct-cut silage were largely offset by increased effluent losses from the silo, so little difference was found in the quantity and quality of forage available to the animals. Handling of the wetter material increased machinery, fuel, and labor costs for transport and feeding. The economic value of direct-cut silage was found to be very poor. Producers of high-moisture silage experienced an economic loss, even with no cost for a preservative treatment.

Many dairy farmers have considered the use of grazing to reduce feed costs and improve farm profit. *DAFOSYM* was used to model the performance and economics of a 60-cow dairy farm in central Pennsylvania and a 100-cow operation in southern Michigan with and without the use of grazed alfalfa (**Rotz and Rodgers, 1994 and Rotz, 1996**). The net cost of feeding the herd decreased with grazing through reduced use of conserved forages, corn grain, and soybean meal. Because grazing animals spent less time in the barn during the grazing season, less bedding was required with less manure hauled each year. Altogether, these effects provided a 12% reduction in the average feed and manure handling cost. Grazing reduced the total feed and manure handling cost by $0.73 to $1.00/cwt of milk produced compared to the confined feeding system where the savings was dependent upon other assumptions on farm management. The net return or profit margin of the farm increased by about $150/cow or $60/acre.

DAFOSYM was used to evaluate the economic benefits of measuring pasture yield as a tool in managing grazing dairy cows (**Sanderson et al., 2001**). Error in pasture measurement was found to reduce farm annual net return by $8 to $198/ha depending upon the type of grazing and feeding strategy used. *IFSM* was used to illustrate that using more complex mixtures of forage species in pasture could increase annual net return of a Pennsylvania dairy farm by up to $200/cow (**Sanderson et al., 2006**). In another application, *IFSM* was used to determine the environmental benefits of converting a beef farm in Maryland from a corn based system used prior to 1990 to a current perennial grassland system with intensively managed grazing. The change reduced nitrate leaching loss 56%, denitrification loss 50%, and phosphorus runoff loss by 75% while increasing farm net return (**Crosson et al., 2007**).

DAFOSYM was used to evaluate the potential long-term environmental impact and economic benefit of varying the level of concentrate supplementation on seasonal grazing dairies in Pennsylvania (**Soder and Rotz, 2001**). Farm profitability increased as supplementation increased, but at a decreasing rate with each successive level of supplement. At higher supplementation levels, grazing dairy farms showed greater profitability than a farm with animals fed in confinement. Economic risk or year-to-year variation also decreased as concentrate supplementation increased. Grazing farms showed an environmental benefit compared to the confinement farm by decreasing nitrogen leaching loss. In a related study, feeding a partial total mixed ration to grazing dairy cows was found to provide a viable feeding strategy for decreasing environmental impact while maintaining profitability (**Soder and Rotz, 2003**). A confinement farm showed the greatest annual net return, but this return was only a little greater than that of a grazing farm supplemented with mixed rations.

Economic risk was highest for the confinement farm compared to grazing farms.

Manure handling has become an important issue in animal production. *DAFOSYM* was used to evaluate and compare manure systems using long-term storage with spreading, injection, or irrigation to the less costly daily-haul system commonly used in the upper Midwest (**Borton et al., 1995**). In cases where long-term storage systems were required to protect the environment, the annual net cost of manure handling (total manure cost minus the value of manure nutrients) was found to increase by up to $65/cow for small (60 cow) and $45/cow for large (250 cow) dairy farms.

Comparisons of three tillage and four manure-handling systems on representative dairy farms showed mulch tillage to be the most economical tillage system (**Harrigan et al., 1996**). Mulch tillage returned $15 to $25/cow each year over conventional tillage with a 30% reduction in machinery, fuel, and labor costs. A modified no-till system provided a higher return than conventional tillage, but when compared to mulch tillage, savings in fuel and labor were offset by higher costs for pesticides. The highest net return among manure-handling systems was associated with short-term storage and daily hauling, but this economic advantage diminished if credit was not given for the value of all manure nutrients when spread daily. Long-term manure storage concentrated labor for spreading in the spring and fall. With limited labor and equipment, this delayed tillage and planting and increased annual feed costs as much as $24/cow.

Two primary roughages for dairy herds are corn silage and alfalfa. Whole farm simulation was used to compare the relative merits of these two forages when varying amounts of the forage requirement (none, one-third, two-thirds, and all on a DM basis) came from ammoniated corn silage and the remainder from alfalfa (**Borton et al., 1997**). The highest net return was from alfalfa at 100% of the forage requirement, but differences in net returns across forage systems were small compared with the variation among years caused by weather. Changes in farm size, soil type, crop yield, milk production, relative prices, and manure handling assumptions did not affect the conclusions of the analysis. Given the lack of a strong economic advantage among the forage systems, the practice of having at least one-third of the forage requirement provided by each of the forage crops was favored to improve crop management, feeding management, manure disposal, and labor use.

Whole-farm impacts of using a corn silage processor on the forage harvester were assessed through long-term simulations (**Rotz et al., 1999a**). Processing improved packing in the silos, increased the digestibility of the silage, which reduced supplemental feed requirements and/or improved milk production. When processing was used on farms having 100 or 400 high-producing Holstein cows with 40% of the forage requirement met by corn silage, the treatment provided about a 2% increase in milk production, a small decrease in supplemental grain feeding, and a $50/cow improvement in the annual net return or profit of the farm. Without an increase in milk production, the annual economic benefit dropped to $5/cow. By increasing the amount of corn silage fed to 75% of the total forage requirement, processing provided a 4% increase in milk production with an annual economic benefit near $100/cow.

More efficient use of protein feed supplements on dairy farms can potentially reduce the nitrogen import in feeds, excretion in manure, and losses to the environment. A simulation study illustrated that more efficient feeding and use of protein supplements increased farm profit and reduced nitrogen loss from the farm (**Rotz et al., 1999c**). Compared to soybean meal as the sole protein supplement, the use of soybean meal along with a less rumen-degradable protein feed reduced volatile loss by 13 to 34 kg/ha of cropland with a small reduction in leaching loss (about 1 kg/ha). Using the more expensive protein supplement along with soybean meal improved the annual net return by $46 to $69/cow, depending upon other management strategies used on the farm. Environmental and economic benefits were generally greater with more animals per unit of land, higher milk production levels, more sandy soils, and/or a daily manure-hauling strategy.

Soybean production is rapidly increasing on dairy farms. A whole farm analysis was conducted to determine the potential long-term economic benefit to producers and the environmental impact of this management change to growing and feeding soybeans as a protein feed-supplement (**Rotz et al., 2001**). The production of soybeans as a cash crop increased annual farm net return by up to \$55/cow when ample cropland was available to produce most of the feed requirement of the herd. Once the soybeans were fed in either a raw or roasted form, most of this economic benefit was offset, reducing the increase in annual net return to less than \$15/cow. With a more restricted land base, there was less economic benefit in shifting land from corn or alfalfa production to soybeans, whether they were produced as a cash crop or for feed. Little environmental benefit from reduced N loss or soil P accumulation was obtained by growing soybeans on dairy farms.

Use of small grain crops in the rotation increased farm net return while reducing the risk or year-to-year variation in net return (**Rotz et al., 2002a**). Annual net return was increased by up to \$116/cow when double-cropped barley or single-cropped wheat was harvested as grain and straw, by about \$30/cow for double-cropped barley silage, and \$50/cow for double-cropped rye silage. Nitrogen leaching loss over the farm was reduced by 10 kg/ha when 40% of the corn was double cropped with small grain, and soil phosphorus accumulation was reduced by 2 kg/ha.

Whole-farm simulation with *DAFOSYM* was used to evaluate the long-term effects of changes in feeding, cropping, and other production strategies on phosphorus loading and the economics of actual dairy farms in southeastern New York (**Rotz et al., 2002b**). Alternative farm management options provided a long-term phosphorus balance for the farm as long as the production and use of forage was maximized and recommended minimum dietary phosphorus amounts were fed. Management changes were demonstrated that eliminated the long-term accumulation of soil phosphorus while improving farm profitability.

IFSM was verified to simulate the production and nutrient flows of the De Marke experimental dairy farm in the Netherlands (**Rotz et al., 2006**). On this farm, technology such as a low ammonia emission barn floor, enclosed manure storage, manure injection into the soil, and the underseeding of a grass cover crop on corn land were used to reduce nitrogen loss and improve nutrient recycling. Simulation was then used to evaluate the environmental and economic impacts of using this technology on representative farms in Pennsylvania. Total nitrogen loss from the farms, primarily in the form of ammonia emission, was reduced by 25 to 55% with an 8 to 55% reduction in P runoff loss. The cost of this technology was greater than the value of the nutrients saved causing a reduction in annual net return of \$65 to 88/cow.

Simulation of farm production systems, supported by case study farm data from four Pennsylvania dairy farms, was used to compare economic benefits and environmental impacts of dairy production systems using either organic or conventional practices. Four production systems were compared representing organic grass, organic crop, conventional crop with grazing, and conventional confinement production. Whole-farm budgets using prices that reflect recent conditions showed an economic advantage for organic over conventional production. A sensitivity analysis showed that this economic advantage was dependent upon a higher milk price for producers of organic milk as influenced by the difference in milk production maintained by herds using organic and conventional systems (**Rotz et al., 2007**). Environmental concerns for organic production were 1) long-term accumulation of soil nutrients due to the importation of poultry manure for crop fertilization and 2) greater soil erosion and runoff loss of phosphorus due to greater use of tillage for weed control in annual crops.

Application as a Teaching Aid

In addition to its primary purpose as a research tool, the Integrated Farm System Model also provides an effective teaching aid. Students in Bio-Systems Engineering, Agronomy, Crop and Dairy and Animal Science can use the model to learn more about the complexity of the many interactions that occur within a crop and livestock-production system. Students may study the effects of relatively simple changes such as the size of a tractor or other machines. Such a change influences the timing of field operations, fuel and labor requirements, the quality of feeds produced, and milk production as well as the cost of production and farm profit. More complex problems may be studied, such as maximizing the profit of a given-size farm, optimizing the machinery set or structures used on a farm, or a major change in production strategy.

The model can also be used in extension-type workshops. Extension field-staff, private consultants, and producers may use this model to study the impacts of various technological changes on farms in their area. With some experience, the model can be used to assist with strategic planning and provide useful information on the selection of equipment, structures, and in planning for farm expansion. Various cropping systems and feeding strategies can also be compared along with numerous other options in farm management to determine more economical and environmentally friendly production systems.

The Windows® operating system and user interface enhances the usefulness of the program as a teaching aid. As in many Windows®-based programs, the main program window opens to display a series of menu options and icons that are used to direct the user through major model functions. Dialog boxes are used to view or modify model parameters. Files supplied with the model provide default values for all parameters of example farms. Parameters are easily changed by modifying values in an entry box, selecting the appropriate option from a list box, or setting the desired value through a scroll box. Either metric or English units of measurement can be used.

A Windows®-type help system assists the user in preparing a simulation and interpreting the results. Help can be obtained in any part of the program by pressing the F1 key or by using the context-sensitive help button. The internal user guide provides a description of the information required or the output received. Major functions and relationships used throughout the model are documented in the provided reference manual.

Model Availability

The Integrated Farm System Model is available from the website of the Pasture Systems and Watershed Management Research Unit of the Agricultural Research Service (http://www.ars.usda.gov/main/site_main.htm?modecode=19-02-05-00). After entering this site, click on "Software" in the left column. It may also be obtained by providing the search-term "IFSM" in the appropriate search box on the ARS website (http://www.ars.usda.gov/main/main.htm). Information on the model and complete instructions for downloading and setting up the program are provided. The name and address of those downloading the program are requested for our records. The program operates on computers that use any version of the Microsoft Windows® operating system.

Model Overview

The IFSM model is a whole-farm simulation model of crop, dairy, or beef production. Farm systems are simulated over many years of weather to determine long-term performance, environmental impact, and economics. As such, the model is a long-term or strategic planning tool. All of the major processes of crop production, harvest, storage, feeding, milk or beef production, manure handling, and crop establishment are simulated, as well as the return of manure nutrients back to the land. By simulating various alternative technologies and/or management strategies on the same representative farms, the model assists the user in determining alternatives that provide a desired level of farm production or profit.

Model Design

The farm model is generic in design. Systems that use a wide range of crop rotations, feeding strategies, equipment, facilities, and other management options can be evaluated. The model is limited only by the crop options and management strategies defined as available in the program. Since this model has so much flexibility, however, it creates more responsibility for the model user. Describing a given production system requires the use of many model parameters. Determining appropriate values for these parameters may require some time and effort. Cross-checking parameters is necessary to make sure that everything needed is entered. For example, when a new crop is added to the model, the appropriate harvest method and associated equipment must also be added and the storage facilities and feeding strategy may need to be adjusted. Applying the model to new situations always requires some calibration or verification to assure that the farm system is adequately described.

The farm model is designed to represent the performance and economics of a farm firm. As such, the simulated system boundaries are the farm boundaries. All resources brought onto the farm are inputs to the system and those leaving the farm are the system outputs. The economic analysis includes all of the major production costs on typical farms. These costs are associated with resources brought onto the farm, while income is received for products leaving the farm.

An assumption in model design is that no interaction exists between the farm firm and the surrounding markets. Thus, the resources purchased by the farm firm do not affect input prices, and the crop yield or products produced do not affect commodity prices. This simplification of ignoring market considerations and price risk is necessary to allow the model to be used more specifically to analyze the technical and economic production efficiency of a farm system for a given regime of relative prices.

The production period of the modeled farming system is one year. Over this year, the farm's resource base is assumed to be at steady-state with neither acquisition nor disposal of durable assets (equipment, facilities, animals, etc.). Although the model is designed for multiple-year simulations, this procedure reflects replications of system performance under various single-year weather conditions, not a view of the system performance over several consecutive years.

The accounting period for the model is also one year. All dollar returns from milk, feed, and animal sales are realized in the same year as the costs incurred to produce those feeds and milk. This assumption allows the measure of system performance to reflect one year's use of resources to produce that year's production. End-of-year crop inventories are sold and feed shortages are purchased to maintain steady state accounting of resources.

This model is designed for long-term or strategic evaluations. Even though the model can be used to track farm performance over a specific year or two of weather, the recommended use of the model is for long-term simulations over many years of weather. When predicted values are compared to actual farm values for specific years, performance measures such as crop yields may show substantial error. Over many years, however, these performance measures should adequately represent the variation encountered on real farms.

The farm model is designed primarily for use in the temperate regions of the northern United States and southern Canada. Most of the validation and application of the model has been done for the Midwest, Northeast, and Pacific Northwest regions of the United States, along with some application in Ontario and Quebec, Canada. Recent applications have also included farms in northern Europe, where climatic conditions are not greatly different from those in North America. Although the model has been applied to other regions of the world, such as Brazil and New Zealand, care must be taken in verifying and/or calibrating the model to other climates.

Model Input

Input information is supplied to the program through three data files: farm, machinery, and weather parameter files. The farm parameter file contains data that describe the farm. This includes crop areas; soil characteristics; equipment and structures used; number of animals at various ages; harvest, tillage, and manure handling strategies; and prices for various farm inputs and outputs. The machinery file includes parameters for each machine available for use on a simulated farm. These parameters include machine size, initial cost, operating parameters, and repair factors. Most farm and machinery parameters are quickly and conveniently modified through the menus and dialog boxes of the user interface. Any number of files can be created to store parameters for different farms and/or machinery sets for later use in other simulations.

The weather data file contains daily weather for many years at a particular location. Weather files for all states of the U.S. are available with the model, and users may create new files for other locations. All files are in a text format so they can be easily created or edited with most text editors or spreadsheets. When creating a new weather file, the exact format of the weather data file must be followed. This format is similar to the standard format for weather data established by the International Benchmark Sites Network for Agrotechnology Transfer (*IBSNAT*) project. The first line contains a site abbreviation, the longitude and latitude for the location, the atmospheric carbon dioxide level, a parameter indicating the hemisphere (Northern=0.0, Southern=1.0), and a parameter for the average N concentration in precipitation (0.1 – 10 ppm). The remainder of the file contains one line of data for each day. The daily data includes the year and day of that year, total daily solar radiation (MJ/m^2), mean temperature (°C), maximum temperature (°C), minimum temperature (°C), total precipitation (mm), and average wind speed (m/s). Only 365 days are allowed each year, so one day of data must be removed from leap years. For the daily values, the first column must be five characters wide and each of the other six columns are six characters wide.

Model Algorithm

The model is a structured program that uses numerous objects or subroutines to represent various processes on the farm. There are nine major submodels that represent the major component processes. These major components are: crop and soil, grazing, machinery, tillage and planting, crop harvest, crop storage, herd and feeding, manure handling, and economic analysis. The functions, relationships, and parameters used in each of these submodels are described in detail in the following sections of this reference manual. The emphasis of this section is to describe the linkage and flow of information for the overall model (**Figure 1.1**).

The model begins by gathering input information. All parameters stored in the requested farm and machinery parameter files are read. The model user can modify most of these parameters by editing the displayed values in the input menus and dialog boxes. If the files are saved, the modified values become permanently stored in the file or new files can be created using different names.

After the input parameters are properly set, a simulation can be performed. The first step of the simulation execution is the initialization of numerous arrays of information in the model. This initialization sets all simulation variables to the same starting condition. Next, the machinery system used on the farm is set up. This procedure links all the appropriate machinery into operations for tillage, planting, harvest, feeding, etc. The performance and resource requirement rates are determined for each operation (See **Machinery** section).

The remainder of the simulation is performed on a daily time-step for each year of weather data. Weather data is read for the 365 days of the first year from the weather file. Each of the major farm processes is simulated daily through those weather conditions, and then the next year of weather data is read. This continues until the requested number of simulated years is complete.

In a given year, the simulation begins with spring manure-handling, tillage, and planting operations. A sequence of these operations is simulated through time on a daily time-step until all are completed or available time for these operations is used (See **Tillage and Planting** section). Up to six operations can be used for the tillage and planting of each crop. On any given parcel of land, field operations must occur in a sequence, but more than one operation can occur simultaneously. Soil moisture on the field surface is tracked through time to predict days suitable for fieldwork. The moisture is increased by rainfall and decreased through evapotranspiration and moisture flow to lower soil layers. Field operations are allowed only on suitable days when moisture is below a critical level. Tillage follows manure handling in the sequence of operations. A delay in planting due to untimely operations creates a delay in crop growth, which effects crop yield and quality. The average planting date determined for each crop is used as the seeding date for the simulation of crop growth.

Following spring operations, growth and harvest of each crop is simulated on a daily time-step over the full year (See **Crop and Soil** section). Only the crops used on the farm are simulated. If grazing is used, the first crop simulated is pasture. Pasture production is simulated each day and the quantity of forage produced is totaled for each month of the growing season. This monthly production provides a forage source for balancing the rations of animals on pasture (See **Herd and Feeding** section).

Alfalfa and grass forage for harvest are simulated next. The alfalfa and grass growth routines predict daily yield and nutrient content throughout the growing season. At harvest time, a subroutine simulates field machinery operations, drying, and rewetting in three-hour increments throughout the day (See **Crop Harvest** section). Losses and nutritive changes due to machine operations, plant respiration, and rain damage are accounted for in predicting the quantity and quality of forage harvested. Each grain crop is then simulated with the order being small grain, corn, and finally soybeans. Grain-crop models predict grain and silage yields, and the harvest routines account for losses and resource requirements during harvest (See **Crop Harvest** section).

At the completion of the daily simulation of the growth and harvest of each crop, the storage of that feed is simulated. The storage processes are simulated on an annual time step, where the dates of filling, refilling, and emptying of structures influence the losses and changes in nutrient content that occur (See **Feed Storage** section). For outside storage of hay, daily weather conditions are considered in predicting losses and nutrient changes.

The next step in the simulation is feed utilization and herd production. Feed allocation, feed intake, milk or animal production, and manure production are predicted for each animal group making up the herd. Most often these processes are simulated on an annual time step, where feed rations for all animals are formulated for the year based upon the feeds produced that year (See **Herd and Feeding** section). If pasture or a seasonal calving herd is used, feeding and herd production processes are simulated on a monthly time step. The pasture available on a given month and the stored feeds produced that year are used to feed the animal groups each month. Supplemental feeds are purchased to meet protein and energy requirements of the herd, and excess feeds are sold.

Following the herd simulation, the manure produced is tracked through the scraping, storage, and application processes to predict ammonia nitrogen losses and the whole-farm balance of nutrients (See **Manure and Nutrients** section). Manure production is predicted from the feed dry matter (DM) consumed and the digestibility of those feeds. Ammonia volatilization is simulated on daily time step as influenced by ambient temperature and rainfall. Following the prediction of losses, whole-farm mass balances of nitrogen, phosphorus, and potassium are determined as the sum of all nutrient imports in feed, fertilizer, deposition, and legume fixation minus the exports in milk, excess feed, animals, manure, and losses leaving the farm.

Fall operations are then simulated on a daily time-step beginning with manure application. Each fall operation, including any manure handling, tillage, and planting, are simulated in sequence through time until the last day of the year (See **Tillage and Planting** section). Operations are performed only on days suitable for fieldwork. Erosion of sediment is predicted as a function of daily runoff depth, peak runoff rate, field area, soil erodibility, slope, and soil cover. Phosphorus transformation and movement is simulated among surface and subsurface soil pools of organic and inorganic phosphorus. Edge-of-field runoff losses of sediment-bound and soluble phosphorus are predicted as influenced by manure and tillage management as well as daily soil and weather conditions.

At the end of each year, an economic analysis is performed based upon the performance of the farm during that year. All costs associated with growing, harvesting, storing, and feeding of crops, milking and care of the animals, and the collection, storage, and application of manure back to the cropland are included (See **Economics** section). A whole-farm budget is used, which includes fixed and variable production costs. Annual fixed costs for equipment and structures are the product of their initial cost and a capital recovery factor where this factor is a function of an assigned economic life and real interest or discount rate. The resulting annual fixed costs are summed with predicted annual expenditures for labor, resources, and products used to obtain a total production cost. This total cost is subtracted from the total income received for milk, animal, and excess feed sales to determine a net return to the herd and management. No carryover of inventories is considered; so, the economic analysis of each year can be considered an independent measure of farm performance and economics for that specific weather year.

Following the economic analysis, the simulation proceeds to the next weather year, and the process is repeated. This annual loop continues until the requested number of simulated years is complete. After the simulation is complete, all performance and economic information is organized and written to output files.

Measures of farm performance, production costs, and the net return over those costs are determined for each simulated year. All input parameters, including prices, are held constant throughout the simulation so that the only source of variation is the exogenous input of weather. Distribution of the annual values obtained can then be used to assess the risk involved in alternative technologies or strategies as weather conditions vary. Using statistical terminology, each system alternative can be considered a treatment, and each simulated year is a replicate of farm performance for the specific weather conditions of the year. Thus a multiple year simulation provides an estimate of the frequency or probability of attaining a certain level of system performance. A wide distribution in annual values implies a greater degree of risk for a particular alternative. The selection among alternatives can be made based upon the average annual measure of performance or the probability of attaining a desired level.

Model Output

The model creates output in four separate files. Following a simulation, the files requested appear in overlaying windows within the primary IFSM window where they can be selected and viewed. The four output files are the summary output, the full report, optional output, and parameter tables. The summary output provides several tables that contain the average performance, costs, and returns over the number of years simulated. These values include crop yields, feeds produced, feeds bought and sold, manure produced, a breakdown of feed production, manure handling and other farm costs, and the net return or profitability of the farm. Values are provided for the mean and standard deviation of each over all simulated years. The more extensive full report includes these values and more. In the full report, values are given for each simulated year as well as the mean and variance over the simulated years.

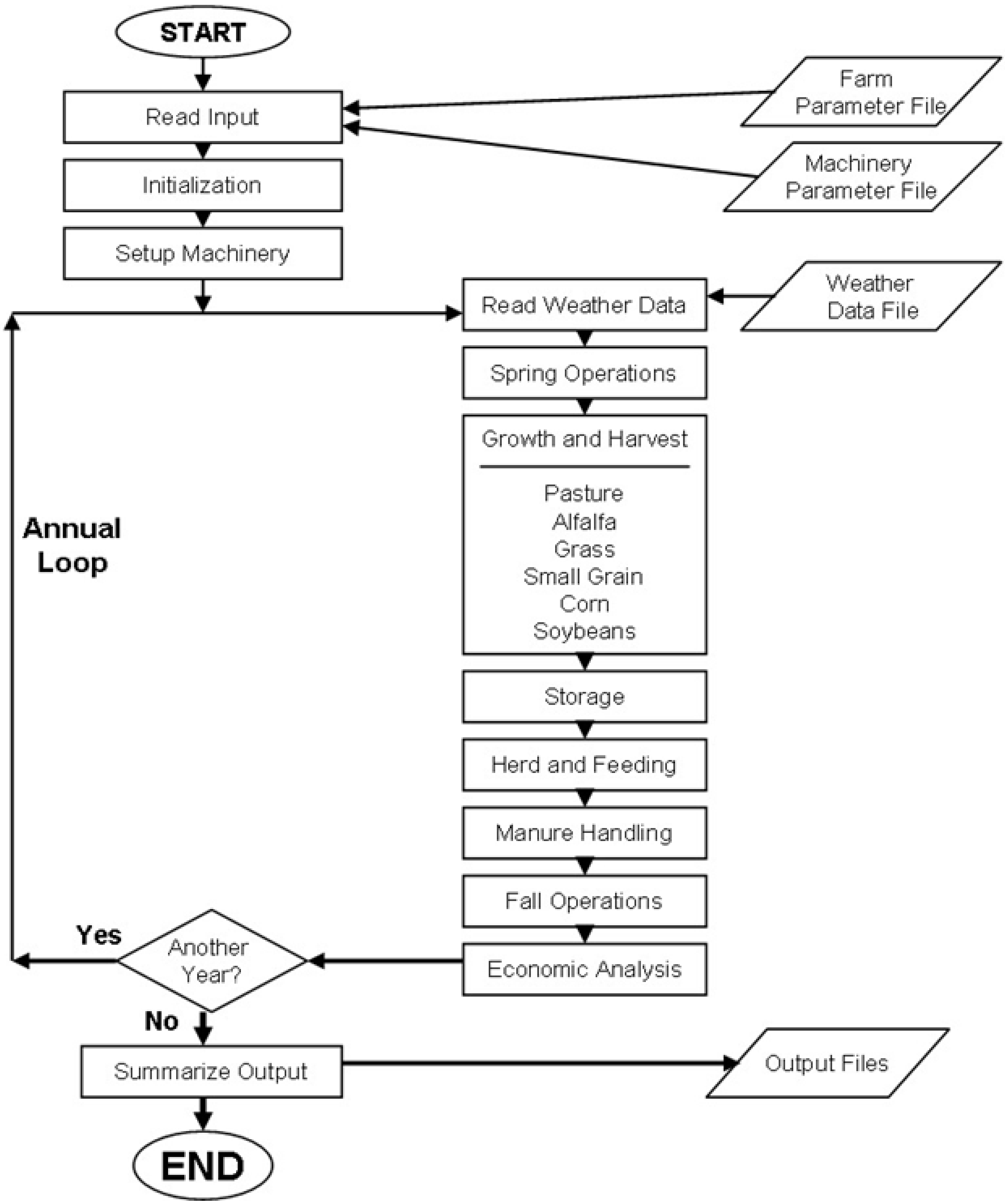
Optional output tables are available for a closer inspection of how the components of the full simulation are functioning. These tables include daily values of crop growth and development; a summary of the suitable days for fieldwork each month; daily summaries of forage harvest operations; annual summaries of machine, fuel, and labor use; and a breakdown of how animals are fed. Optional output is best used to verify or observe some of the more intricate details of a simulation. This output can become very lengthy and as such is only available when requested. To obtain a file of manageable size, simulation of only a few years is recommended when obtaining daily or monthly data options.

Parameter tables also can be requested. These tables summarize the input parameters specified for a given simulation. Any number of tables can be requested, and these tables are grouped by major sections of model input. These sections include: crop, soil, tillage and planting parameters; grazing parameters; machine parameters; harvest parameters; storage and preservation parameters; herd, feeding, and manure parameters; and economic parameters. These tables provide a convenient method for documenting the parameter settings for specific simulations.

Several aspects of the model output can be plotted. These include the pre-harvest and post-harvest crop yields, total feed and manure costs, net return for the farm, and the whole-farm balance of the three major crop nutrients (nitrogen, phosphorus, and potassium). Annual values of these output numbers are ranked from smallest to largest and plotted as a cumulative probability distribution. These plots can be viewed on the monitor and printed on a compatible printer.

Figure 1.1 - Model Algorithm

Overall algorithm of the Integrated Farm System Model



CROP AND SOIL INFORMATION

A general soil model is used to predict the tractability of soil for field operations and the moisture and nitrogen available for the growth and development of each crop. Precipitation, runoff, evapotranspiration, moisture migration, and drainage are tracked through time to predict the moisture content in multiple layers of the soil profile. Soils are generally described as clay loam, loam, sandy loam, and loamy sand with deep, moderate, or shallow depths. Parameters used to describe soils include available water holding capacity, surface albedo, evaporation and drainage coefficients, moist bulk density, runoff curve number, and the organic matter, silt, clay, and sand contents. With these characteristics, the lower limit of extractable water (permanent wilting point), drained upper limit (field capacity), and saturated moisture contents are determined using relationships described by Saxton et al. (**1986**).

The soil is modeled in five layers for grass and four layers for other crops with all layers having the same soil characteristics. In all crops, the top three layers are relatively thin surface layers with thicknesses of 30, 45, and 75 mm. In grass, the fourth layer is 200 mm thick and the fifth layer extends from the 350 mm depth to the bottom of the soil profile or the crop rooting depth, whichever is first limiting. In other crops, the fourth layer extends from the 150 mm depth to the bottom of the soil profile or the crop rooting depth. The maximum depth or bottom of the profile is the assigned available water holding capacity divided by the difference between the drained upper and lower limits of the soil (mm moisture/mm soil). Typical rooting depths of 1.5 m are used for corn and soybeans, 1.2 m for small grains, 1.8 m for alfalfa, and 0.8 m for grass.

Soil Water Balance

Soil moisture is predicted in the layers considering the water entering, moving through, and leaving the soil profile (**Jones and Kiniry, 1986**). Moisture entering the top soil layer is precipitation plus irrigation water minus runoff. Daily precipitation is obtained from the weather data provided as model input. If irrigation is used, additional water is added in 20 mm increments on days when the soil moisture drops below 60% of that at field capacity. Water runoff is calculated using the USDA Natural Resources Conservation Service runoff curve number, where the amount of runoff is related to the amount of precipitation and the moisture content in the top 45 cm of the soil profile (**Jones and Kiniry, 1986**). The incoming moisture fills the top layer until its drained upper limit is met. Remaining moisture moves through the first layer to fill the second layer. This filling effect occurs for each of the layers until the soil profile (all layers) is filled to the drained upper limit. At this point, moisture drains to the underlying ground water and is unavailable to the crop.

Moisture is extracted from the soil by evapotranspiration, i.e. water loss through evaporation from both soil and plant surfaces. Soil evaporation is determined using the two-stage method developed by Ritchie (**1972**). In stage 1, soil evaporation is limited by energy. In stage 2, soil evaporation declines as a function of time from the beginning of this stage. Plant transpiration is a function of the solar radiation level, ambient temperature, crop albedo, leaf area index, and soil-moisture availability (**Jones and Kiniry, 1986**). Moisture from soil evaporation is subtracted from the upper layer of the soil profile and plant transpiration is taken from the lower layers. Transpiration moisture is divided among layers depending on crop type. In grass, 15% is taken from the second layer, 25% from the third, 35% from the fourth, and the remainder taken from the larger lowest layer. In other crops, 15% is taken from the second layer, 25% from the third, and the remainder taken from the larger lower layer. Moisture removal from each layer is limited to the lower limit of extractable moisture for that layer.

Unsaturated moisture flow among the soil layers allows moisture to migrate toward equilibrium. Moisture moves up or down through the soil profile when the moisture level in a layer is greater than that in an adjacent layer. Moisture flow rate is a function of the soil water diffusivity and the difference in soil-moisture level between layers (**Jones and Kiniry, 1986**).

The link between soil moisture and the growth and development of the crop is modeled using a water stress factor (**Jones and Kiniry, 1986**). This factor varies from 0 to 1, where 1 represents no stress on the crop. Values are less than 1 below the critical soil moisture where stress begins. This critical soil moisture is normally set at half the available water-holding capacity in the root zone. Below this level, the water stress factor declines in proportion to available soil moisture toward zero at the lower limit of available moisture. Plant transpiration and the associated moisture uptake declines in proportion to the decrease in the water stress factor. In grass, species-specific rooting depths influence how much soil water is available to each species.

The initial soil moisture content in the spring is set on a spring thaw date. The thaw date is determined from an accumulation of degree-days in which the degree-day value for a given day is the average daily temperature above freezing (°C). Until a maximum average daily temperature of 7°C is reached, the accumulation of degree-days is divided by 6. If an average daily temperature of less than 0°C occurs, the accumulation is reinitialized. The soil is considered thawed when the degree-day accumulation reaches 14.

The initial soil moisture following the spring thaw is normally set at field capacity (the drained upper limit moisture content). In a dry climate or following a relatively dry winter season, this initial moisture is reduced. Total precipitation for the first 90 days of the year is divided by the available water-holding capacity of the soil. If this ratio is less than one, the initial soil moisture content is reduced in proportion toward a minimum level at 30% of field capacity.

Soil Nitrogen Balance

Soil *N* is tracked in two soil layers. The upper layer is the sum of the three upper soil layers defined for soil moisture, and the lower layer is the same as that defined for soil moisture. Nitrogen movement and transformation within and among soil layers is modeled with functions mostly from the DAYCENT model (**DAYCENT, 2007**) with some from the Nitrate Leaching and Economic Analysis Package (NLEAP) model (**Shaffer et al., 1991**). Total soil *N* in each soil layer includes nitrate, ammonia, crop residue *N*, manure organic *N,* and other soil organic matter. Transformation among these nitrogen pools and flow among layers is predicted on a daily time step. Initial levels for these pools are set to represent the soil following a growing season. Fertilizer in a nitrate or ammonia form and manure organic and inorganic *N* are added to the upper soil layer on the corresponding application date. A small amount of nitrate is also added to the upper layer from precipitation using a user-assigned *N* content in rainfall. Nitrates flow down through the soil profile with soil-moisture movement.

Rotation from a legume crop also provides additional crop residue *N* for use by the succeeding grain crop. Added residue *N* is 200 kg/ha from rotated alfalfa and 63 kg/ha from rotated soybeans. Considering that about 70% of the crop residue *N* is recycled into the succeeding crop, this provides *N* credits of about 140 and 45 kg/ha for rotated alfalfa and soybeans, respectively.

Nitrogen uptake by the crop is limited by available soil *N* or the *N* demand of the crop. Nitrogen stress factors are used to link crop growth and development to soil *N* level. These stress factors vary between 0 and 1 as defined by Jones and Kiniry (**1986**). The stress factor on any given day is determined from the ratio of *N* uptake over *N* demand by the crop. In grass, species-specific rooting depths influence how much soil *N* is available to each species.

Nitrogen losses from the soil due to volatilization, leaching, and denitrification are predicted each day (**DAYCENT, 2007**). Volatilization is a function of the amount of ammonia in the upper layer, temperature, and a volatilization rate. Leaching loss on a given day is related to the amount of nitrate in and the amount of moisture that drains from the lowest sublayer of the soil profile simulated (see **Nitrous Oxide** section). The concentration of *N* in moisture leaving the soil profile is the ratio of the *N* leached to the total amount of moisture that drains. Denitrification is a function of the water-filled pore space and is limited by either the nitrate or carbon dioxide available in the soil (see **Nitrous Oxide** section).

Alfalfa

Growth Processes

Alfalfa growth is simulated using ALSIM1 Level 2, a model developed by Fick (**1977**). This deterministic model simulates the physiological processes of alfalfa growth, incorporating both biological and environmental elements. Rather than predicting production on an individual plant basis, crop production is measured in units of *DM* mass per unit area of the field. A few modifications were made to the original ALSIM model to (a) perform multiple-day harvest periods along the daily yield-quality time path, (b) reset regrowth as a function of the length of the prior harvest period, and (c) use the soil model described above.

Daily growth of alfalfa is predicted for leaves, stems, basal buds, and total non-structural carbohydrate reserves. The primary unit for crop growth is material available for top growth and storage (*MATS*). *MATS* represents the pool of photosynthates created each day after respiration has been deducted (**Fick, 1977**). This material accumulation on a given day is a function of solar radiation level, crop leaf area, atmospheric CO2 level, day length, ambient temperature, and soil moisture availability. *MATS* is used primarily in the growth of leaves and stems with the remainder stored as total nonstructural carbohydrates in the crown and taproots (*TNC*). A portion of *MATS* would normally be used for root growth, which is not included in this model. To compensate for this assumption, a portion of *MATS* is allocated to other plant parts that are not tracked by the model.

A portion of the *TNC* is used for the development of basal buds, which then controls the development of new stems and leaves. Light must be supplied and materials must be present in either the leaf or basal bud pools for photosynthesis to occur. Basal bud yields (*BUDS*) are predicted as a function of the growth rate of buds, the growth rate of leaves coming from bud elongation, the growth rate of stems coming from bud elongation, *TNC*, and the relative growth rate of plant material (**Fick, 1977**).

Leaf and stem growths are modeled using similar functions (**Fick, 1977**). Leaf growth is the sum of leaf growth rate and the growth rate from bud elongation minus senescent loss. Leaf growth rate on a given day is a function of day length, current leaf mass, *MATS*, and a water stress factor. Growth from bud elongation is related to solar radiation level, ambient temperature, day length, *BUDS*, and water stress. Shading of the crop is the main cause of loss due to senescence as described by Hunt et al. (**1970**). Senescence is a function of a senescence rate, the decay time of senescing leaves, and day length. Stem growth is modeled like leaf growth except that stem growth from bud elongation is defined as 10% of that for leaf-bud elongation. Crop growth continues into the fall until the crop freezes (i.e., average daily temperature drops below -3°C).

Total non-structural carbohydrate is a function of *MATS*, the growth rate of buds, the growth rate of leaves and stems, and *TNC* respiration rate (**Fick, 1977**). *TNC* respiration is calculated from the maintenance respiration loss of *TNC* and the fraction loss of *TNC* to respiration when buds are formed or regrowth occurs. Plant life depends upon the supply of either photosynthates or accumulated *TNC*. If there is no photosynthesis or the *TNC* level drops below 5 g/m² the model simulates crop death. The *TNC* respiration portion of this model includes a maintenance component for overwinter use of *TNC*.

The water stress factor is modified from the ALSIM model to accommodate IFSM's multiple-layer soil model. This factor is a function of soil moisture level weighted across soil layers. Ten percent of the water stress factor depends upon the soil moisture in the upper three layers, and the other 90% depends upon the soil moisture in the larger lower layer. This distribution is used to reflect a deep-rooted crop that draws moisture from deep in the soil profile.

Alfalfa yield on any given day is the sum of stem and leaf *DM*. This yield represents a pure stand of alfalfa in its first production year. To better represent yields found on farms, a yield adjustment factor is used to increase or decrease the predicted yield by a set amount. This amount is the product of a yield persistence factor and an adjustment factor supplied by the model user. The persistence factor represents the yield decline that occurs each year over the life of the stand. This factor is related to the designated life of the stand and the intensity of the harvest schedule. Increasing the number of harvests during the season and/or reducing crop maturity at the time of harvest reduces persistence and thus reduces the average yield of alfalfa over the life of the stand. Typical yield reductions are 0, 0-7, 0-13, and 0-30% for the first, second, third and fourth year of stand life, respectively, where the high end of the range represents more frequent cutting schedules.

The time of crop establishment also effects alfalfa yield. When the crop is established in the spring, a first cutting does not occur on that portion of the crop. So, if a four-year stand life is specified, 25% of the crop is established each year, and that portion does not provide a first-cutting harvest. When the crop is established in late summer or fall, a full growth and harvest schedule is assumed the following year.

Harvest results in removal of top growth, and thus the resetting of leaf and stem pools to zero. During harvest the updated values of the supply of photosynthates (*MATS*), the accumulated nonstructural carbohydrates in the root reserves (*TNC*), and the water available to the plant in the soil profile are temporarily stored in the model. Once the total area of the alfalfa crop has been mowed, the starting date for regrowth of the subsequent cutting is set to a date one third of the time between the first and last day of the current harvest. *TNC*, *MATS*, and available soil water are then reinitialized at the stored values corresponding to the appropriate regrowth start date. Regrowth continues for as long as environmental conditions are appropriate, or until a subsequent harvest is initiated. This procedure allows the alfalfa crop to continue to grow and be harvested following a predicted growth quality curve through an extended multiple-day harvest period. It also delays regrowth of the subsequent cutting, reflecting the impact of slow or delayed harvests on yields and quality of subsequent cuttings.

This model was designed to simulate alfalfa production in the Great Lakes area, so the user should be aware of some assumptions and limitations to the model. The first assumptions are that the crop is pure alfalfa and the soil is well drained with no significant fertility problems. With these assumptions, the model may tend to overestimate average yields. Also, the basic growth-rate calculations depend upon leaf-area and light-absorption relationships measured in Ontario, Canada at

43.5°N latitude; so, the model may not function as well at more southerly locations with different light conditions. To partially compensate for conditions where the model may not function as desired, a user-specified yield adjustment factor can be used to adjust the predicted yield while maintaining year-to-year yield variations due to weather.

Nutritive Characteristics

The primary nutritive characteristics used in the model to describe forage quality are crude protein and neutral detergent fiber contents. Whole crop quality is determined from the individual characteristics of leaf and stem components and the portions of the crop that are leaf and stem material. The amount of leaf and stem DM available on a given day is obtained from the growth relationships described above. Quality contents of leaves and stems are determined by separate relationships using empirical models obtained from Fick and Onstad (**1988**):

$$CPL = 72.90 - 6.96 \ln (GDD + 1.0) \qquad [2.1]$$

$$CPS = 26.2 - 0.039 (GDD) + 0.000022 (GDD)^2 \qquad [2.2]$$

$$NDFL = 20.8 \qquad [2.3]$$

$$NDFS = 24.7 + 0.083 (GDD) + 0.0000448 (GDD)^2 \qquad [2.4]$$

where *CPL* and *CPS* = Crude protein content of leaves and stems, respectively, %
NDFL and *NDFS* = Neutral detergent fiber content of leaves and stems, respectively, %
GDD = Growing degree-days above 5°C, °C-d

Perennial Grass

Multiple-Species Characteristics

The model allows simulation of up to four forage species grown together in a grass pasture. One species from each of the following plant functional groups can be simulated: (1) cool-season grasses, (2) cool-season legumes, (3) cool-season forbs, and (4) warm-season grasses. The following species from each functional group are available:

Cool-season grasses:

- Kentucky bluegrass (*Poa pratensis)*
- Orchardgrass (*Dactylis glomerata)*
- Perennial ryegrass (*Lolium perenne)*
- Tall fescue (*Festuca arundinacea)*
- User defined

Cool-season forbs:

- Chicory (*Cichorium intybus)*
- User defined

Cool-season legumes:	Warm-season grasses:
• Red clover (*Trifolium pratense)* • White clover (*Trifolium repens)* • User defined	• Bermudagrass (*Cynodon dactylon)* • Switchgrass (*Panicum virgatum)* • User defined

Users may adjust the physiological parameters of a species to represent local varieties, or they may define their own species by specifying the necessary physiological parameters. To simulate two cool-season grasses growing in a mixture, users can modify the parameters of another functional group's species to make it behave like a cool-season grass.

Growth Processes

Growth of each species in the sward is predicted from emergence to the end date of vegetative growth using functions from the GRASIM model developed by Mohtar et al. (**1997**). This model was originally designed to simulate the effect of intensive grazing management practices on daily biomass production. In our model, the grass component is used to predict pasture production as well as plant growth for hay and silage production.

This model includes photosynthetic transformation and general growth functions, where light energy is transformed into carbohydrates (**Johnson et al., 1983**). Gross photosynthetic rate on a given day is primarily a function of the solar radiation level, day length, ambient temperature, atmospheric CO2 level, and the crop leaf area. Photosynthetically fixed carbon is then the product of this gross rate, a CO2-to-carbon conversion factor, and the most limiting of four potential stress factors. These factors represent stresses or adjustments due to ambient temperature, soil-moisture availability, soil *N* availability, and stored carbohydrate levels in the plant.

The carbohydrates produced are partitioned into root and shoot growth and maintenance using partitioning coefficients. The photosynthate in above-ground growth is allocated between two pools: storage and structure (**Mohtar et al. 1997**). The daily change in the storage pool is computed as the photosynthetic input minus storage and maintenance respiration. The change in the structure pool is shoot growth minus the senescent loss. Senescence increases with the amount of structural *DM* in the crop, ambient temperature, and the crop physiological stage of development.

The model simulates nitrogen fixation performed by the legume (e.g., clover) portion of the pasture, if present, using functions adapted from Wu and McGechan (**1999**). First, using data from Harris and Clark (**1996**), the model assumes a constant 1.11 g/m² dry weight of legume roots for every percentage of the pasture occupied by legumes. For example, with 20% of the pasture in legumes, dry weight of legume roots equals 22.2 g/m². The model multiplies this value times a constant nodule:legume root ratio of 0.16 (**Wu and McGechan, 1999**) and the maximum amount of *N* fixed per gram of nodule mass (110.6 mg *N*/g nodule dry weight/day) (**Wu and McGechan, 1999**). Multiplication of these values determines maximum daily *N* fixation in the pasture. For example, with 20% legumes, maximum *N* fixation equals 3.9 kg N/ha/day. Subsequently, the model multiplies maximum *N* fixation times variables (with values from 0-1) that represent (1) mineral *N* (ammonium and nitrate) in the upper soil layer, (2) soil temperature, and (3) legume water stress to determine the amount of *N* fixed daily. The soil mineral *N* multiplier decays exponentially from 1 to 0.15 as mineral *N* increases from 0 to 180 kg *N*/ha (**Wu and McGechan, 1999**). The soil temperature multiplier equals a linear interpolation of a trapezoidal function in which maximum *N* fixation occurs between 13 and 26°C with no *N* fixation below 0°C or above 30°C (**Wu and McGechan, 1999**). The legume water stress multiplier uses the equation of Jones and Kiniry (**1986**) described earlier. During a simulation, the model calculates the amount of nitrogen fixed each day and then, using a value from Høgh-Jensen and Schjoerring (**1997**), transfers 22% of it to the soil ammonium (NH4) pool, where it becomes available for uptake by grass and forb components of the sward.

Crop *DM* yield is determined assuming that carbohydrates constitute 40% of plant *DM*. Thus, total *DM* yield on any given day is 2.5 times the sum of the storage and structure carbohydrate pools of all species in the sward. Leaf and stem *DM* accumulation is the difference between that added each day for each plant component through growth and that removed through senescence. Dry matter added through leaf growth is a function of the total crop *DM* accumulation and the crop stage of development (described next). The remaining new growth is allocated to stem growth. Stem senescent loss is set at 30% of the total crop senescent loss, with the remainder being leaf *DM*.

Phenology

If the user chooses to simulate a cool-season grass, the model simulates its phenological development through six physiological stages, based loosely on a scale developed by Moore and Moser (**1991**):

Stage	Description	Index Value
vegetative V1	early vegetative (germination)	crop stage = 1.0
vegetative V2	late vegetative (primordia initiation)	1.0 < crop stage = 2.0
reproductive R1	spikelet to end of leaf growth	2.0 < crop stage = 3.0
reproductive R2	end of leaf growth to grain fill	3.0 < crop stage = 4.0
reproductive R3	grain fill to physical maturity	4.0 < crop stage = 5.0
reproductive R4	physical maturity to dry down	5.0 < crop stage = 6.0

Crop stage is predicted from the daily accumulation of a developmental rate (**Thornley et al., 1995**), where developmental rate varies throughout the six stages. For most pasture and hay or silage harvest applications, development remains within the first three stages. Due to great differences among species' functional groups, equations predicting cool-season grass phenology have not been adapted for cool-season legumes, cool-season forbs, or warm-season grasses. Consequently, phenology of these species is not simulated.

The potential rate of crop-stage development varies according to the morphological stage of development (i.e., number of leaves and tillers, described below). Whether the potential rate of development becomes the actual development rate depends upon stage of development and time of year. The actual development rate always equals the potential rate for grass in vegetative stage V1. For later stages, the actual development rate equals the potential rate only until the summer solstice; after the summer solstice, no development occurs. In addition, for reproductive stages the actual rate is reduced by a multiplier that decreases linearly from 1.0 to 0.0 as the number of reproductive tillers falls below half of the total number of tillers.

In vegetative stage V1, the potential stage-development rate equals the leaf-emergence rate (described below) divided by 3.0. In vegetative stage V2, the potential stage-development rate equals a maximum rate (0.28) that can be limited by three multipliers representing the effects of photoperiod, temperature, and soil moisture. The photoperiod multiplier increases linearly from 0.3 to 0.95 as photoperiod increases from 8 to 16 hours, then increases linearly to 1.0 as photoperiod increases above 16 hours. The temperature multiplier monotonically increases from 0 at 0°C to 1.0 at 20°C. The soil moisture multiplier ranges between 1.0 and 1.4, moving at 40% of the change in IFSM's water stress factor for plant growth. The potential development-rate during vegetative stage V2 is multiplied by the photoperiod multiplier times the minimum of the temperature and soil-moisture multipliers. The number of primordia equals the total number of leaves times 0.6.

In reproductive stage R1, the potential stage-development rate equals the leaf-emergence rate divided by the number of primordia (plus 1) times the soil-moisture multiplier calculated for vegetative stage V2. In reproductive stages R2 and R3, the potential stage-development rate equals a maximum rate (0.05) times the temperature and soil-moisture multipliers calculated for vegetative stage V2. In reproductive stage R4, the potential stage-development rate equals a maximum rate (0.1) times the temperature multiplier calculated for vegetative stage V2.

The model represents cool-season grass morphology by simulating the number of leaves and tillers per square meter of pasture. The initial number of tillers is set at 8000, all of them vegetative. The model calculates leaf-emergence rate as a maximum rate (0.15 leaves/tiller/day) that can be limited by three multipliers representing the effects of photoperiod, temperature, and soil moisture. The photoperiod multiplier increases linearly from 0.7 to 0.9 as photoperiod increases from 8 to 16 hours, then increases linearly to 1.0 as photoperiod increases above 16 hours. The temperature multiplier is a parabola that reaches its maximum value (1.0) between 20 and 25°C. Below 0°C and above 45°C, no leaf emergence occurs. The soil moisture multiplier ranges between 0.9 and 1.0, moving at one-tenth the change in IFSM's water stress factor for plant growth, which is a function of soil water content, soil water-holding capacity, and species-specific sensitivity to a ratio of the two. The leaf-emergence rate is multiplied by the photoperiod multiplier times the minimum of the temperature and soil-moisture multipliers. The model adds newly developed leaves to the simulated plant as long as the period of leaf growth has not ended (i.e., crop stage = 3.0).

The model calculates a tiller appearance rate equal to the leaf-emergence rate times 0.481. The maximum number of tillers is limited to 10640 up to the summer solstice; after the summer solstice, the maximum number of tillers decreases to 8000. The model then calculates "tiller days", equal to 3.0 divided by the leaf-emergence rate. The number of new tillers equals the minimum of (1) tiller-growth rate times the number of tillers or (2) the number of tillers required to reach maximum divided by tiller days times a multiplier describing the influence of LAI. The number of senescing tillers equals the minimum of (1) 20% of the vegetative tillers or (2) the number of tillers above the maximum times the leaf-emergence rate. If the grass is in vegetative state V2 (1.0 < crop stage = 2.0), the number of new reproductive tillers equals the number of vegetative tillers times the stage-development rate, but only until the summer solstice. After the summer solstice, no new reproductive tillers are produced.

Nutritive Characteristics

Nutritive characteristics calculated for plants harvested from the sward include whole plant crude protein and *NDF* contents (**Buxton et al., 1995**). For grass, crude protein equals 6.25 times the *N* concentration in the plant material, where *N* concentration is that taken up by the plant divided by the plant biomass *DM*. Nitrogen uptake is related to soil *N* availability and the nitrogen demand of the crop. Nitrogen demand on a given day is the difference between the critical *N* concentration desired by the plant and the actual N concentration in the plant. For cool-season grasses, the critical *N* concentration is predicted as an exponential function of the predicted crop stage of development (**Jones and Kiniry, 1986**). For cool-season legumes and forbs the critical *N* concentration is a function of plant *DM* (kg/ha) and the maximum *N* concentration (MAXNC) (**Gastal and Lemaire, 2002**):

$$\text{critical } N = \text{MIN(MAXNC, MAXNC } (DM/1000)\text{-0.5)} \qquad [2.5]$$

For warm-season grasses, the same base equation is used, but with a different exponent:

$$\text{critical } N = \text{MIN(MAXNC, MAXNC } (DM\,/1000)\text{-0.37)} \qquad [2.6]$$

The average crude protein content of the sward equals mean crude protein content of all species present, weighted by the *DM* of each.

Neutral detergent fiber (*NDF*) concentrations (both digestible and indigestible) are predicted separately for the leaf and stem components of each species. The *NDF* concentration on a given date is the total *NDF* accumulated in the leaves or stems divided by the accumulated leaf or stem *DM*. Similar relationships are used to predict the *NDF* accumulation in leaves and stems. That accumulated each day is the difference between that added through growth and that lost through senescence. That added through growth is a function of the *DM* added through growth, ambient temperature, and for cool-season grasses, crop stage of development. The base rate of *NDF* accumulation differs by functional group, with warm-season grasses accumulating digestible and indigestible *NDF* at a higher rate than cool-season species (**Fritschi et al., 1999**; **Mandebvu et al., 1999**).

The model calculates daily total *NDF* accumulation in leaves and stems as a maximum rate (1.18) times the daily structural biomass growth times multipliers representing the effects of temperature and relative total *NDF* accumulation rate by crop stage. The temperature multiplier equals 0.87 for mean daily temperatures up to 10°C and increases by 0.02 (0.03 for warm-season grasses) for every degree over 10°C. For cool-season grasses, the relative total *NDF* accumulation rate for leaves varies little, increasing from 0.35 to 0.37 as crop stage increases from 0 to 5, while the relative total *NDF* accumulation rate for stems is larger and varies more, increasing from 0.55 to 0.75 as crop stage increases from 0 to 5. For cool-season legumes, the relative total *NDF* accumulation rate for leaves and stems is fixed at 0.30 and 0.45, respectively. For cool-season legumes, the relative total *NDF* accumulation rate for leaves and stems is fixed at 0.40 and 0.60, respectively. For warm-season grasses, the relative total *NDF* accumulation rate for leaves and stems is fixed at 0.66 and 0.76, respectively.

The model calculates daily indigestible *NDF* accumulation in leaves and stems as the daily total *NDF* accumulation times multipliers representing the effects of temperature and relative indigestible *NDF* accumulation rate by crop stage. The temperature multiplier equals 0.74 for mean daily temperatures up to 10°C and increases by 0.04 (0.03 for warm-season grasses) for every degree over 10°C. For cool-season grasses, the relative indigestible *NDF* accumulation rate for leaves increases from 0.5 to 0.75 as crop stage increases from 0 to 5, while the relative indigestible *NDF* accumulation rate for stems increases from 0.45 to 0.82 as crop stage increases from 0 to 5. For cool-season species, the relative indigestible *NDF* accumulation rate for leaves and stems is fixed at 0.40 and 0.45, respectively. For warm-season grasses, the relative indigestible *NDF* accumulation rate for leaves and stems is fixed at 0.65 and 0.60, respectively. An additional small increase in indigestible *NDF* is possible in leaves or stems, equal to a base rate (0.003 for cool-season grasses, 0.002 for warm-season grasses) times the amount of digestible *NDF* (total *NDF* minus indigestible *NDF*) in leaves or stems, respectively, times the indigestible NDF temperature multiplier.

Senescent loss of *NDF* is a function of the senescent loss of *DM* predicted in the growth component above, the fraction of the crop that is leaves or stems, and the *NDF* concentration in the lost material. In-vitro true digestibility (*IVTD*) of leaves and stems of each species is calculated by dividing digestible *DM* (*DM* minus indigestible *NDF*) of leaves or stems by leaf or stem *DM*, respectively. The average *NDF* and *IVTD* concentrations of the sward equals mean *NDF* and *IVTD* of all species present, weighted by the *DM* of each.

Corn

Growth Processes

Corn biomass (silage) and grain yields are predicted from seeding through maturity. Functions for predicting above ground growth and phenological stage are taken from the CERES-maize model (**Jones and Kiniry, 1986**). As implemented in the Decision Support System for Agricultural Technology (DSSAT) version 3.0 (**Tsuji et al., 1994**). The model simulates the growth and development of a single plant that is representative of a full crop. Phenological development of leaf, stem, ear, and grain mass is predicted daily based upon soil and weather conditions. This development occurs in six physiological stages (emergence through harvest maturity) using information on the accumulation of thermal time or photoperiod (**Jones and Kiniry, 1986**).

Genetic parameters are used in setting the limits for stepping from one developmental stage to the next. To simplify our model, two genetic parameters are assigned as functions of a relative maturity index defined as days until maturity. The genetic parameters, *P1* and *P5*, as defined by Jones and Kiniry (**1986**) are estimated with the following relationships:

$$P1 = 4.0\ (RMI) - 220 \qquad [2.7]$$

$$P5 = 6.0\ (RMI) + 70, \text{ but no greater than } 685 \qquad [2.8]$$

where *RMI* is the relative maturity index in days. Other genetic parameters are set at $P2$=0.5, $G2$=750, and $G3$=9.

Our model differs from the *DSSAT* model in that root growth is not modeled. Instead of predicting the root uptake of moisture to predict the moisture stress effect on plant growth, a water stress factor is simply calculated from the available soil moisture. This factor varies linearly from 1 at the soil moisture level where plant stress begins (normally about 50% of field capacity) to 0 at the lower limit of extractable soil moisture. The water stress factor is weighted across soil layers. For corn, 30% of the water stress factor is dependent upon the soil moisture in the upper three layers, and the other 70% is dependent upon the soil moisture in the larger lower layer. This factor was used to control the growth rates of various plant parts as implemented in the *DSSAT* model (**Ritchie and**

Otter, 1985).

Growth is driven by carbon fixed through photosynthesis. Dry matter production on a given day is a function of the solar radiation level, ambient temperature, plant leaf area, and the moisture stress imposed on the plant (**Jones and Kiniry, 1986**). Partitioning of the *DM* produced among the plant components varies with the developmental stage of the crop. In stages 1 and 2, the above ground growth is restricted to leaf growth. Daily growth of leaf area per plant, total plant leaf area, and leaf mass are determined until tassel initiation. Leaf growth is related to the amount of *DM* produced and ambient temperature as influenced by any stress imposed by inadequate availability of soil moisture and nitrogen.

Tassel initiation through the end of leaf growth and silking is modeled in the third stage. In this stage, daily growth of leaf mass and area continue to be calculated in addition to daily stem growth (**Jones and Kiniry, 1986**). Stem growth is a function of daily leaf mass, leaf number, and the number of leaves at tassel initiation. The partitioning of *DM* between leaf and stem growth varies with the number of leaves on the plant.

In stage 4, growth is predicted from silking to the beginning of effective grain filling. It is in this stage that ear growth begins, leaf growth stops, and stem growth continues. Ear growth is proportional to the accumulation of growing degree-days times the water stress factor (**Jones and Kiniry, 1986**). Stem growth is then proportional to ear growth. The average accumulation of plant *DM* over the duration of this developmental stage is used to set the number of grain kernels on the ear.

Effective grain filling occurs in stage 5. During this stage, daily total grain growth is calculated with daily biomass production divided among grain, stem, and root growth. Plant *DM* is also translocated from the stems and leaves to assist grain filling. Grain filling is influenced by ambient temperature and any stress imposed by low soil moisture or soil *N*. At physiological maturity (stage 6), all crop growth functions cease but the senescence of crop material continues.

Total leaf senescence is calculated throughout all six developmental stages. Leaf senescence due to drought stress, competition for light, and low temperature are determined based upon total plant leaf area, the sum of daily thermal time, and soil moisture stress (**Jones and Kiniry, 1986**).

Grain and silage yields are tracked throughout each day of a simulation. Grain yield is the single plant grain mass times the plant population. Silage yield is the total biomass yield, which includes the sum of the plant leaf, stem, cob, and grain masses multiplied by plant population. For control over predicted grain and silage yields, yield adjustment factors are used to increase or decrease predicted yields a set amount each day over all simulated years. This gives the model user the ability to adjust or set the long-term average yield while maintaining year-to-year variation as influenced by weather.

A rotation effect is also added to adjust corn yield according to the preceding crop. For corn that follows corn, the grain and silage yields are reduced 10%. This reduction represents a typical yield difference between continuous corn and corn following a legume crop (**Rotz et al., 2001**). The grain and silage yield adjustment factors are reduced by this amount times the portion of the corn crop that follows corn each year.

The moisture content of the standing crop decreases as the crop matures. The moisture content prior to the grain filling stage is set at 85%. As the crop matures, the moisture content decreases linearly with the accumulation of thermal time reaching 60% moisture at physiological maturity. Following physiological maturity, the crop dries while standing in the field. A drying rate is predicted each day based upon the average daily temperature (**Van Ee and Kline, 1979**):

$$DR = 0.028 + 0.0025\ (TAV) \qquad [2.9]$$

Grain moisture content is predicted as an exponential function of the accumulated drying units:

$$GMC = 0.14 + 0.35\ e^{-TDR} \qquad [2.10]$$

where *TDR* is the sum of the daily drying rates since physiological maturity.

Preharvest field loss of grain may also occur following physiological maturity. For the first 45 days after maturity is reached, the loss in grain *DM* yield is 0.15% per day. After 45 days, this increases to 0.38% per day.

Corn can be grown as a double crop following a spring harvest of small grain, which requires a linkage between the two crops. If double cropping is used, the corn crop is split to allow a portion to follow the small grain. Planting and initiation of the growth of this portion occurs within a few days after small grain harvest is completed, and thus varies with the small grain growing and harvest conditions. The initial soil conditions (moisture and *N* level) for this portion of the corn are set to that following the small grain crop. Since the small grain has extracted soil moisture during spring growth, there is less available to the corn causing a greater dependence upon summer precipitation. This along with a shorter growing season reduces corn yields and increases their annual variation. For this portion of the corn crop, *RMI* is reduced as the planting date is delayed. The remaining corn crop is grown using the early spring soil moisture and *N* levels and the assigned planting and harvest dates and *RMI*. Both portions of the corn crop are simulated through daily growth and harvest processes to predict the total corn production on the farm.

Nutritive Characteristics

Nutritive values include grain and whole-plant crude protein, neutral detergent fiber (*NDF*), *P* and *K* contents, and stover *NDF* content. If double cropping of corn after a small grain crop is used on the farm, the nutritive content of both portions (that following the small grain and that not following a spring crop) of the corn crop are determined as a function of their growth and harvest conditions. When both crops are harvested as silage, a weighted average of the nutrient contents of the two corn crops is used to determine the nutritive value of the feed available to the animal.

Crude protein concentration is a function of available *N* during the growing season. The crude protein of grain is set at 10% of *DM* (**NRC, 1989**). Crude protein for the whole plant is 6.25 times the *N* content where *N* content is that taken up by the crop divided by the crop mass. Nitrogen uptake is related to soil *N* availability and the nitrogen demand of the crop. Nitrogen demand on a given day is the difference between the critical *N* concentration desired by the plant and the actual *N* concentration in the plant. The critical *N* concentration is predicted as an exponential function of crop stage of development (**Jones and Kiniry, 1986**).

Crop fiber content is the total fiber established during the growth of individual plant components divided by crop mass. Neutral detergent fiber levels in growing leaf, stem, cob, and grain tissue are 68, 63, 80, and 12%, respectively. Thus, *NDF* levels vary with the relative rates of growth of the plant components. During grain filling, the transfer of carbohydrates (non *NDF DM*) from the stover to grain further increases *NDF* levels in the stover. Stover *NDF* content is the total non-grain fiber in the plant divided by the *DM* mass of the non-grain (leaf, stem, and cob) portion of the plant. Phosphorus content in grain and silage are set at constant levels of 0.29 and 0.22 % and *K* contents are 0.37 and 0.96 %, respectively.

Small Grain

Growth Processes

The small grain component includes the prediction of phenological development, biomass (silage) yield, grain yield, and the nutritive contents of the whole plant and grain. Functions for predicting above ground growth and phenological stage come from the *CERES*- small grain models as implemented in the Decision Support System for Agricultural Technology (*DSSAT*) version 3.0 (**Tsuji et al., 1994**). Phenological development is predicted in six stages from emergence to harvest maturity based upon the accumulation of thermal time or thermal development units (**Ritchie, 1991**). As implemented in the *DSSAT* model, the same routine is used for all small grain crops, but several functions are different among the crops. Genetic parameters are used in setting the limits for stepping from one developmental stage to the next. Genetic parameters assigned for wheat, barley and oats are listed in **Table 2.1**.

Changes in leaf, stem, ear, and grain mass are predicted each day based upon soil and weather conditions. The major processes simulated include biomass growth, leaf expansion and tillering, leaf senescence, leaf area, stem growth, storage of mobile assimilates, ear and panicle growth, grain number, and grain filling. Functions used to predict these processes through each physiological stage are taken from the *DSSAT* model (**Ritchie and Otter, 1985**). Factors affecting growth and development are generally similar to those described above for corn.

Our model differs from the *DSSAT* model in that root growth is not modeled. Instead of predicting the root uptake of moisture to predict the moisture stress effect on plant growth, a water stress factor is simply calculated from the available soil moisture. This factor varies linearly from 1 at the soil moisture level where plant stress begins (normally about 50% of field capacity) to 0 at the lower limit of extractable soil moisture. The water stress factor is weighted across soil layers. For small grain crops, 30% of the water stress factor is dependent upon the soil moisture in the upper three layers, and the other 70% is dependent upon the soil moisture in the larger lower layer. This factor controls the growth rates of various plant parts as implemented in the *DSSAT* model (**Ritchie and Otter, 1985**).

The small grain component predicts yields similar to those predicted by the *CERES* or *DSSAT* models. Because these yields represent a single plant or small plot, they often over predict actual farm yields. For more control over predicted grain and silage yields, yield adjustment factors are used to increase or decrease predicted yields a set proportion each day over all simulated years. Therefore, the model user is able to adjust or set the long-term average yields while maintaining year-to-year variation due to weather influences.

The moisture content of the standing crop decreases as the crop matures. The whole-plant moisture content prior to the grain filling stage is set at 85%. As the crop matures, the moisture content decreases in proportion to the accumulation of thermal time, reaching 50% moisture at physiological maturity. Following physiological maturity, the crop dries while standing in the field. As described above for the corn component, a drying rate is predicted each day based upon the average daily temperature:

$$DR = 0.034 + 0.0035\ (TAV) \qquad [2.11]$$

Grain moisture content is predicted as an exponential function of the accumulated drying units:

$$GMC = 0.14 + 0.11\ e^{-TDR} \qquad [2.12]$$

where *TDR* is the sum of daily drying rates since physiological maturity. Preharvest field loss of grain may also occur following physiological maturity. After five days past maturity, the loss in grain *DM* yield is 0.2% per day.

Nutritive Characteristics

Nutritive characteristics of the crops include grain, stover, and whole-plant crude protein, neutral detergent fiber (*NDF*), *P*, and *K* contents. Crude protein of grain is set at 13.8% (***NRC, 1989***). That for the whole plant is 6.25 times the *N* content where *N* content is that taken up by the crop divided by the crop mass. Nitrogen uptake is related to soil *N* availability and the nitrogen demand of the crop. Nitrogen demand on a given day is the difference between the critical *N* concentration desired by the plant and the actual *N* concentration in the plant. The critical *N* concentration is a function of crop stage of development. The *N* content of mature stover (for straw bedding) is set at 0.69% (4.3% crude protein).

Crop fiber content is the total fiber established during the growth of individual plant components minus that lost through senescence divided by crop mass. Neutral detergent fiber levels in growing leaf and stem tissue are set at 45% and 65%, respectively. Senescent leaves and stems are assumed to contain 70% *NDF*. Thus, *NDF* levels vary with the relative rates of growth and senescence of the plant components. During grain filling, the transfer of carbohydrates (non *NDF DM*) from the stover to grain further increases *NDF* levels in the stover. Stover *NDF* content is the total non-grain fiber in the plant divided by the *DM* mass of the non-grain portion of the plant. To determine whole plant *NDF*, grain *NDF* is added assuming that wheat grain is 19% *NDF* and barley grain is 32% *NDF* (***NRC, 1989***). Phosphorus contents in grain, straw, and silage are set at constant levels of 0.38%, 0.12%, and 0.27% and K contents are 0.44%, 2.84%, and 1.39%, respectively.

Soybean

Growth Processes

The soybean growth model is similar in structure to the corn and small grain models, but with less detail. A simpler approach is used because only grain yield predictions are required. The relationships for predicting phenological stage were taken from the *SOYGRO* model (**Jones et al., 1991**) as implemented in *DSSAT* version 3.0 (**Tsuji et al., 1994**). With these relationships, dates are predicted for emergence, first flower, pod initiation, seed initiation, end of vegetative growth, physiological maturity, and harvest maturity. Dates are predicted each year based on accumulated thermal time and photoperiod.

Vegetative growth of the plant from emergence to the end date of vegetative growth is predicted using a model developed by Sinclair (**1986**). His relationships are used to predict photosynthetic carbon accumulation, leaf development, vegetative mass, and *N2* fixation. Our soil model is used to predict soil moisture in multiple layers. The water stress factor proposed by Sinclair was replaced with the linear relationship described above for corn and small grain crops. The water stress factor is weighted across soil layers with 30% of the factor dependent upon the soil moisture in the upper three layers, and the other 70% dependent upon the soil moisture in the larger lower layer. Because the legume crop produces the *N* required, *N* availability is assumed to never limit crop growth. Available soil *N* is used by the crop with any additional *N* requirement met through *N2* fixation.

Grain yield is determined by integrating the seed growth rate from the seed initiation date through physiological maturity. Seed growth rate (*SGR*) on a given day is a function of ambient temperature, photosynthetic carbon production, and water stress:

$$SGR = R\,(TF)\,(0.6 + 0.4PF)\,(0.7 + 0.3WSF) \qquad [2.13]$$

where R = maximum potential seed growth rate, g/m^2
TF = temperature factor for grain growth, 0 to 1
PF = photosynthetic factor, 0 to 1
WSF = water stress factor, 0 to 1

The maximum potential seed growth rate is adjusted by the user (yield adjustment factor) to a value in the range of 8 to 10 g/m^2. This provides flexibility in setting the long-term average yield while maintaining the year-to-year variation from weather. The function used to predict the temperature factor for grain growth was obtained from the *SOYGRO* model (**Wilkerson et al., 1983**). The value varies around an optimum hourly temperature between 21 and 23.5 °C. The photosynthetic factor increased in proportion to the daily photosynthetic carbon accumulation with a value of 1.0 when the daily accumulation was more then 50% of the maximum potential accumulation. The maximum potential accumulation was set at 30 g/m^2.

After the crop has reached physiological maturity, preharvest field loss of grain may occur. For the first 15 days following maturity, no loss is assumed but after that period, a *DM* loss of 1.0% per day is assumed.

Nutritive Characteristics

Nutritive characteristics of soybean grain are set to typical values (***NRC, 1989***). Crude protein, *NDF*, *P*, and *K* contents are 42.8, 15.0, 0.65, and 1.8 % of *DM*, respectively. Nutrient levels are used to determine nutrient removal by the crop, nutrient availability in feed, and nutrients removed from the farm in grain sold. Prediction of the nutrient uptake of the whole plant is unnecessary since all nutrients other than those in the grain are returned back to the soil.

Table 2.1 Small Grain Genetic Coefficients

Genetic coefficients used to predict growth and development of small grain crops (**Tsuji et al., 1994**)

	Spring Barley	**Winter Barley**	**Winter Wheat**	**Oats**
Relative rate of vernalization (P1V)	0.5	6.0	6.0	6.0
Relative delay for shortened photoperiod (P1D)	1.0	3.0	3.0	1.0
Relative grain filling duration (P5)	3.5	2.0	4.0	3.5
Kernel number per unit of stem and spike (G3)	4.0	3.0	3.8	3.3
Optimal kernel filling rate (G2)	3.0	3.0	1.6	1.5
Non-stressed dry weight of stem and spike (G3)	4.0	4.0	1.9	4.0
Phylochron interval in thermal time (PHINT)	95.0	95.0	95.0	95.0

GRAZING INFORMATION

A portion of the forage produced on the farm can be fed directly to animals through grazing. Either alfalfa or grass-based pasture can be used. If a grass crop is produced on the farm and grazing is used, the pasture will be a portion or the entire grass crop. When no grass crop is produced and grazing occurs, then the pasture is assumed to be alfalfa (i.e., alfalfa model is used to predict available forage). The portion of the crop to be grazed (pasture or grazed area) is designated by the user. Therefore, any portion up to all of the crop area (grass or alfalfa) produced on the farm can be grazed. The grazing area cannot include both alfalfa and grass-based forages. Corn, small grain and corn stover crops can also be grazed with the appropriate model used to predict available yield.

The amount of pasture available for grazing can vary throughout the year and is specified as spring, summer, and fall grazing areas. Spring grazing occurs during the months of April, May, and June. Summer grazing occurs in July and August, fall grazing occurs in September and October, and late fall or winter includes the remaining months. Forage produced during these months and excess carryover from previous months on the designated land area provides the amount of pasture available for animals to graze. The model provides control over the yield and nutritive content of pastures for the portion of the crop grazed.

Pasture Production

Yield

Either the grass or alfalfa crop models are used to predict pasture growth and yield. The model used depends upon the predominant pasture crop selected. With either model, pasture growth is simulated on a daily time step from the beginning of the growing season. The only difference between this simulation and that done for harvested forage is the timing of forage removal and the amount of forage removed. Because of differences between the grass and alfalfa models, there is some variation in the way available pasture is predicted between these two crops. In either case, the quantity of forage available each month is that grown on the available pasture land during the month plus any unused pasture forage from the previous month.

For a grass-based pasture, production is simulated using thirty-day intervals between harvests, the dates when forage is removed. The available forage is determined by the designated pasture utilization efficiency. This efficiency is about 60% for a well managed rotational grazing system. A greater value can be used to represent over stocking and a lower value will represent continuous grazing. This sets the amount made available to the grazing animals. The remaining portion, which provides the initial conditions for regrowth, is split equally between structural and storage carbon pools in the grass model (See the **Crop and Soil** section). During the first three months of regrowth, the portion of the remaining crop that is leaf material is set initially to 80% of the structural DM. For the remaining months, the initial amount of leaf material is 50% of the remaining structural DM. The initial N concentration of the remaining forage is set at 1.5% (9.4% CP) or the predicted N concentration of the crop before any forage was removed, whichever is less.

In an alfalfa-based pasture, production is predicted a little differently because of differences in the way the crop models function. Alfalfa growth is simulated throughout the season, assuming five harvests in which the entire crop is removed at each harvest. These harvests occur at the end of May, June, July, August, and October. This simulated harvest occurs in one day, and the initial conditions for regrowth are set the same as those used for alfalfa following mechanical harvest. The amount of pasture forage available to grazing animals each month is 60% of the predicted growth during that month; so, the amount of forage considered available is not directly related to the amount removed in any given harvest.

A standing corn crop can be grazed, normally in August where the available area is set by the user. Grazed corn area is then not available for harvest. The corn model is used to predict the corn biomass and nutrient content available for grazing. If other pasture is available in the same period, the total forage available to grazing animals is the sum of pasture and corn. The nutrient content of that forage is a weighted average of that from the two sources. An annual small grain crop can also be grazed using a similar algorithm as that used for grazed corn. After that portion of the small grain crop is grazed, it is no longer available for harvest. Corn stover can also be grazed from a specified area where the available biomass is that from the non grain portion of the crop. If corn is not produced on the farm or ranch, this feed source is assumed to be available on a neighboring farm. The nutrient content of this feed is set as that available in late fall and winter.

Yield adjustment factors, designated by the model user, can be used to modify the yield values predicted. The predicted amount of available forage is multiplied by two adjustment factors. The first is the yield adjustment for the associated crop (alfalfa, grass or other). Therefore, the factor designated for that crop adjusts yield for both the harvested and grazed portions of that crop. In addition, a second factor can modify the grazed yield further. This factor represents any loss in yield due to grazing from factors such as trampling of the crop. Each of these factors can be modified as desired to obtain the appropriate long-term yields for the conditions simulated. Although the mean yield is modified, the relative variation through the season and across simulated years remains as predicted by the model.

Nutritive Content

Predicting the nutritive content of grazed forage is difficult since animals are selective in what they consume. Grazing animals tend to eat the plants and the parts of given plants that are highest in nutritive value. Therefore, prediction of the nutritive content of the whole crop is not relevant. For simplicity, the nutritive contents of pasture are assigned different values during the various months of the grazing season. Assigned nutritive contents include: crude protein (CP), protein degradability, acid detergent insoluble protein (ADIP), net energy for lactation (NEL), neutral detergent fiber (NDF), phosphorus (P), and potassium (K). In addition, the calculation of fill and roughage units (See the **Herd and Feeding** section) requires values for the portion of the crop that is large particles and the NDF content of those large particles. Different values are assigned for each of the following time periods: early spring (April through May), Late spring (June), summer (July and August), early fall (September and October), and late fall and winter (November through Maerch).

Nutritive content information for each season is assigned by the user. Although these values can be changed, default values assigned represent a well-managed pasture in the northern U.S. that uses rotational grazing (**Fales et al., 1995**). Crude protein is set at 26% in the spring, drops to 23% in the summer, and rebounds to 26% in the fall. Net energy for lactation starts at 1.57 in the spring and slowly decreases to 1.42 in the fall. Neutral detergent fiber starts at 52% in the spring, increases to 55% in the summer, and drops to 53% in the fall. The rumen degradability of protein is set at 80% of CP, and the ADIP content is set at 2% of DM. Phosphorus and K contents are a function of the predominant crop. For grass-based pasture, the assigned P and K contents are 0.35% and 3%, respectively. For alfalfa, the P content is 0.26%, and the K content is 2.5% of DM.

Fill and roughage units for the pasture are determined as a function of the fill or roughage factors, NDF contents of small and large particles, and the portion of the crop in small and large particle pools (equations are given in the **Herd and Feeding** section). Assigned fill factors for pasture are 1.2 for the large particle pool and 0.5 for the small particle pool. Roughage factors are 1.0 and 0.7 for large and small particles, respectively.

Pasture Equipment and Operations

Fence and Watering Equipment

Information on the required fence, watering equipment, and related materials is used primarily for the economic evaluation of systems. Simulations do not include the size and number of paddocks, the rotation cycle through paddocks, and the moving of fence to modify paddock size. The model user provides information on the investment in fence and watering equipment, and the labor needed to manage this equipment and the grazing animals. Any other miscellaneous equipment required for grazing management can be included with the investment in watering equipment. This information is used to determine the production costs related to pasture (See the **Economics** section).

Fence is defined in two categories: perimeter and temporary fence. Perimeter fence normally represents a more permanent fence such as high tensile wire stretched across heavy posts. This category would also include gates used in this fence. Any initial investment for creating lanes for moving animals should also be included in this category. The economic life of this category is greater than that of the temporary fence (See the **Economics** section). Temporary fence is electric fence that is primarily used to divide paddocks. When temporary fence is set greater than zero, electricity used to power the fence is included as energy use.

Labor used in pasture management should include that needed for evaluating pasture and the animals on that pasture, labor for moving temporary fence and watering equipment, and that required for retrieving animals for milking or moving them to new paddocks. This labor requirement should not include reseeding, mechanical harvesting, overseeding, or clipping operations because these are specifically included in other parts of the model.

Clipping

By default, most of the pasture area is assumed to be clipped once per year, but the model user can set the number of field operations. If this value is set to zero, no clipping or similar field operations occur. For other values less than one, a portion of the land area is covered with the operations, and for greater values multiple operations are simulated. The rate or field capacity of the operation and the fuel consumption rate are functions of the size and type of mower used and the tractor used to power the mower (See the **Machinery** section). By default, a small rotary cutter is used, which is powered by the tractor designated as the mower tractor or the transport tractor in the miscellaneous machinery menu.

The pasture area covered each year by the operation is set to the area defined as the summer grazing area. Additional pasture area may be mechanically harvested once or twice during the season and thus does not require additional clipping. The amount of time spent in the clipping operation is this pasture area divided by the rate or capacity of the operation. This time defines the number of hours the designated machinery is used and the amount of labor required. Fuel consumed during the operation is the operating time multiplied by the fuel consumption rate for the operation (See the **Machinery** section). Thus the amount of fuel and labor used for pasture operations is controlled by the number of pasture operations specified.

Overseeding

The overseeding operation can be modeled much the same as pasture clipping. This operation only influences machinery, fuel, and labor use; it has no direct effect on the life cycle of the pasture or the yield and nutritive contents of the pasture. Such effects must be considered when setting the stand life, the yield adjustment factors, and the nutritional value of the pasture crop.

The overseeding operation only occurs when the stand life of the grass or alfalfa crop used is set by the user to be greater than four years. The pasture area overseeded each year is set at one fourth of the maximum grazing area. The time spent overseeding is this overseeded area divided by the operation rate. This time is used as the machinery operating time and the labor requirement for the operation. The tractor used is that designated as the transport tractor. Fuel use is the time spent overseeding multiplied by the fuel consumption rate for the operation. This operation is removed by setting the operating width or speed of pasture seeding to zero in the machinery parameters.

Pasture Use

Grazing Strategies

A grazing strategy is defined by the animal groups placed on pasture and the amount of time they have access to the pasture. Nine options are available for defining dairy animals on pasture: older heifers, older heifers and dry cows, all heifers, all heifers and dry cows, dry cows, lactating cows, all cows, older heifers and all cows, and all animals. Within these options, older heifers are those over one year of age. The amount of pasture allocated to each animal group depends upon the number of animal groups allowed on the pasture and the time each day they are on pasture. Dairy animals can be on pasture quarter days (4-5 hours per day) during the grazing season, half days (9-10) hours per day during the grazing season, full days (16-18 hours per day) during the grazing season, or full days (18-20 hours per day) all year. All year grazing implies that the animals are maintained outdoors year around even though pasture growth may not be available during some months of the year. When not on pasture, animals are maintained in the selected housing facility. If they are on pasture all year, a housing facility is not needed.

The grazing season varies with location, as set by the model user. For a 7 month grazing period, animals are on pasture from Aril to October. For 8 or 9 month periods, late fall grazing is available using stockpiled or growing forage. For longer periods, early spring and winter grazing are permitted when forage is available.

For beef cattle, the animals on pasture is defined as part of animal management. Any or all of the animal groups making up the herd can be grazed on pasture. Partial day grazing is not available for beef cattle since these animals are always on pasture for full days during the grazing season and often for the full year.

Pasture Allocation

Pasture is allocated along with other available feeds to meet the nutrient needs of each animal group in the herd while making best use of the available pasture. This is done by developing a partial total mixed ration that best compliments the quantity and nutrient content of the pasture consumed (See the **Herd and Feeding** section). The pasture consumed by a given animal group is limited by either that available or the maximum amount of pasture forage that can be consumed by that animal.

The maximum consumption is the maximum amount of this forage that can be included in the animal diet along with the available supplemental feeds required to maintain the desired production level (or as close to this level as can be obtained). Diets of each animal group are formulated with a linear program set to maximize forage use in rations (See the **Herd and Feeding** section).

Determining the amount of pasture forage available to each animal group requires proper allocation among the different groups of grazing animals. This allocation is done by comparing the available roughage from pasture with roughage available from other forages on the farm and the roughage requirement of the herd. Allocation is done each month to make best use of the pasture available that month, and stored feed inventories are modified to prepare for the allocation next month. The goal in the allocation each month is to use as much of the available pasture as possible and to use stored forages at an appropriate rate so that stocks last most of the year. For example, if both alfalfa and corn silage is being fed along with pasture, both forages are used each month at a rate where they will not be depleted much before the last simulated month of the year.

For any given month, the roughage available from pasture and other forages is the concentration of roughage units in each forage times the amount of that forage available. The roughage requirement for meeting the forage needs of the herd is estimated as a function of the number of animals in each feeding group times their average body weight times their fiber intake constraint summed over all six animal groups (See the **Herd and Feeding** section).

Rations are balanced for each of the six animal groups each month of the year. The portion of the total forage fed to each animal group that comes from pasture is set comparing available roughage to that required. If a surplus of pasture forage exists on the farm, all of the forage in the ration is provided by pasture for all animal groups that are grazed. For months when forage must be supplemented to meet herd needs, pasture is allocated first to grazing heifers and dry cows (if they are grazed). Any remaining pasture is combined with available hay and silage or purchased hay to meet the roughage needs of the lactating cows. The ratio of pasture forage in the ration to that from hay and silage is set based upon the quantity of roughage available from each compared to that required to meet the animal's needs. Although pasture use is set to distribute available pasture across all animal groups using that pasture, the full amount of available pasture forage can be depleted. In any month where the available pasture is depleted before all animals are fed (and months when pasture is not available), any remaining animals are fed using hay and silage.

The amount of pasture consumed each month is limited by that available as predicted by the growth model. The amount consumed is also limited by the forage requirement of all animal groups grazed. Any excess forage (available pasture forage minus that consumed) is available for grazing the following month. If too much pasture forage remains unused by the grazing animals during most or all weather years, the model user should consider reducing the grazed area during one or more parts of the grazing season. This allows more of the forage crop to be mechanically harvested with less available for grazing.

MACHINERY INFORMATION

The machinery component is used to determine the performance and resource use rates for all machinery operations on the farm. These rates include field capacity, throughput capacity, engine load, fuel consumption, electrical use, and labor requirement. For harvest operations, rate values are determined for six potential yields over a full range of possible crop yields. This matrix of information is carried to the harvest component where an actual yield at any given point in the simulation is used to set all rates for that yield. This is done by interpolating between the closest yields above and below the given yield to find appropriate rates for the specific conditions at that point in the simulation. For all other operations, the machinery component determines the rates that can be achieved for the given conditions and those conditions do not vary throughout the simulation.

Both parallel and sequential operations are modeled. Parallel operations are those in which two or more machinery components are performing their distinct functions simultaneously and interdependently. As an example, many harvest operations are parallel with harvest, transport and unloading occurring simultaneously. A delay in one component can affect the other two. Sequential operations are continuous and independent from other operations. This category includes most tillage, planting, and feeding operations where one machine is used to complete each operation. Parallel operations require a modeling procedure that is a little more complex than that of sequential operations.

Relationships are used to predict the performance and power requirements of each operation based upon the type and size of equipment used and the machinery parameters specified to describe each machine. With this information, engine load and the rates for the use of fuel, electricity, and labor are determined.

Work Performance

Field Capacity

The rate at which work is completed by an operation is modeled using field capacity and throughput capacity. Effective field capacity is expressed in area covered per unit time. It is a function of field speed, working width, and field efficiency:

$$EFC = S(W)(FE)\,/\,10 \qquad [4.1]$$

where EFC = effective field capacity, ha/h
S = average field speed, km/h
W = working width, m
FE = field efficiency, decimal

Effective field capacity includes lost performance from field efficiency. This efficiency is used to model time lost due to short intermittent reductions in working width, turning, minor field adjustments, and temporary slowing in the field. ASAE (**2000**) provides ranges for field efficiencies of major farm operations. Field efficiency is specified for each operation in the machinery parameter file. Typical or default values are listed in **Table 4.1** and **Table 4.2**. The model user can modify these values with the use of a text editor. The machinery parameter file must be opened with the editor, the appropriate changes made, and the file saved as a text file taking care to not change the format of the file.

Throughput capacity is a measure of the operation's ability to process material as expressed in material flow per unit of time (e.g. tonnes of *DM* per hour). Throughput capacity is primarily used to model harvest and feeding operations. For harvest operations, throughput capacity is field capacity times the crop *DM* yield. In feeding operations, a user specified throughput capacity is used unless this capacity is limited by the power available for the operation.

For parallel operations such as harvest, the capacity of the machinery system must be determined. The capacity of the system is limited to the capacity of the slowest component. A cycle time is needed to determine the rates for parallel operations. The cycle time is the time required for one transport unit to move through a complete cycle. Therefore, cycle time is the sum of the support time between the transport unit and the harvester, travel time from field to storage with a full wagon, support time at storage, extra time the transport unit must spend at the storage site to help with unloading, travel time from storage to field with an empty wagon, and idle time waiting for the harvester.

Travel times of the transport vehicle to and from the field are calculated as the user specified transport distance divided by the transport speed. The transport speed is the maximum speed that can be obtained based upon available engine power and the power required to move the vehicle. This speed is limited to a maximum value of 29 km/h for tractor and wagon transport and 45 km/h for truck transport. Transport speed of a full vehicle is normally lower than that for the return trip due to the difference in engine load caused by the weight of the material transported.

Time spent hitching and unhitching wagons and similar activities can be grouped and defined as support time. Support time at the storage site may include unhitching and hitching if extra wagons are available or the time required positioning a wagon for unloading. The user specifies the support time required for each operation, with recommended values between 0.05 and 0.08 hour for the total interface time per cycle. For dump trucks, hitching and unhitching are not required so the support time is reduced to 0.03 h per load.

The time to fill a wagon depends on the throughput capacity of the harvester and the transport wagon or truck capacity. Dry matter capacity of the transport vehicle is the user specified capacity times the*DM* content of the harvested crop. The time required to harvest one load of forage or grain, is the load size (transport vehicle capacity) divided by the throughput capacity of the harvester. When more than one transport vehicle is used, all are assumed to be of the same type and carrying capacity.

Most often the transport unit must wait for the unloading system to empty the wagon or truck. This may be as rapid as the dumping of the vehicle, but this still requires some time. The unloading time is the wagon or truck capacity divided by the unloading rate. Unloading rates vary with the type of unloading device used. For small bales, the unloading rate is 5.0 tonnes/man-h times the number of people available for unloading. When unloading into a bunker silo, the unloading rate is 12 loads per hour times the *DM* capacity of the transport vehicle. With silage bagging, the unloading rate is a function of the size of the bagging device used or the tractor power available. The maximum unloading rate is the maximum throughput capacity of the bagging machine as specified by the user in the machinery parameters. If the tractor used to power this machine does not have enough power to operate the machine at full capacity, the rate is decreased to a level that the tractor can deliver under a 70% engine load.

In the case of a mechanical blower and tower silo, the maximum material flow rate is:

$$FM = [0.37\,(\mathrm{AP})(\mathrm{LD})(\mathrm{EFM})] \,/\, H \qquad [4.2]$$

where *FM* = the flow rate of wet matter, t/h
AP = available power from the tractor power-take-off drive, W
LD = maximum allowable continuous tractor load, decimal
EFM = mechanical efficiency of blower, decimal
H = the height of the tower silo, m

The average continuous load on the tractor powering the blower is set at 71% of the maximum available tractor power. Mechanical efficiency of the blower is 0.08 for grain crop silage and 0.06 for wilted grass or alfalfa silage. The unloading rate is then the flow rate times the *DM* content of the forage.

On large farms, several harvesters may be working simultaneously to harvest a crop. The total maximum harvest rate is then the product of the number of harvesting units and the harvest rate of a single harvester. When more than one harvester is used, it is implicitly assumed in the model that all are of the same size and capacity and they use the same sized tractor. The same assumptions apply if more than one unloading device is used.

Total system capacity or work rate is limited by the lowest rate of the individual components. This limiting component is determined by calculating the time required for one transport vehicle to complete a full cycle of loading, transport, and unloading. Throughput capacity is then the material handled during the cycle divided by the cycle time. The system capacity is the minimum of the harvest (or loading), transport, and unloading capacities. Cycle time per unit of material harvested by the system is the amount of material harvested divided by the system capacity. Those operations that are not limiting the system harvest capacity (normally transport and unloading) are idle for a portion of the cycle. Idle times for those operations are the difference between the full system cycle time and the sum of the work and support times for those operations.

Field Speed

Field speed for each operation is calculated to satisfy three criteria: maximum desirable speed, maximum allowable throughput, and maximum allowable tractor load. The maximum speed that satisfies the minimum of these three potential speeds is used as the operating speed for an operation.

Maximum desirable speed is a practical speed limitation to prevent excessive wear or malfunction of the machinery used. This maximum speed is that specified by the user as a parameter for a given machine.

An implement's physical limit to process material is known as the maximum throughput capacity. Maximum throughput is also a machine parameter specified by the model user. The field speed at this limit is determined by setting the throughput capacity at this maximum value and dividing by crop yield to obtain effective field capacity. Knowing field capacity, working width, and field efficiency, equation 4.1 is used to solve for field speed.

Setting the available power and solving for speed determines potential speed at maximum engine load. This speed is a function of the maximum *PTO* power available from the tractor (or engine of a self propelled machine), a safety factor for tractor power selection, and the average power requirement of the operation. The power requirement is determined using the relationships described in the following section where the requirement is a function of the working width, tractor mass, rolling resistance, slope of the terrain, wheel slip, drawbar pull, and the power required per unit of throughput. A speed is determined using these relationships where the available power is set at 71% of the maximum available power and the speed that can be maintained with that power is determined.

Power Performance

Power Requirement

When modeling machinery systems, two forms of power requirement must be considered: peak demand and average demand. The peak power requirement occurs at maximum load or at maximum throughput under slippery or sloped conditions, and this establishes the minimum tractor size that can be matched with a given implement. Average power requirement occurs at average load, average throughput, and under normal soil conditions. It is used to establish average fuel consumption.

Average tractor power available is the maximum or rated power available from a given tractor or self-propelled machine reduced by a safety factor to assure that the actual tractor will also satisfy peak demand. This factor is the ratio of peak or maximum *PTO* equivalent power available to the average power required by the machine powered by the tractor. Typical values for the safety factor range from 1.25 to 1.6. Higher values are used when peak demand is considerably higher than average demand, i.e., when there are large variations in yield, slope, and soil conditions. A fairly conservative safety default factor of 1.4 is used in this model. Although the user can change this parameter, a text editor is required to modify the value in the farm parameter file. The average power available in any operation is the maximum available (rated power) divided by the safety factor. The rated available power for every tractor and self-propelled machine is set as a machinery parameter, which the model user can modify.

Average power required from a tractor or self-propelled machine is the sum of the tractor, drawbar, and *PTO* power requirements. The tractor component is the tractor-axle power required to move the tractor itself. Tractor-axle power is determined by the tractor weight, the friction force against the wheels, the tractor speed, the wheel slip, and the slope of travel (**ASAE, 2000**):

$$TRPWR = \left[\, 9.8\ (TRM)\ (RCC\ (\cos\theta) + \sin\theta\ (S)\ (CF_1)\ (SLF)\,\right] / 3600 \qquad [4.3]$$

where $TRPWR$ = tractor axle power requirement, kW

TRM = tractor mass, kg
RRC = a rolling resistance coefficient, dimensionless
θ = the angle of the slope of travel
CF_1 = a conversion factor from axle power to *PTO* equivalent power, 1.10
SLF = wheel slip, decimal

Rolling resistance and slip are determined using parameters and relationships documented in the *ASAE* Machinery Management Standards (**ASAE, 2000**). Although the slope can be modified in the machinery parameter file, it is normally set to zero. Taking the average of the uphill and the downhill slopes derives this value. A normal rolling resistance coefficient for operations on firm soil (harvest and manure handling) is 0.08.

Drawbar power is the tractor-axle power required to pull the drawbar load. This is calculated using the drawbar pull, tractor speed, and slip factor:

$$DBPWR = DBL\ (S)\ (SLF)\ (CF2) \qquad [4.4]$$

where $DBPWR$ = drawbar power requirement, kW
DBL = the draft load on the drawbar, N
$CF2$ = a conversion factor for drawbar power to *PTO* equivalent power, 1.2

Draft load is the force required to propel an implement in the direction of travel (**ASAE, 2000**). There are essentially two types of draft. The first is functional draft or the force required to overcome soil and crop resistance. The second is the force required to overcome rolling resistance of the implement (**Harrigan and Rotz, 1995**).

Functional draft is primarily used for tillage and planting equipment. This draft is a function of the implement type, implement width, tillage depth, and speed of operation (**ASAE, 2000**):

$$DBL = 100[A+B(S)+C(S)^2](W)(D) \qquad [4.5]$$

where A, B, and C = machine specific parameters
D = tillage depth for major tillage tools, cm

Machine specific parameters are obtained from the *ASAE* Machinery Management Standards (**ASAE, 2000**). Default values set in the machinery parameter file for tillage and planting operations are listed in **Table 4.1**. These values can be modified, using a text editor.

The draft caused by the rolling resistance of a trailing implement or wagon is the force required to overcome the resistance against the rolling wheels. This draft is determined using relationships similar to that used to determine the tractor axle power requirement (equation 4.3). In this case the mass is that of the trailing implement and/or wagon and the rolling resistance is modified for the smaller wheel sizes.

PTO power requirement is the power-take-off power needed to drive rotating implements. The total *PTO* requirement is the sum of up to three requirements: base power, power per unit width, and power per unit throughput (**ASAE, 2000**):

$$PTOPWR = E+F(W)+G(MT) \qquad [4.6]$$

where $PTOPWR$ = power-take-off power required, kW
E, F, and G = machine specific parameters
MT = material throughput, t DM/h

Machine specific parameters for major farm operations are defined in the *ASAE* Standards (**ASAE, 2000**). Values used in the model for each operation are listed in **Table 4.2**. These parameters are found in the machinery parameter file, and they can be modified using a text editor.

Available Power and Load

Power available for a given operation is that specified for the tractor or self-propelled machine used to power the operation. This is the rated engine power that is specified for each tractor, self-propelled machine, or truck. The average load on the tractor or other power source is the average power requirement of the operation divided by this maximum available power. This average loaded cannot exceed 0.71 (safety factor of 1.4). As described above, when conditions cause the load to exceed this level, the field speed and throughput capacity of the operation are reduced to a level that meets this maximum level. This assures that the average demand on the tractor or self-propelled machine is reasonable, and it allows additional power for peak load conditions.

Energy and Labor

Energy Use

Fuel and electricity use are determined for each individual operation based upon the size of the equipment used and the power required to perform the operation. Diesel engines, gasoline engines, or electric motors can power farm operations. The type of engine or motor used is specified as a machine parameter, and thus can be modified by the model user. For gasoline and diesel engines, fuel use (liters/h) is a function of the size of the tractor or other engine used and the load on the engine (**ASAE, 2000**):

$$FUEL = FC\ (PWR)\ (FUE)\ (LD)\ (FUI) \qquad [4.7]$$

where $FUEL$ = fuel use (L/h)
FC = rate of fuel consumption, L/kW-h
PWR = maximum available or rated engine power, kW
FUE = fuel use efficiency, fraction
LD = tractor or engine load, fraction from 0 to 1
FUI = fuel use index, fraction

Fuel use efficiency is a factor that reduces fuel use to account for time spent on turning and minor adjustments during which the engine is running at less than operating speed. This efficiency is defined by taking the average of 1.0 plus the field efficiency. Thus, when the field efficiency set for an operation is reduced, the fuel use efficiency decreases at half the rate. The fuel use index accounts for time spent getting the machine to the field and similar support time. This index is normally set to 1.10. Engine load for any operation is the average power required to perform the operation divided by the maximum available power.

The fuel consumption rate for diesel engines is a function of engine load and throttle setting (**ASABE, 2010**):

$$FC = PTM\ (0.22 + 0.096 / LD) \quad [4.8]$$

where *PTM* is the partial throttle multiplier:

$$PTM = 1 - (T - 1)\ (0.45\ LD - 0.877) \quad [4.9]$$

where T = throttle setting, fraction from 0 to 1

For simplicity, the throttle setting is set as 50% greater than the engine load with a maximum value of 1.0. So for engine loads greater than 0.66, the throttle is assumed to be at a maximum.

For gasoline engines, the relationship is:

$$FC = PTM\ (\ 2.74\ (LD) + 3.15 - 0.203 \sqrt{\ (697\ (LD))}\ ) \quad [4.10]$$

For electric powered equipment, electrical use (kW-h/h) is a function of available power or the rated output of the motor and the load on the motor:

$$ELECT = LD\ (PWR)\ (FUE)\ (FUI) \quad [4.11]$$

Fuel and electric use per hour of operation are determined for each operation based upon the size and type of equipment used. For harvest operations, rates of use are determined for six potential crop yields over a range from minimum to maximum possible yields. For other operations, a single average rate is sufficient. These rates are used in other parts of the model to determine the total fuel and electric use for each operation used on a given farm by multiplying the rate times the total time for the operation.

Labor Use

A rate for labor use is also determined for each operation. One person is assumed to be required for operating each tractor, self-propelled machine, or truck used in each operation, and that person is assumed to work as many hours as the machine is used. In operations such as forage harvest where harvest, transport, and unloading are occurring simultaneously, operators are required for each part of the operation. Each operator works the total time required for the overall operation. Therefore, if part of the operation such as transport includes some idle time waiting for a wagon to be filled or emptied, that idle time is included in the total rate of labor use.

There are a couple exceptions where machines operate with less labor input then the hours of equipment use. Examples are bale grinding and manure pumping. For bale grinding, the operator is assumed to be doing other feeding tasks during a portion of the grinding time. For manure pumping, the pump operates without labor input during much of the spreading time. For these operations, the labor input is reduced to a portion of the operation time.

A few operations may require labor in addition to that needed to operate machines. An example is the unloading of small hay bales. This additional labor requirement is specified in the machinery parameter file, and it can be modified with a text editor. For unloading small bales, the default labor requirement is two people in addition to the tractor or elevator operator. There are also a couple operations such as manual feeding where machines are not used. In these cases, the labor is assumed to be provided by one person.

All labor required for each operation is totaled to give a total requirement per hour of operation (man-h/h). This rate of labor is used in other parts of the model to determine total labor use by multiplying the rate times the hours required to complete each operation.

Table 4.1 Machine Draft Parameters

Typical or default values for the field efficiencies and machine specific draft parameters of simulated tillage and planting operations.

	Field	**Machine**	**Specific Draft**	**Parameters**
Operation	**Efficiency**	A	B	C
		N/cm^2	$N\text{-}h/km\text{-}cm^2$	$N\text{-}h^2/km^2\text{-}cm^2$
Subsoiler	0.85	2.24	0.00	0.018
Moldboard plow	0.80	4.20	0.00	0.037
Coulter-chisel plow	0.85	2.86	0.17	0.000
Tandem disk	0.85	1.93	0.10	0.000
Field cultivator	0.85	2.03	0.12	0.000
Seedbed conditioner	0.85	2.25	0.14	0.000
Rotary hoe	0.85	5.00	0.00	0.000
Rolling aerator	0.85	54.00	0.00	0.000
Corn planting, conventional	0.65	15.00	0.00	0.000
Corn planting, zone-till	0.65	38.00	0.00	0.000
Grain drill conventional	0.70	10.50	0.00	0.000
Grain drill, no-till	0.70	29.00	0.00	0.000

Table 4.2- Machine Power Parameters

Typical or default values for the field efficiencies and machine specific power parameters of simulated operations.

	Field	Machine	Specific Draft	Parameters
Operation	**Efficiency**	E	F	G
		kW	kW/m	kWh/t DM
Hay mowing	0.80	0.00	1.20	0.000
Mower-conditioner	0.80	0.00	3.00	0.600
Mat maker	0.80	0.00	4.00	9.200
Double swath raking	0.80	0.00	1.00	0.000
Hay tedding	0.80	0.00	1.50	0.000
Pasture seeding	0.80	2.00	0.00	0.000
Round baling	0.80	4.00	0.00	1.400
Chop to the ground	0.80	6.00	0.00	4.000
Pasture mowing	0.80	0.00	5.00	0.000
Round bale mover	1.00	0.00	0.00	0.000
Corn silage harvest	0.80	6.00	0.00	3.300
Alfalfa silage chop	0.80	6.00	0.00	4.000
Direct-cut alfalfa	0.80	6.00	0.00	5.700
Rectangular baler	0.80	2.00	0.00	1.300
Hand pickup of bales	0.80	0.00	0.00	0.000
Grain harvest	0.80	35.00	0.00	2.200
Hand feeding of hay	1.00	0.00	0.00	0.000
Self fed round bales	0.40	0.00	0.00	1.000
Bale grinder	1.00	5.00	0.00	4.500
Hand fed silage	1.00	0.00	0.00	0.000
Mobile feed mixer	1.00	0.00	0.00	2.100
Mixer & conveyor	1.00	0.00	0.00	2.800
Computer feeder	1.00	0.00	0.00	1.100
Bale drier, ambient	1.00	0.00	0.00	1.300
Bale drier, heated	1.00	0.00	0.00	1.100
Solid spreader	0.90	0.00	0.00	0.200
Slurry spreader	0.90	0.00	0.00	0.200

Manure injection	0.90	0.00	16.00	0.200
Skid steer loader	0.70	8.00	0.00	0.000
Manure pump/agitator	0.70	0.00	0.00	0.130
Gutter cleaner	1.00	4.00	0.00	0.200
Nurse tank transport	0.80	0.00	0.00	0.000
Manure irrigation pump	0.90	10.00	0.00	0.000
Round bale wrapping	1.00	10.00	0.00	0.000
Silage bagging	1.00	5.00	0.00	2.000
Manure booster pump	0.90	0.00	0.00	0.000

TILLAGE AND PLANTING INFORMATION

Tillage and planting operations occur on days within a time period specified when soil and weather conditions are suitable for field work. Up to six sequential operations can be specified by the model user for establishing each crop. This allows flexibility for the use of a single no-till operation, a set of reduced tillage operations, or a full set of conventional tillage operations. The rate at which work is completed and the subsequent fuel use and labor requirement are all determined based upon the size and type of equipment specified for each field operation.

Suitable Days

Suitable working days are the days available during which field operations can be performed. Therefore, before any field operations are simulated, the days during the year that are suitable for fieldwork are determined. This is done during the simulation of crop growth. Soil moisture conditions are predicted for each day of the year before, during, and after the growth and development of each crop (**Rotz and Harrigan, 2005**; **Harrigan et al., 1996**). For spring operations, suitable days are determined considering a fallow soil; whereas, days suitable for summer and fall operations are determined using the soil under or following the growing crop. A day is considered suitable when the soil moisture conditions support the tractability of the equipment.

The suitability of a given day is decided by comparing the moisture in the upper three soil layers (surface to 30 mm, 30 to 75 mm, and 75 to 150 mm) to preset limits for each layer. The moisture level in the remainder of the soil profile does not directly affect tractability. Soil moisture limits for tractability vary by soil texture and the type of field operation performed. Soil is generally considered tractable or suitable for field operations when soil moisture to the depth of tillage is near 95% of field capacity (**Rutledge and McHardy, 1968**), but higher levels are acceptable for some operations. Higher moisture is also more tolerable for coarse soils than fine-textured soils, and higher moisture is allowed when there are opportunities to alleviate soil compaction prior to spring planting. These remedial activities include fall tillage under drier soil conditions, winter freezing and thawing action, and spring tillage operations.

Machine tractability is decided using tractability coefficients set by the model user. A tractability coefficient is the ratio of allowable moisture in a soil layer to that at field capacity (the drained upper limit). Typical values range from 90 to 100% of field capacity on clay soils and up to 108% on sandy soils. The limit for the top two layers is normally set a little lower than that for the third layer because tractability is most sensitive to the surface conditions. Tractability coefficients also vary with the type of field operation and the time of the year. A slightly drier soil is required for spring tillage, manure injection, and planting than is allowed for fall tillage or spring surface spreading of manure. Wetter soil can be tolerated for these latter operations because soil compaction can be alleviated through spring tillage or the winter freeze/thaw process.

Six tractability coefficients are specified as parameters for each soil type. Coefficients are set for spring tillage and planting operations, fall tillage and planting operations, and fall harvest and manure spreading operations. Coefficients for the top two layers and the lower layer for each of the three types of operations are user specified. Increasing these coefficients relaxes the soil moisture constraints allowing more suitable days for fieldwork.

A few field operations are simulated that do not fall within the three designated types. These are surface spreading of manure in the spring and manure injection in either the spring or fall. For simplicity, the tractability coefficients for surface spreading in the spring are determined by increasing the spring tillage coefficients by 1.5%. Injection of manure in the spring uses the coefficients for spring tillage, while manure injection in the fall uses the fall tillage coefficients.

During daily simulations, moisture levels in the upper three soil layers on any given day are compared to the appropriate coefficients to determine if any of the types of field operations can occur. Soil moisture must be below the critical limits of all three layers to allow a given operation to occur. An array of information is established for the three types of operations over 365 days. For each operation and each day, the full day is designated as suitable or not suitable for fieldwork. During the simulation of various operations, a given operation can only be performed on days designated as suitable for that operation when labor and tractor time are available beyond that required by any competing operations on the farm.

The number of days predicted as suitable for fieldwork is primarily influenced by the tractability coefficients assumed for a given simulation (**Rotz and Harrigan, 2005**). Thus, the selection of appropriate tractability coefficients is important. Tractability coefficients should be set considering the type of operation performed and the texture of the soil. Based upon our experience with the model and the work of others (**Rotz and Harrigan, 2005**), a set of generally recommended values is given in **Table 5.1**. Model users are encouraged to evaluate the suitable days predicted for specific simulated conditions. These coefficients and other soil parameters can be adjusted to provide more or fewer suitable days. If heavy equipment is used or the soil is known to readily compact, lower coefficients should be used. Likewise, for light equipment and soils with an established sod, higher coefficients may be acceptable.

Crop residue on the soil surface slows moisture evaporation and thus influences the days suitable for fieldwork. Residue cover primarily reduces stage 1 evaporation by reflecting solar radiation, reducing wind velocity and temperature at the soil surface, and providing a barrier or resistance to moisture migration (**Rotz and Harrigan, 2005**). The reduction in stage 1 drying has been shown to be nearly linear with increasing residue cover until the soil is completely covered. Further residue continues to reduce drying but at a diminished rate. Experimental studies have measured 40 to 60% reductions in soil moisture loss under heavy residue covers compared to bare soil. In our model, residue effects are determined with a linear reduction in stage 1 evaporation of 0 to 50% with increasing residue cover from 0 to 100%.

Residue cover is influenced by the previous crop grown and the type of tillage system used. Three major tillage systems are defined as conventional, mulch, and no-till. Conventional tillage represents the use of a moldboard plow where the soil is inverted leaving no residue on the surface. Mulch tillage represents the use of a chisel plow or similar tool, which leaves a major portion of the residue on the surface. For mulch tillage of corn and small grain crops, residue is assumed to cover 50% of the soil surface in the fall with 40% coverage in the spring. For no-till systems of these crops, all residue remains on the surface providing 90% coverage in the fall and 80% coverage in the spring. For soybean residue, coverage is 50% of that assumed for corn and small grains.

The suitable days predicted for each type of field operation can be viewed as an optional output. The number of days suitable each month of each year is provided. This information is then summarized over all weather years to provide the number of suitable days each month at 50, 80, and 90% probability levels. The 50% probable number of days is the mean over the years simulated. The 80% and 90% probable values are determined for each month as the average number of suitable days in that month minus the product of the statistical t value and standard deviation of those values. The t values are set considering single tailed probabilities of 0.2 or 0.1 for the 80% and 90% probability levels, respectively. For an 80% probability, t values range from 1.38 to 0.86 depending upon the degrees of freedom (number of years simulated). For a 90% probability, t values range from 3.08 for one year to 1.32 for more than 20 years. An 80% probability represents the minimum number of suitable days that can be anticipated in 8 out of 10 weather years. This probability level is often used in the design of field machinery sets to select the smallest machinery system that allows field operations to be completed most years.

Tillage and Planting Operations

Operation Sequence

Tillage and planting operations primarily occur in the spring and/or fall. Spring operations are simulated prior to crop growth based upon the fallow soil conditions of the spring. Fall operations are simulated following crop growth using the soil moisture after crop production. Spring operations are distinguished from fall operations based upon operation starting dates designated by the model user. Operations beginning prior to day 180 (June 28) are spring operations and all others are simulated as fall operations.

The simulation of spring operations normally begins on day 80 (March 20) or when the soil thaws, whichever is later. No operation can occur prior to the user specified earliest starting date. Spring operations begin with manure application and proceed through the designated sequence of tillage operations ending with planting. For any given block of land, an operation must be completed before the next operation can occur. Over all land though, more than one operation can occur simultaneously if enough machinery and labor is available. The model user however, sets the constraint on the number of operations that can occur simultaneously. This value must be set to reflect the number of tractor operators and/or tractors available to perform simultaneous operations; the model does not include any internal check on the number available.

The model user also sets the maximum number of hours that tillage and planting operations can be performed during any given suitable day. On smaller farms, one person may be responsible for all fieldwork plus care of the livestock. On larger farms, one or more workers may spend most of their time with fieldwork. The number of hours per day must be set to reflect the size of the operation and the other responsibilities of the available labor. Operation time available on any given day for tillage and planting is the number of simultaneous operations being performed times the number of available hours per day.

Fall operations follow the same sequence as spring operations beginning with manure application if any is done. Fall operations cannot begin until after a portion of the crops are harvested. For example, fall operations can be performed on land where corn silage has been harvested, but the fall operations cannot be completed until after the harvest of corn grain is completed. Fall tillage operations can also be delayed by fall forage harvest operations. On days when a late forage harvest is being performed, those days are not available for other operations. Depending upon equipment and labor availability, tillage and manure handling is scheduled either in a series, where completion of manure spreading is required before tillage can begin, or as parallel operations where tillage and spreading progress simultaneously.

Tillage and planting operations are simulated over the land area in each crop. After a given operation is completed for one crop, it proceeds to the next. The sequence through the crops is the same for both spring and fall operations. Tillage and planting begins with alfalfa and proceeds through grass, small grain, corn, and soybean crops. Operations, of course, only occur for those crops grown on the farm.

After either the fall or spring operations are simulated, a check is made to determine if all operations were completed. If any were not completed for that particular year, a warning message is provided. This indicates that the equipment used was too small to complete the work within the suitable days available in the given year. It is normal for this to occur a few times during a simulation, particularly for fall operations. There are occasional years when weather patterns do not allow a timely finish. The assumption is made in the model that fall operations during these years are completed through extra long working hours, and all costs for those operations are accounted. If operations are not completed during many of the simulated years, some parameter changes are necessary. Changes can include the use of larger equipment, allowing more hours per day for those operations, allowing more operations to occur simultaneously, and increasing the tractability coefficients for the selected soil.

Daily Simulation

Tillage and planting operations are simulated using essentially the same algorithm for each crop. The first step is to determine the number and type of operations used from the information specified by the model user. For each operation, the field capacity is obtained from the machinery component of the model (See the **Machinery Information** section). This capacity is used to determine the amount of work completed each day the operation is performed.

In the daily simulation, the first operation begins on the first suitable day following the specified starting date for that operation. For fall operations, the crop must also have been removed from the field. During that day, the land area covered by this operation is the field capacity times the number of hours per day available for tillage and planting operations. If multiple units are used for an operation (for example two tractors and plows), the field capacity is that for the multiple units. The total operation hours available for that day are reduced by the number of operator hours used in the first operation.

The second operation is then simulated if its starting date is met and further operation time is available that day. If the second operation has a greater field capacity than the first, the amount of land covered by the second cannot exceed that completed by the first operation. Following the second operation, the operation hours available for that day is reduced by the amount used in the second operation. If further time is available (and more than two operations can occur simultaneously), a third operation is simulated if its starting date is met. This continues through the sequence of required operations for that crop.

Simulation then proceeds to the next crop where it follows the same procedure. Each operation occurs in sequence, as operation time is available. This process continues through each crop for this simulated day. The simulation then increments to the next suitable day for field work, and the sequence is repeated. This process continues until all operations are completed for all crops or until available time (suitable days) is exhausted. For spring operations, the last date available for planting is day 180 (June 28). For fall operations, the last date for tillage is the last day of the calendar year (day 365). If a planting operation is not completed due to lack of available time, the land area for that crop is reduced accordingly, i.e. if only half of the crop is planted on a given year, then the land area for growth and harvest of that crop is reduced by half for that year. This represents a major timeliness loss due to undersized equipment and/or very poor weather conditions.

This algorithm allows the completion of each operation in sequence over all crops. The first and last dates in which each operation is performed on each crop is recorded and made available in the optional output of the model. The hours used in all tillage and planting operations are totaled for each week of the year, and this value is also available in an optional output that gives a breakdown of labor use by operation.

Resource Use

At the end of each simulated year, machine, energy, and labor use are totaled. The total hours each machine is used is determined as the sum of the time that particular machine spent on each operation for each crop. The time the machine is used is the effective field capacity of the operation using that machine times the crop area. Machines used in tillage and planting include each tillage and planting implement and the associated tractors used to operate those implements.

Fuel, electricity, and labor use are also totaled across all operations and crops. Fuel use for each operation is the fuel consumption rate multiplied by the hours required to complete the operation for each crop. The fuel consumption rate for each operation is that determined in the machinery component section of this model (See the **Machinery Information** section). Total fuel use in tillage and planting operations is calculated by summing up all of the fuel used over all the operations and all the crops. Electricity use is determined with the same procedure, but electrical use would seldom occur in tillage and planting operations.

Labor used in tillage and planting is determined by assuming that one person is required to perform each operation. Labor required is calculated, as the time required for each operation summed over all operations and all crops produced.

Tillage and planting can be done as custom hired operations. With custom hire, the model performs the same daily simulation using the equipment and operations specified by the model user. In this case though, machine, energy, and labor use are ignored or set to zero. Instead the land area tilled and planted in each crop is totaled. This land area is then multiplied by the custom rate to obtain the custom cost for completing the work.

Table 5.1 - Tractability Coefficients

Typical or default values for tractability coefficients for different soil types and field operations.

	Spring Tillage[1]		Fall Tillage[1]		Fall Harvest[2]	
Soil Type	**Upper[3]**	**Lower[4]**	**Upper**	**Lower**	**Upper**	**Lower**
Clay loam	0.92	0.94	0.99	1.00	1.03	1.01
Loam	0.94	0.96	1.02	1.03	1.04	1.02
Sandy loam	0.96	0.98	1.03	1.05	1.06	1.04
Loamy sand	1.00	1.00	1.04	1.04	1.08	1.06

[1]Includes manure injection
[2]Includes surface spreading of manure in spring or fall
[3]Top 75 mm of soil profile
[4]75 to 150 mm depth in soil profile

CROP HARVEST INFORMATION

Crop harvest includes the harvest of forage and grain crops. Forage harvest normally requires multiple field operations, with field curing playing a major role in preparing the crop for safe storage and good preservation. Fewer operations are required for grain crops harvested as either silage or grain, where the moisture content in the standing crop is most often at or near a suitable moisture level for preservation. This being so, field curing either is not required or it plays a relatively minor role in the harvest process. Because of the differences in the required processes for forage and grain crops, separate models are used.

Forage Crops

Forage crops consist of alfalfa and grass. The same model is used for both crops, with a few differences in parameters and functions. Forage may be harvested as direct-cut silage, field wilted silage, high-moisture hay, or dry hay. Different processes are used depending upon the equipment available. Silage can be chopped with a forage harvester or baled in large packages, and hay can be baled in large or small packages. In the case of direct-cut harvest, one operation is used to mow and chop the standing crop for high-moisture silage. Most often, the harvest process includes a mowing operation, field curing or wilting, and a chopping or baling operation. A raking operation is typically used prior to baling or chopping to narrow or combine swaths. Tedding operations may also be used during field curing to help speed the drying of the crop.

To simulate harvest, the area planted in alfalfa or grass is divided into plots where each plot is the amount of crop that can be harvested (baled or chopped) by the given machinery system in 3 h of continuous work. Therefore, the size of the plot is a function of the machinery set used for harvest. Each plot is simulated through the sequence of required operations including drying in the field and rewetting due to rain or dew. Losses due to plant respiration, rain damage, and machine operations are tracked. Leaf and stem losses are determined individually, and crop nutrient content changes according to the change in leaf to stem ratio and the change in the nutrient content of each.

Operation Performance

Forage harvest begins when several criteria for harvest are met. The first criterion is an acceptable yield. If the yield of the standing crop is less than 400 kg/m², harvest of that crop is bypassed until a later cutting. This only occurs under draught conditions for harvests later in the growing season. When an acceptable yield is available, the remaining criteria include calendar date, forage nutritive content, weather, and the completion of corn planting. To initiate mowing, the simulated day must meet or exceed the earliest possible starting date for the particular harvest as specified by the model user. The *NDF* content of the standing crop must also be greater than or equal to that specified in the model input as the desired *NDF* content for that particular harvest. If the crop is immature (low *NDF*), harvest is delayed up to 10 days. After this period, harvest begins even if the crop is not at the desired nutritive content. For the first cutting, a check is also made to see that corn planting is complete. If not, forage harvest is delayed until planting is complete. This assures that time, labor, and equipment are available to complete forage harvest. The final check is weather. If more than 2 mm of rainfall occurs that day, mowing is delayed. The first day in which all of these criteria are met, the first plot is mowed.

Mowing continues on each day with 2 mm or less rain, but there is a constraint on the number of plots that can be curing (mown but not harvested) on any day. No more than three silage or six hay plots can be curing at one time. This is done to prevent the mowing operation from getting too far ahead of harvest. The crop continues to grow with a change in yield and nutritive content each day until it is mowed. Mowing sets the initial yield and nutritive content of a particular plot before field curing begins. When all plots for a particular harvest or cutting are completed, mowing ends until the criteria for initiating harvest is met for the next cutting.

As each plot is mowed, a matrix of information describing that plot is established. Characteristics tracked for the forage in each field curing plot include operations completed, total dry mater, leaf fraction, moisture content, nutrient content (*CP*, *NDF*, and digestible *DM*), swath width, and the time this plot has laid in the field since mowing.

Forage harvest is simulated on a daily basis with each day divided into five time periods. The first period begins at sunrise. The length of the period is equal to the day length minus 9 h. The next three periods are 3 h in length, and they encompass the time when most harvest operations are conducted. The fifth and final period is the night period, which is determined as the remainder of the 24 h in the day. Since a plot is defined as the crop area that can be harvested in 3 h, only one plot can be harvested in each daytime period.

The field curing of each plot is simulated through each period of each day until harvest is complete. Yield, nutritive content, and moisture content are updated each period based upon the drying and rewetting processes experienced and the losses and quality changes that occur. Over the night period, an increase in moisture content due to dew absorption is predicted. On days when rain occurs, crop moisture content increases with the amount of rain. The time that the rain occurs is randomly assigned to one or more of the five time periods during the day. For large amounts of daily rainfall, the rain is assigned to multiple periods with a maximum of 12 mm per period. Following small amounts of rain early in the day, some drying can occur later in the day. Relationships used to predict these processes are described in the following sections.

If raking and tedding operations are used, these operations are performed when the corresponding criteria are met for a given plot. Raking and tedding operations are performed during a period of the day with up to two plots completed during any given period.

For tedding, several options are available in setting the criteria to perform the operation. The model user selects these criteria for each harvest. The options are: after rain only, soon after mowing and after rain, second day after mowing if the moisture content is greater than 40% and after rain, and first and second day of field curing when the moisture content is greater than 40% and after rain. When simulating the tedding operation after rain, the operation occurs early on a rain-free day following any day or series of days when rain occurs. For tedding after mowing, the operation is performed during the time period immediately following the mowing of the particular plot. For the options related to hay moisture content, tedding is done during the first period of the day on plots with greater than 40% moisture. Tedding spreads the crop over the full field surface increasing its exposure to the drying air and solar radiation. The stirring and fluffing action also increases the drying rate by 30% for the rest of that day.

Raking can be used following rain and/or prior to the chopping or baling process. When used following rain, the process is simulated after the crop begins to dry following a day or period of days with rain. Raking increases the drying rate by turning the swath, but it can also inhibit drying by narrowing the swath, thus reducing its exposure to the drying air and solar radiation. The raking operation must be completed on a given plot before the baling or chopping operation can occur. This raking operation is normally done when the plot reaches a moisture content within 10 percentage points of the desired moisture content for harvest. For example, hay to be baled at 20% moisture content or less is raked at about 30% moisture. Raking prior to harvest normally occurs in the morning of the day the plot is baled or chopped. Not more than two field curing plots may be raked at any point in time to avoid having the raking operation to far ahead of the baling or chopping operation.

For field cured forage, either a baling or chopping operation completes harvest after the forage has reached a desired moisture content. The model user sets this desired moisture content for each harvest of each crop. When field curing plots are dry enough to bale or chop, harvest has a higher priority than mowing during that time period. Therefore, plots ready for harvest are baled or chopped before additional crop is mowed. Of course, when no plots are curing, no harvest is possible. If at least 3 h are left in the day (until sunset) and a curing plot is dry enough to harvest, then it is harvested. For a second plot to be harvested on that day, one of the plots must be ready for harvest with at least 6 h (two periods) left in the day. Three plots is the maximum number that may be harvested in a day, and this can only occur if one of the plots is dry enough for harvest with three harvest periods left in the day. The maximum field working time for forage harvest is, therefore, 9 h per day.

If more than one plot is ready for harvest in a given harvest period, a decision must be made as to which to harvest. Two criteria are used to select the best plot to harvest. The first is forage moisture content. Normally the driest plot is harvested first. If the driest plot is very low in quality (probably from rain damage), the higher quality plot is selected. The quality selection is determined if there is more than 10 percentage points difference in digestible *DM* between the plots.

For direct-cut harvest of forage, only one operation is simulated and field curing of the forage is bypassed. Harvest begins following the same criteria as described for mowing. Forage plots are harvested each day when rainfall is no more than 2 mm until the harvest is complete.

The length of time from the beginning of a harvest until completion is tracked to assure that the harvest is performed in an appropriate amount of time. If the equipment used is exceptionally small and/or the weather conditions over a particular harvest are very poor, the total harvest period may become excessively long. If the harvest period exceeds 39 calendar days, all remaining plots are destroyed and regrowth is initiated. A warning message is provided indicating that an excessive amount of time was spent on a particular harvest. If this occurs, the model user should increase the size of the equipment used for forage harvesting so that all plots are harvested within a reasonable time (normally less than two weeks).

During the field curing process, some plots may lie in the field for excessive amounts of time and thus loose much of their nutritional value. This will occur during extended periods of rainy weather and poor drying conditions. A maximum field curing time is set at 14 days, and a maximum *NDF* content is set at 80%. If a plot lies in the field more than this amount of time or the *NDF* content climbs above this level due to excessive loss, the plot is destroyed. A plot is normally destroyed by simulating a chopping operation where the crop is blown back on the field. If a forage harvester is not available on the farm, the hay is baled but it is not used as feed.

For each harvest or cutting, the model user specifies the preferred method of harvest. If silage harvest is specified, all of the crop for that cutting will be harvested as silage unless the available silos become filled to capacity. If this occurs, the priority for harvest shifts to baling, and the remaining forage will be harvested as hay. By the next cutting, some silage is used from the available silos thus allowing additional room for more silage harvest. If the harvest is being conducted in the fall when weather conditions are not suitable for making baled hay, the harvest operation is ended when the silos are full and any remaining forage is left standing in the field.

As each plot is harvested, it is directed towards a storage location according to the quality of the harvested forage. The ability to separate forage by quality level in storage can improve the allocation of forages to the animal groups that best use the nutrients contained in that forage (See the **Herd and Feeding** section). A critical *NDF* level, specified by the model user, is used to separate high- from low-quality forage. When the average *NDF* content for a forage plot is above this level, the plot is stored in the lower-quality location.

One to four silos of fixed capacity may be specified for silage storage. The first two silos are for high-quality forages; the second two are for lower-quality forages. When the first silos are filled, all remaining forage is forced into the second silos regardless of its quality. If a low value for the critical *NDF* level is used, all or most of the forage will be placed in the silos designated for high-quality silage and these silos will be filled to capacity. In such a case, the remaining forage is forced into the silos designated for low quality forage even if the forage has a low *NDF* content. If the critical *NDF* for storage is set high, the opposite trend can occur. When all silos are filled, the remaining forage must be harvested as dry hay.

After all plots for a given crop and harvest are completed, the *DM* production, moisture content, and nutritive contents of the harvested forage are aggregated for the simulation of storage processes. The average moisture content of the harvested forage of a particular type (low-quality or high-quality) is the harvested *DM* in each plot times the moisture content summed over all plots of that type and divided by the total harvested *DM*. The growth simulator is set for regrowth starting at a date one-third of the time between the first and the last mowing dates of all plots. Therefore, a delay in harvest affects the regrowth and thus the yield and nutritive content of the subsequent cutting. The next cutting begins when the forage crop growth again satisfies the date, yield, and maturity criteria for the subsequent harvest.

Field Curing

Field curing to prepare the crop for storage is an important part of most forage harvest systems. This process involves drying as well as the rewetting caused by dew and rain absorption. Field curing can be a relatively short period of wilting for silage harvest or a longer period to produce dry hay.

Field drying is influenced by any conditioning treatment used on the crop, the swath structure, and the weather conditions. The primary effect of swath structure is the width of the swath and the resulting swath density. When the swath is spread over more of the field surface, it is exposed more to the drying air and radiant solar energy and thus dries more rapidly. The primary weather conditions that influence drying rate are solar radiation and ambient air temperature. High soil moisture can also slow drying. During the first day following mowing, the crop will dry more rapidly than on following days. This occurs because as the forage on the swath surface dries, drying becomes more difficult from forage on the bottom of the swath. A raking operation will turn the swath stimulating a similar increase in drying.

Different conditioning treatments can be used to speed the field drying process. The four options modeled are: No conditioning, standard mechanical conditioning, chemical conditioning, and very intensive conditioning in the form of maceration and mat drying (**Rotz et al., 1990**). No conditioning is the process of mowing the forage without any treatment. Standard conditioning includes mechanical crushing of the crop with intermeshing rubber rolls. Chemical conditioning includes the same mechanical treatment plus the crop is sprayed with a 2.8% solution of potassium carbonate in water. This treatment is only effective on alfalfa. Maceration and mat drying is an experimental process where the crop is shredded and pressed into a mat for rapid drying.

Drying rate for both alfalfa and grass crops using mechanical conditioning is modeled as a function of the environment, swath density, and the application rate of the chemical conditioning treatment (**Rotz and Chen, 1985**):

$$DR = \left[\left(SI(1+9.30AR)+(5.42DB) \right) / \left(66.4\ SM + SD(2.06-0.97\ DAY)(1.55+21.9AR)+3037 \right) \right] \quad [6.1]$$

where DR = drying rate constant, 1/h
SI = solar insolation, W/m²
DB = dry bulb temperature, °C
DAY = 1 for day of mowing or raking, 0 otherwise
SM = soil moisture content at the time of mowing, % dry basis
SD = swath area density, g/m²
AR = chemical application rate, g solution/g plant DM

Standard mechanical conditioning alone is modeled by setting the chemical application rate, AR, to zero. For grass forage crops, AR must be zero since this treatment is not effective on grass. Drying rate with no conditioning is modeled following the work of Rotz et al. (**1987**). The drying rate determined for standard mechanical conditioning is reduced by 44% on first cutting, 27% on second cutting, and 0% on third and fourth cuttings.

Rain tends to reduce the effectiveness of the chemical conditioning treatment, i.e., following a period of rain, chemically treated alfalfa dries only slightly faster than untreated. To model this phenomenon, the drying rate following 5 to 15 mm of rainfall is set as the average of the drying rate with standard conditioning and the drying rate with chemical conditioning. For accumulative rainfall greater than 15 mm, drying rate for chemically treated material is set equal to that of mechanical conditioning alone, i.e. the chemical treatment has no further effect.

Maceration and mat drying is modeled as a function of the density of forage in the mat (or swath density) and the drying rate with standard mechanical conditioning (**Rotz et al., 1990**). When this process is specified, the drying rate determined for standard conditioning is adjusted as:

$$DR_M = 1361 \left[DR_s / (1604+SD) \right]^{0.868} \quad [6.2]$$

where DR_M = Drying rate constant of mat, per hour
DR_s = Drying rate constant of conventional swath, per hour

For lower values of swath density, the mat process increases the drying rate by about 250%, but as the density of the mat increases, the increased drying rate drops to less than 50%.

The initial moisture content at the time of mowing is a function of the time of the year, the time of the day, and the maturity of the crop. With the moist growing conditions of the spring and fall, the maximum moisture content of the standing crop is 5.0 on a dry basis (5 parts moisture per 1 part DM). In the summer (normal second and third cuttings), this maximum value is 4.5. This maximum value is further reduced by 0.03 for every hour after sunrise. To represent the maturing crop, the initial moisture content is reduced by 0.05 for every day after the initiation of that particular harvest.

The change in moisture content of the crop across each period of the day is described as an exponential function of the moisture ratio, the drying rate, and time. The moisture ratio is determined assuming an equilibrium moisture content of zero, which gives the following relationship (**Rotz and Chen, 1985**):

$$M_c = \left[M_o \Big/ e^{DR(DT)} \right]^{0.868} \qquad [6.3]$$

where M_c = moisture content at end of period, fraction dry basis

M_o = moisture content at beginning of period, fraction dry basis

DT = Drying time or length of period, h

The time the forage is actually drying, DT, is the length of the harvest period (3 h except for the early morning period). Using the equations for DR (6.1) and Mc (6.3), the moisture content of each forage plot is simulated through time as a function of daily weather data with the moisture content updated at the end of each harvest period. To adjust for diurnal variation in solar radiation and temperature, the drying rates for periods 1, 2, 3, and 4 are multiplied by factors of 0.8, 1.4, 1.26, and 0.7, respectively.

Another important consideration in the field curing process is the amount of rewetting that occurs. Models for dew and rain absorption were developed through consideration of moisture absorption theory (**Rotz, 1985**).

Dew is absorbed into hay following an exponential function of the moisture ratio, swath density, and the length of the night period:

$$M_f = M_e + (M_i - M_e)(e^{-WRD(T/SD)}) \qquad [6.4]$$

where M_f = moisture content in morning, fraction dry basis

M_i = moisture content in evening, fraction dry basis

M_e = equilibrium moisture content of hay in the night environment, fraction dry basis

T = length of night period, h

WRD = dew moisture absorption orate of hay, g/m² – h

= 4.0 g/m²– h

The time during the night is calculated as 24 h minus the day length. Day length, calculated in the plant growth routines, is a function of the day of the year. The equilibrium moisture content is modeled as an exponential function of relative humidity and wind velocity (**Rotz, 1985**):

$$M_e = \left[0.4 + (3.6 / (e^{0.2(WIND)})) \Big/ e^{2.5(1 - RH)} \right] \qquad [6.5]$$

where RH = average relative humidity over night, fraction

$WIND$ = average wind velocity over night, m/s.

Since relative humidity and wind velocity values are not available in the weather data file, reasonable estimates are made. Although crude, these estimates are justified because their value has only a small impact on the overall model predictions. Relative humidity is determined as a function of the temperature drop from the maximum temperature (TMAX) of the previous day to the minimum temperature during the night (TMIN):

$$RH = AMIN\left(1,\ 1 - e^{-0.2(TMAX-TMIN)}\right) \qquad [6.6]$$

This relationship provides reasonable values, biased toward high humidity. Wind velocity is determined as a stochastic function with a bias toward low wind speeds.

$$WIND = 10\ e^{-4.5(RAND)} \qquad [6.7]$$

where *RAND* is a uniformly distributed random number between 0 and 1.

Rewetting from rain absorption is modeled using a form of the moisture content equation shown above. In this case, equilibrium moisture content is fixed at a value of 4. Since the wetting period duration is not known, it is assumed to be proportional to the amount of rainfall (**Rotz, 1985**):

$$MOF = 4.0 + (Mo - 4.0)\ e^{-WRR(rn/SD)} \qquad [6.8]$$

where *MOF* = moisture content following rain
rn = rainfall, mm
WRR = rain moisture absorption rate of hay, g/m²-mm
= a constant rate of 150 g/m²-mm (**Rotz, 1985**)

Dry Matter Losses

During the harvest processes, DM losses occur in the forage due to plant and microbial respiration, rain damage, and each machinery operation. Separate functions are used to predict each type of loss. Losses are determined and subtracted from the current DM of each forage plot as it moves through each of the harvest processes. After harvest is complete, the total DM of each type of forage is determined by summing the harvested DM of all plots that make up each particular forage type, i.e. all plots designated as high-quality silage are totaled to determine the harvested quantity of high-quality silage.

Respiration loss is a function of the respiration rate and crop drying time, where the rate is primarily a function of crop moisture content and temperature (**Rotz, 1995**):

$$R=0.00017\ (T_a)\ (m) \qquad [6.9]$$

where R = rate of respiration loss, fraction DM/h
m = crop moisture content, 0.2 to 0.9 wet basis
T_a = average diurnal temperature, 0° to 40°C

The respiration loss during each time period is the rate for that period multiplied by the length of the period. A sum of the losses during all periods from the time of mowing until the plot is harvested gives the total respiration loss for that plot.

Direct losses due to rain damage of field curing forage consist of leaf loss and leaching loss. The impact of raindrops on alfalfa causes some leaves to sever from the stem and wash to the soil surface. Leaching loss occurs when soluble plant constituents dissolve and are washed from the crop. The portion of crop DM lost through rain induced leaf shatter is determined as (**Rotz, 1995**):

$$DML_l = 0.011\,(f_l)(2 - m)\,rn/SD \qquad [6.10]$$

where DML_l = portion of crop DM lost through rain induced leaf shatter, fraction
f_l = initial portion of crop DM that is legume leaves, fraction
rn = amount of rainfall, mm
SD = swath density (mass per area covered), kg DM per m²

For grass crops, the value of fl is set to zero. For alfalfa, the initial leaf portion is obtained from the growth model. Leaf loss is determined for each time period where rain occurs.

Rain leaches the more soluble constituents from field curing forages. The magnitude of this loss is proportional to the amount of rain that occurs with influences from crop NDF and moisture contents (**Rotz, 1995**). Mechanical conditioning also increases the crops susceptibility to leaching loss, but chemical conditioning of forage has no influence on rain-induced losses. Leaching loss is modeled as:

$$DML_r = 0.0061\,(F_c)\,(1- NDF)(0.9-m)(rn) \qquad [6.11]$$

where DML_r = portion of crop DM lost through leaching by rain, fraction
F_c= Conditioning factor,
= 1.0 for crushing, crimping or flail conditioning
= 0.8 for no conditioning
= 3.0 for macerated and matted forage
NDF = neutral detergent fiber concentration in forage DM, fraction

Rain damage is adjusted on any crop where maceration and mat drying is used (**Rotz et al., 1990**). With this technology, leaf material is well macerated and pressed into the mat, so the leaf loss predicted for standard conditioning (Equation 6.10) is reduced by 50%. Macerated material is very susceptible to leaching though, so the leaching loss predicted for standard conditioning is multiplied by three (Equation 6.11).

Each machine operation that occurs on each forage plot causes DM loss. Major operations include mowing and conditioning, tedding, raking, baling and chopping. The type of machines used and the operating parameters of those machines influence the amount of loss incurred. Crop factors such as species, maturity, moisture content, leaf fraction, and swath structure may also influence the loss. In alfalfa, mechanical losses influence the relative amounts of leaf and stem material remaining in the forage, which effects forage nutrient contents. In grass crops, leaf material does not detach easily, so losses are assumed to equally affect leaf and stem components.

Loss from mowing and conditioning is a function of the amount of delicate (legume) leaves on the crop, crop maturity, and machine design (**Rotz, 1995**):

$$DML_m = 0.006\,f_m\,(1+2\,f_l)\,S \qquad [6.12]$$

where DML_m = portion of crop DM lost during mowing and conditioning, fraction
S = crop stage of development factor,
= 1 at early to late vegetative stage for legumes, boot stage for grass
= 2 at early to mid-bloom stage for legumes, heading stage for grass

= 3 at late to full bloom stage for legumes, anthesis stage for grass

f_m= mower factor,

= 0.5 for cutterbar or disk mower without conditioning

= 1.0 for cutterbar or disk mower with roll or light flail conditioning

The fraction of the loss that is leaves is normally set at 75% in alfalfa crops. For grass, the loss is assumed equally distributed between leaf and stem components.

Tedding loss is greatly affected by crop moisture content, particularly in alfalfa. As the crop dries, leaf shatter increases exponentially (**Rotz, 1995**). Tedding loss is predicted as:

$$DML_t = 0.044\ (1 + 6 f_l)(1\text{-}m)^{1.5} \qquad [6.13]$$

where DML_t= the portion of crop DM lost during tedding, fraction

m = crop moisture content, fraction

f_l = initial portion of crop DM that is legume leaves, fraction

For grass crops, fl is set to zero indicating that there are few leaves susceptible to shatter loss. For alfalfa, this value is the ratio of leaf DM to total forage DM following the mowing operation. Normally, much of this loss is leaf material. The fraction of the loss that is leaves is predicted as a function of crop moisture content (**Rotz, 1995**):

$$R_l = 0.9 - 0.4\ m \qquad [6.14]$$

Raking loss is influenced most by crop moisture content and the density of the forage laying in the swath or windrow (**Rotz, 1995**). Loss increases as the crop moisture content decreases, particularly below 30% moisture. When the crop is spread over much of the field surface, it is more difficult to gather with the rake and loss increases. Raking loss is predicted as:

$$DML_{rk} = [0.02\ (1+2f_l\ M)(1\text{-}m^{1.5})]\ /\ SD \qquad [6.15]$$

where DML_{rk} = portion of crop DM lost during raking, expressed as a fraction.

As in the tedding model, fl is set to zero for grass crops. For alfalfa, this value is the ratio of leaf DM to total crop DM following all previous processes and operations that occurred to that particular plot. The fraction of the total loss that is leaf DM is determined as:

$$R_l = 0.8 - 0.4\ m \qquad [6.16]$$

Dry matter losses during the baling of hay typically vary between 2 and 5% of yield with a greater loss from some large round baler designs. Baler losses include pickup, chamber, and ejector losses. Pickup loss varies between 1 and 3% of crop yield with the loss primarily influenced by the density of the swath or windrow and crop moisture content (**Rotz, 1995**):

$$DML_p = 0.003\ /\ m\ (SD) \qquad [6.17]$$

where DML_p = the portion of crop *DM* lost at the pickup, fraction

Chamber loss is material that is disassociated and dropped during the formation of the bale in the baling chamber. The amount of chamber loss is largely influenced by crop moisture content with greater loss in drier material. Although baler design can influence this loss, a typical small rectangular baler or variable chamber baler is used (**Rotz, 1995**). The portion of crop DM lost from the baler chamber is:

$$DML_b = 0.0025\, f_b \,/\, m^{1.2} \qquad [6.18]$$

where DML_b = portion of crop DM lost from the baler chamber, fraction

f_b = baler factor,

= 1.0 for typical baler designs and daytime baling

For small rectangular balers, a bale ejector is often used to throw bales into a trailing wagon. With this added equipment there is a small additional loss. Ejector loss is a function of the moisture content of the hay harvested:

$$DML_e = f_l\,(0.04 - 0.1\, m) \qquad [6.19]$$

where DML_e = portion of crop *DM* lost from the baler ejector expressed as a fraction.

Generally more leaf material is lost from balers than stem material. The fraction of the total loss that is leaves is set at 0.4 for pickup loss and 0.8 for chamber and ejector losses.

Losses from a forage harvester used to chop silage include pickup and drift loss. Pickup loss is predicted using the same relationship as the baling operation. Drift loss occurs as the chopped material exits the spout of the harvester and travels toward a trailing wagon or truck. Dry forage is more susceptible to drift loss than wet forage. Drift loss is predicted as (**Rotz, 1995**):

$$DML_c = 0.002 \,/\, m^4 \qquad [6.20]$$

where DML_c = fraction of crop *DM* lost from the harvester spout.

The predicted loss increases from 0.5 to 3.2% as moisture content deceases from 80% to 50% with a typical loss of 1.5% at 60% moisture.

The model user can adjust the average loss that occurs from machinery operations. In the operation section of the machinery parameter file, the average DM loss is listed for each operation. These values can be modified through the use of a text editor. By adjusting these values up or down, all internal calculations are adjusted proportionally. The same variation occurs around harvest conditions, but the long-term average is adjusted to the new amount. This adjustment is only useful for exploring the impact of using machines that allow different amounts of loss.

Forage Nutrient Content

Most losses affect the nutrient content of the remaining forage. Losses such as respiration and leaching remove more of one nutrient than others. This relative difference in nutrient loss affects the nutrient concentration in the remaining forage. Leaf loss also affects nutrient concentration because leaves contain greater nutritive value then stem material. As leaves are lost, the overall nutritive content of the remaining forage decreases.

When DM is depleted from the crop by respiration, the change in concentration of any plant constituent or nutrient is predicted based upon its rate of loss relative to total dry matter loss (**Rotz, 1995**). Thus, the effect of DM loss on nutrient concentration is:

$$C_f = (C_i - aL) / (1\text{-L}) \qquad [6.21]$$

where C_f = final nutrient concentration, fraction

C_i = initial nutrient concentration, fraction

L = portion of total DM depleted from crop, fraction between 0 and 0.4

a = ratio of the loss of the given nutrient to the total loss, fraction

The value of 'a' varies among plant constituents. Dry matter lost in respiration is primarily readily available carbohydrates (glucose, fructose, and sucrose) with little loss of nitrogen (crude protein) and structural carbohydrates (fiber). Thus, the change in concentration of nutrients in the remaining forage can be readily predicted. To model changes in concentration of crude protein, neutral detergent fiber, and other forage plant constituents not used in plant respiration, the value of *a* is zero. For highly digestible carbohydrates, the value of *a* is 1. Respiration losses are assumed to have equal effect on leaf and stem plant components.

Leaching loss occurs when soluble plant constituents dissolve and are washed from the crop by rain. These constituents, primarily from the cell contents of the forage plant, are highly digestible nutrients for the animal. As a result, leaching loss causes a substantial decrease in digestibility and an increase in fiber concentration in the forage.

The change in concentration of nutrient constituents resulting from leached DM is predicted using the same equation given for respiration. Dry matter lost is all highly digestible, so *a* is equal to 1 when predicting the concentration of digestible nutrients. For predicting fiber concentrations, *a* is zero since little fiber or cell wall material is lost. Leached DM is about 30% soluble nitrogen or CP (**Rotz, 1995**), so *a* is 0.3 when predicting the change in CP. Because the nitrogen loss is soluble nitrogen, the concentrations of insoluble nitrogen (ADIP), expressed as a fraction of DM, increase similar to fiber, i.e. $a = 0$. Leaching loss is assumed to affect leaf and stem components equally.

Leaf loss can occur from rain damage or machine operations. In either case, the effect on forage nutrient content is the same. Since leaves contain a different concentration of nutrient constituents than stem material, any loss of leaves results in a change in nutrient concentration of the forage. The quantity and nutrient contents of leaf and stem material are individually tracked for the forage in each plot. For alfalfa, the overall quality of the remaining forage is reduced in relation to the loss of leaves. Since alfalfa leaves are more digestible, higher in crude protein, and lower in fiber than stem material, the loss of leaves causes a decrease in digestible nutrients and crude protein, and an increase in fiber concentration. For grass, leaf loss is essentially the same as that for stem material, so the nutrient concentrations in the crop do not change.

The quantity of leaf and stem DM and the nutrient contents (CP and NDF) of leaf and stem material are among the characteristics of forage plots tracked through time. After each simulated harvest period of each day, the DM yield and nutrient contents of leaf and stem components are updated based upon the losses that occurred from processes that took place to that plot during that period. Therefore, the nutrient content of forage in any plot at any point in the harvest process and at the completion of harvest is the leaf DM times the given nutrient content plus the stem DM times the nutrient content divided by the total crop DM. The overall nutrient content of the harvested forage of a particular type (low-quality or high-quality) is the harvested DM in each plot times the nutrient content summed over all plots of that type and divided by the total harvested DM.

Resource Use

Resources used in forage harvest include machinery, labor, fuel, and electricity. The amount of each used is dependent upon the machinery system used in the harvesting process and the amount of time required to complete each task.

The model user specifies the harvest system used in each cutting or harvest of each forage crop including the size and type of machinery available. As mentioned above, harvest system types include direct-cut silage, wilted chopped silage, wilted bale silage, and baled hay. Different harvest systems can be used on different cuttings of each crop. The appropriate machinery must be selected to complete all requested harvest types. If the user does not select a required machine, a warning message indicates the machine needed.

By design, the model allows considerable flexibility in selecting machinery systems. This flexibility allows the user to work with a wide range of machinery, but this also places some responsibility on the model user. The user must set up a reasonable system to complete the required work in a reasonable amount of time. There are warning messages that occur if parts of the system are too different from that required. Often the model will simulate the processes even though they may not be the most economical or practical methods for completing the work. The optimal system for a simulated farm is sometimes best determined by simulating various options to determine those that maximize farm profit.

The time required to complete each operation is the land area covered divided by the effective field capacity of the operation. This field capacity is determined by interpolation among the capacity values developed in the machinery component across potential crop yields (See the **Machinery Information** section). The average effective field capacity for a particular harvest is determined based upon the preharvest crop yield. Since a forage plot is defined as the amount of land harvested in 3 h for baling and chopping operations, the total time required for these operations is essentially three times the number of plots harvested.

The annual use of each machine is the total time required to complete all operations in which that machine was used summed over all harvests. For machines used in transport and unloading, this time normally includes some idle time, because each machine is considered to be in use during the full operation cycle, i.e. machine use equals operation time.

The resources used in forage harvest are determined as the rate of use for each machinery operation times the number of hours required to complete the operation. Fuel, electricity, and labor usage rates are determined as a function of crop yield in the machinery component (See the **Machinery Information** section). At the completion of each harvest, the average resource use rate is determined using the average preharvest crop yield. Interpolation within the matrix of rate values provided by the machinery component over a range in potential yields is used to determine the actual rate of fuel, electricity, and labor use for the average yield.

The total resources used in forage harvest are determined by summing that used in all harvests of both alfalfa and grass forage crops. Resource use includes the number of hours each machine is used and the total fuel, electricity, and labor used to perform all operations. Along with total use, uses in hay and silage production are individually tracked to allow an economic analysis of each feed type (See the **Economics** section). These values are used in the economic component along with similar values from other components (tillage, planting, manure handling, and feeding) to determine the machinery, energy, and labor costs for the farm.

Resource use is only considered when the harvest machinery is owned. If custom harvest is specified for any of the harvest operations, the same machinery operations are simulated. Fuel, electricity, and labor are ignored in custom operations, and the number of hours that the machinery is used is not accounted. Instead, the amount of forage harvested or the land area covered by the operation is totaled to determine a custom cost (See the **Economics** section).

Grain Crops

Compared to forage harvest, a simpler model is used to simulate the harvest of grain crops. Grain crops include corn, small grains (barley, wheat, or oats), and soybeans. Corn and small grains can be harvested as silage, high-moisture grain, or dry grain. Soybeans however, can be harvested only as dry grain. The harvest model includes simulation of the machinery operations required to remove and handle the crop, losses that occur, and the resources used during harvest.

Machine Performance

The same base model is used to harvest grain crops for silage, high-moisture grain, and dry grain, but some differences are required to represent the three types of harvest. Harvest operations begin with silage production if silage is used on the farm. Silage harvest is simulated only if a silo is specified for grain crop silage. If a silo is not designated for this type of feed (or it is filled to capacity), silage harvest is bypassed and the model proceeds to grain harvest.

Harvest dates can also be used to control the type of harvest that occurs. For example, if the silage harvest date for a particular crop is set later in the year than grain harvest, silage harvest does not occur for that crop even if a silo is available. Likewise if the starting date specified by the model user for high-moisture grain harvest is later than that for dry grain, high-moisture grain harvest is avoided.

Harvest processes are simulated on a daily time step. For a given crop, silage harvest begins on or after the starting date specified by the model user when criteria are met for crop moisture content and completion of alfalfa harvest. The model user specifies a desired moisture content for silage at harvest. The moisture content of the standing crop (See the **Crop and Soil** section) is compared to this specified level. If the standing crop contains more moisture than that desired, harvest is delayed up to 10 days. On the first day when the moisture content of the crop reaches the desired level, harvest can begin. Harvest is not delayed passed 10 days to avoid excessively late harvest conditions. A check is also made to be sure that the late summer harvest of alfalfa is complete. If not, harvest is delayed to avoid too many operations occurring at the same time.

After silage harvest begins, the crop is harvested each day that is suitable for field operations. A day is suitable for fieldwork when the surface soil moisture is below set limits (See the **Tillage and Planting** section). Harvest proceeds on each suitable day until either the designated silo capacity is filled or the crop is all harvested. If silage harvest is stopped due to the limit of silo capacity, the remaining crop is delayed for grain harvest. The moisture content of the harvested silage (initial storage moisture content) is determined as the average moisture content of all silage harvested from that particular crop.

High-moisture grain harvest begins on or after the calendar date specified by the model user when soil and weather conditions are suitable. Harvest continues each suitable day until the silo capacity designated for high-moisture grain is met or the entire crop is harvested. If crop remains after the silo is full, harvest is delayed on the remaining crop for dry grain harvest.

Dry grain harvest begins on or after the date specified by the model user when the crop has reached full maturity. If the crop has not reached maturity, harvest is delayed up to 10 days. If maturity is not obtained within this 10-day window, harvest is then begun to avoid excessively late harvest conditions when suitable days are difficult to obtain.

The moisture content of the grain at harvest is obtained from the crop growth component (See the **Crop and Soil** section). This moisture content may be too high for satisfactory storage and thus require drying. Acceptable moisture contents for storage are set at 15.5% for corn and 13.5% for small grains and soybeans. The drying required is the amount of moisture that must be removed to drop the harvest moisture content down to these levels to assure good preservation and storage.

The amount harvested each day is a function of the effective field capacity of the harvest system. Field capacity is obtained from the machinery component where system capacities are predicted across a wide range in possible crop yields (See the **Machinery Information** section). The capacity for a given day is determined using the crop yield on that day. Interpolation within the matrix of harvest capacity versus crop yield information derived by the machinery component is used to determine the capacity for each day of harvest.

Harvested yield is the standing crop yield reduced to account for preharvest and harvest losses. Standing crop yield is that predicted each day by the crop growth component (See the **Crop and Soil** section) including preharvest lost. Silage yield is the total biomass yield. For high-moisture grain or dry grain, the standing crop yield is that predicted in the crop component as grain yield. There is also an option for high-moisture ear corn. This feed includes the corncob and a small amount of additional stalk material. High-moisture ear corn yield is set as 1.25 times the grain yield.

Crop DM harvested each day is the harvested crop yield times the harvest system capacity times the number of hours worked each day. The working hours per day is specified by the model user. For silage and high-moisture grain, the amount harvested is limited by silo capacity. On a day when the available silos become filled to capacity, the amount harvested is that required to fill the silos. Crop area harvested each day is the harvested crop DM divided by the harvested yield. The amount harvested on a given day also cannot exceed the total crop area available.

As the harvest process is simulated, the beginning and the ending dates of harvest for each crop are recorded and provided as output from the model. The beginning date is the first day any type of harvest occurs. If silage is produced from that particular crop, then this date is the beginning of silage harvest. If not, then this is the beginning of either high-moisture or dry grain harvest. The final date is the day of the year when the last of the crop is harvested regardless of the type of harvest. When suitable days are not available late in the year to complete all harvest operations, a warning message occurs to alert the model user. The model assumes though that harvest is completed in some way by working longer hours or under unfavorable soil conditions. Thus the final feed production reflects the harvest of the entire crop even though daily simulation of the harvest process is not possible.

In the case of early harvest of small grain silage, field wilting of the crop maybe required. A very simple field curing model is used. If the moisture content of the standing crop is greater than that required for storage, a mowing operation is included. Crop drying occurs each day that the rainfall is less than 2 mm. The drying rate is such that the crop moisture content (wet basis) decreases by 6 percentage points each day. Chopping is than delayed until the wilting crop reaches the desired moisture content specified by the model user.

With small grain harvest, straw may also be harvested for bedding material. Straw harvest occurs immediately following grain harvest. The amount of straw harvested is determined on a daily time step where the amount available for harvest is 70% of the non-grain crop yield. This yield is determined as the difference between the total biomass (silage) yield and the grain yield of the standing crop. A 30% reduction in straw yield reflects the loss in stubble, which remains in the field including any straw not picked up by harvest machinery.

A baling operation is used to harvest the straw. Depending upon the machinery specified by the model user, baling can be done in small rectangular bales or large bales. The time required for baling is the land area in grain crop (excluding silage land) divided by the effective field capacity of the baling operation. This capacity is again obtained from the machinery component (See the **Machinery Information** section) as a function of potential crop yield. By interpolation, a capacity is determined for the given straw yield. For small bales, the harvest system includes the transport and unloading of the straw for storage. With large bales, a separate transport operation is modeled where the time required is the land area divided by the effective field capacity of the transport operation.

Losses and Nutritive Value

In grain production, some loss may occur in the standing crop prior to harvest. This loss is a function of the length of time the crop remains in the field after it has matured. The date the crop reaches maturity is determined in the crop growth component (See the **Crop and Soil** section). For corn, the preharvest grain loss is 0.15% of the grain yield for each day of delay beyond the physiological maturity date. If harvest is delayed by more than 45 days beyond maturity, this loss increases to 0.38% per day. In small grains the loss is zero for the first 5 days beyond maturity, increasing to 0.2% per day thereafter. Soybeans have no loss for the first 15 days following maturity with a 1% per day loss after that time.

Harvest losses for grain crops are set as fixed values. Unlike forage crops, these losses do not vary with crop and harvest conditions. For silage harvest, the normal loss is 5% of the standing crop yield. This loss is assumed to effect all plant components equally, so there is no change in nutritive value. Therefore, the nutrient contents of grain crop silage entering storage are those predicted for the standing crop (See the **Crop and Soil** section) on the day silage harvest is completed. The loss in high-moisture grain harvest is normally 3.5%, and the loss for dry grain is twice this value or 7% of the standing crop grain yield.

The model user can adjust harvest loss values. These losses are set in the operation section of the machinery parameter file. Silage harvest loss is set on the line defined as corn silage harvest, and high-moisture grain loss is set on the line labeled as grain harvest. For dry grain, the high-moisture grain loss is multiplied by two. Editing the machinery parameter file with a text editor can modify these loss values, but care must be taken to avoid changing the format of the file.

The nutrient contents of harvested grains are defined to be those specified by the model user as the nutrient contents of available feeds. These nutrient contents are assigned in the animal-feeding menu as feed parameters for high-moisture ear corn, high-moisture grain, corn grain, and small grain. Nutrient contents of these feeds do not vary with growing and harvest conditions.

Resource Use

Resources used in grain crop harvest again include machinery, fuel, electricity, and labor. At the end of the harvest season, the resources used are totaled for all types of harvest and for each grain crop produced. Machinery use is a function of the machines used in each harvest operation and the time spent completing each operation. Each machine is assumed to be operating at some capacity throughout the full harvest operation, therefore the hours each machine is used is that required to complete the operation. The time for each operation is the land area harvested by that operation divided by the effective field capacity of the operation. Machine use hours used for silage, high-moisture grain, and dry grain harvest are also tracked separately to enable a partial budget analysis of the costs for each type of feed produced (See the **Economics** section).

Fuel, electricity, and labor use are each determined by multiplying a rate of use by the time required to complete the operation. The rate at which each resource is used is determined in the machinery component of the model over a range of potential crop yields (See the **Machinery Information** section). Through interpolation, an appropriate rate is determined for each resource based upon the standing crop yield at the completion of each type of harvest. Fuel, electricity, and labor use are summed over all harvest operations used on each crop. The use for silage, high-moisture grain, and dry grain harvest are also individually determined for use in the partial budget analysis by feed type.

If custom operations are used for grain crop harvest, resource use is ignored. The model performs the same simulation using the equipment systems specified by the model user, but the hours these machines are used and the fuel, electricity, and labor required are not accounted. Instead the total quantity of wet silage harvested and the total land area harvested as grain are determined. These values are multiplied by the appropriate custom charge for these operations in the economic component of the model (See the **Economics** section).

Corn Silage Cutting Height

An additional option that can be simulated in corn silage harvest is the effect of cutting height. Leaving a long stubble improves feed value of the harvested silage by 1) wasting the least nutritious portion of the plant, and 2) increasing the grain ratio in the harvested forage. Grain contains more protein and energy and less fiber, so increasing the grain to stover ratio provides forage with more favorable nutrient characteristics. Leaving this stubble, though, reduces harvested yield.

A typical or standard cutting height is about 15 cm. If the cutterbar is raised, less of the low quality stubble is harvested, which increases the overall quality of the forage harvested. To simulate this effect, harvested yield is reduced by 40 kg DM/ha per cm of increased cutting height above 15 cm. This stubble is assumed to contain 5.6% CP and 70% NDF. Stubble moisture content is set 20% greater than that in the remaining plant. Moisture, CP, and NDF contents of the harvested crop are then determined by subtracting the stubble quantities from the initial amounts predicted for the standing crop at harvest and dividing this result by the harvested DM. The grain to stover ratio is also adjusted to account for the stover left behind. Although corn variety likely affects these changes, these relationships should well represent general farm practice. These adjusted forage characteristics are tracked through the storage and feeding components to predict effects on animal diet, intake, and production.

FEED STORAGE INFORMATION

Harvested feeds include dry grain, high-moisture grain, dry hay, and ensiled forage. Dry hay can be stored inside a shelter or outdoors exposed to weather. Ensiled forage can include grain crop silage (corn and/or small grain) and grass and/or alfalfa silage. A number of different storage options are provided. These options will be discussed as grain, hay, and silo storage. The primary considerations in modeling feed storage are the DM loss and nutritive changes that occur during storage.

Following harvest, hay or silage can be separated into two levels of quality for storage and feed allocation. All alfalfa or grass harvested with a neutral detergent fiber (NDF) content greater than a user-defined value is considered low quality feed and the remaining material is considered high-quality. Separation of feeds by quality level enables more efficient use of the feeds by animals at various stages of growth and lactation. Neutral detergent fiber is used as the basis of separation because animal intake and production are sensitive to the NDF content of forages. The same model is used to predict losses in forage at each quality level.

Grain Storage

Grain storage is modeled very simply compared to the storage of forages because the changes that occur and their effect on feed value are relatively small. Grain (corn, soybeans, wheat, barley, or oats) harvested for dry storage is either harvested at a moisture suitable for long term storage or it is dried to such a moisture content soon after harvest.

For dry grain, the DM loss that occurs during storage is set at 1% of the total feed DM placed in storage. The nutritive value of the feed removed from storage is set at typical values that are not affected by the type or length of storage (**NRC, 1989**). Nutritive characteristics include crude protein (CP), degradable protein, acid detergent insoluble protein (ADIP), net energy of lactation (NEL), and neutral detergent fiber (NDF) contents. The model user can adjust preset values for these feed characteristics. Thus, growing and harvest conditions do not affect the nutritive value of grain feeds.

The same procedure is used for high-moisture grain. These feeds include high-moisture small grain, shelled corn grain, and ground ear corn. Use of ground ear corn increases the harvested DM by 25%, and it affects nutritive content. For high-moisture grains, the DM loss is 5% of the initial DM regardless of the type of silo used or the length of storage. Nutritive characteristics following storage are again set at typical values (**NRC, 1989**) that can be modified by the model user.

Dry Hay Storage

The hay storage component predicts the DM loss and nutritive changes in baled hay during inside and outside storage. Hay characteristics tracked through the storage process include DM, CP, ADIP, and NDF contents. Characteristics of the material as placed into storage are obtained from the harvest component. When hay is baled before it is totally dry, hay can be treated with a preservative or dried in the barn.

Inside Storage

Hay stored under cover in relatively large stacks normally goes through a heating process during the first few weeks of storage. Heating occurs due to the respiration of microbial organisms (bacteria, fungi, and yeasts) in the hay. Through respiration, carbohydrates in the plant tissue and oxygen are converted to carbon dioxide, water, and heat. These products leave the hay causing DM loss. Hay containing less than 15% moisture is relatively stable and little respiration occurs. In hay with more moisture, microbial respiration causes the hay to heat during the first three to five weeks of storage. Dry matter and nutrient losses due to this microbial activity and nutrient changes due to heating of the hay are modeled. The amount of heating that occurs and the resulting loss is related to the moisture content and density of the hay entering storage.

In practice, the initial DM density of hay bales is a function of the baler adjustment, hay moisture content, and other conditions during baling. In this model, conditions other than moisture content are ignored. Thus, bale density is estimated as a function of the moisture content (Mo) of the hay baled (**Buckmaster et al., 1989b**):

$$D = 100 + 440\,(M_o) \qquad [7.1]$$

where D = bale density, kg/m3
M_o= moisture content at baling, fraction wet basis

The amount of heat developed in the stack during those first few weeks is then determined as a function of the initial moisture content and bale density (**Buckmaster et al., 1989b**):

$$\mathrm{Q} = 104\,(M_o)^{2.18}\,(\mathrm{D})^{0.5} + 5.72\,(M_o)^{1.23}\,(D)^{.94} \qquad [7.2]$$

where Q = total sensible heat generated, kJ/kg DM.

Respiration is a chemical reaction where carbohydrates in the plant material are converted to carbon dioxide, water, and heat that leave the stack. The DM lost from the hay is predicted based upon the theoretical conversion of DM through this chemical reaction (**Buckmaster et al., 1989b**).

$$DML_f = \left[Q+2433\left(M_o - M_f(1\text{-}M_o) / (1\text{-}M_f)\right)\right] \Big/ \left[(1\text{-}M_o)\left(14206\text{-}2433(M_f)/1\text{-}M_f)\right)\right] \qquad [7.3]$$

where DML_f = DM loss during the first month of storage, fraction
M_f= final moisture content of hay in storage, fraction

During the heating process, hay moisture is lost. The moisture content is assumed to drop to 12% where it is considered to be dry and relatively stable for the remainder of the storage time. After the first month of storage, respiration and the resulting loss is assumed to continue at a relatively low rate. This is modeled assuming a loss of 0.3% of stored DM per month during the remainder of the storage period:

$$DML_i = L_f + 0.003\,S_p \qquad [7.4]$$

where DML_i = total DM lost from hay stored inside, fraction
S_p = hay storage period, months

The heating of hay also affects the availability of protein in the hay. Heat accumulation is modeled in degree-days above 35°C. As heat buildup increases, more protein is bound to fiber and thus becomes less available to the animal. An empirical relationship developed from experimental data is used to predict this heat build up as a function of the initial moisture content of the hay:

$$DD = 14000(M_o - 0.12)^{1.6} \qquad [7.5]$$

where DD = heat development, degree days above 35°C.

Outside Storage

Hay stored outside and unprotected experiences the same loss as hay stored inside plus additional loss from weathering of hay on the exposed surface. Dry matter loss often increases an additional 10 percentage units or more with outside storage of large round bales. The type of storage facility, the surface area-to-volume ratio of the bale and the ambient weather primarily influence this additional loss. Total storage loss in large round bales is modeled as the sum of the loss during inside storage plus that due to weathering.

An empirical model is used to predict DM loss due to weathering of large round bales (**Harrigan et al., 1994**). Dry matter loss is a function of bale density, bale diameter, average rainfall per month, and the degree days ambient air temperature is above 0°C during the storage period. Weathering loss for bales on a well drained site or elevated off the soil is given by:

$$DML = \left[DML_i + 0.0018(RAIN)(DDAY)\right] / \left[DENS(\mathrm{DIA}^3)\right] \qquad [7.6]$$

where DML = total DM lost, fraction

DML_i= dry matter lost with inside storage, fraction

$RAIN$ = average rainfall per month of storage, 5 to 17 cm/month

$DDAY$ = degree days over 0°C during storage period, 800 to 10000 °C-day

$DENS$ = bale density, 130 to 224 kg DM/m3

DIA = bale diameter, 1.2 to 1.8 m

When bales are set on damp soil, moisture migrates from the ground into the bale increasing microbial respiration, deterioration, and loss. DM loss is increased as much as 3.5 percentage units. This was modeled by increasing the weathering loss by 0.01 for each month of storage to a maximum of 0.035.

Round bales can also be protected from weathering by wrapping their circumference with plastic wrap. A plastic wrap can reduce weathering loss to about 36% of the loss in an uncovered bale. This was modeled by multiplying the weathering loss portion of the above equation by 0.36, i.e. changing the constant 0.0018 to 0.00065.

Large round bales are sometimes stored in a triangular stack and covered with a tarp. When a well protected stack is placed on a well drained surface, hay losses should fall between that with shed storage and individually wrapped bales. For our analysis, weathering loss in a covered stack was predicted to be half that in individually wrapped bales. This is modeled by replacing the constant 0.0018 of equation 1 by 0.00033.

Nutritive Changes

Dry matter loss and heating during hay storage affect the concentration of most nutrients. Respiration reduces forage quality by decreasing some of the most digestible nutrients. Much of the lost DM is nonstructural carbohydrate, which is oxidized to carbon dioxide and water. As carbohydrates are depleted, proteins and fats also are used in respiration but at a slower rate.

Thus, lost DM is highly digestible, non-fiber material. For hay protected from the weather, the loss is primarily carbohydrates with some protein loss (**Buckmaster et al., 1989b**). Neutral detergent fiber content, therefore, increases in proportion to the total DM loss. Crude protein is lost at 40% of the rate other DM is lost causing a small increase in CP content following storage. Nutritive changes are modeled using Equation 6.21 where parameter a is zero for fiber changes and 0.4 times the initial CP content for changes in CP (**Buckmaster et al., 1989b**).

During outside storage of large round hay bales, changes in CP concentration are highly variable. For our model, CP concentrations are assumed to not change during outside storage, i.e. CP is lost at the same rate as other DM. Crude protein is lost through leaching of soluble forms of nitrogen and slow volatilization of ammonia contained in the hay or produced through microbial respiration.

The heating of hay can cause the formation of ADIP through a Maillard (browning) reaction, which is the polymerization of sugars and other carbohydrates with amino acids. The loss of more soluble nitrogen components also causes a small increase in the ADIP concentration. Thus, the accumulation of ADIP is modeled as proportional to the degree-days the haystack is above 35°C, and the concentration increases with the loss of other DM (**Buckmaster et al., 1989b**):

$$ADIP_f = \left[ADIP_i + 0.00373\ DD\right] / (1 - L) \qquad [7.7]$$

where $ADIP_f$ = final ADIP concentration, fraction

$ADIP_i$ = initial ADIP concentration, fraction

L = hay storage loss with inside (L_i) or outside (L_o) storage, fraction

For outside storage of large round bales, losses are variable. The most digestible portion of hay DM is lost resulting in a decrease in digestible DM content. Fiber concentrations generally increase with the loss of non-fiber constituents but some fiber is also lost. Changes in NDF concentration measured during outside storage of round bales, indicates that on the average 17% of the DM lost is NDF (**Harrigan et al., 1994**). Therefore, the change in NDF concentration is estimated by:

$$NDF_f = \left[NDF_i - 0.17\ \mathrm{L}\right] / (1\text{-L}) \qquad [7.8]$$

where NDF_f = final NDF concentration, fraction

NDF_i = initial NDF concentration, fraction

Hay Drying in Storage

Hay can be harvested at a moisture content as high as 30% and dried for storage. Drying can be done with ambient air or heated air. Drying of hay affects the DM loss occurring during the first month of storage, which affects the resulting changes in nutritive value.

Ambient-air drying represents a haystack with a plenum through the center. An electric powered fan is used to pressurize the air under the stack, which causes air movement through the stack. This air movement carries moisture from the stack, drying the hay to a moisture content suitable for long-term storage (12 to 15% moisture) after about one month of drying. Heated-air drying is similar except that the air is heated for faster drying of the hay.

Hay DM loss with ambient-air drying is modeled as one-third of the way between hay stored at 18% moisture and that stored at the hay's initial moisture content. This is done by determining the loss that would occur in hay at each moisture content using the inside storage model described above. The loss during the first month of storage is 33% of that at the elevated moisture plus 67% of that in relatively dry hay. For heated-air drying, the loss during the first month of storage is assumed to be the same as that occurring in hay baled at 18% moisture content. With either type of drying, the loss during the remainder of the storage period is modeled the same as that for dry hay (0.3% of DM per month). Nutritive changes in the hay are predicted using the reduced DM loss and the same relationships described for inside storage of hay.

For ambient-air drying, the drying unit is assumed to operate throughout the first month of storage. Therefore, the fan in the selected drying unit runs for 744 hours consuming electricity at the rate determined in the machinery component. For heated air, the drying time is two to six days, dependent upon the initial moisture content of the hay. This dryer also includes a heating unit that burns fuel oil. The number of dryers used is the quantity of hay produced divided by the specified dryer capacity (See the **Machinery Information** section). Additional labor for this process is used as specified by the model user.

Preservatives

Hay can be harvested at 20 to 25% moisture contents and treated with a preservative for more stable storage. Preservative treatments can affect the heating and DM loss that occurs during storage (**Rotz et al., 1992**). Preservative options include a propionic acid or similar organic acid mixture and microbial inoculants. Acid treatments reduce the heating in hay, but the DM loss over the full storage period is not affected. For a strong acid mixture, the accumulation of degree-days in the haystack is reduced by 60%, and for a weaker acid mixture, the heat accumulation is reduced 40%. This reduction in heating only affects the increase in ADIP in the hay. The application rate specified by the user is assumed to be acceptable, and it does not affect the preservation that occurs. Microbial inoculants are assumed to have no effect on hay preservation.

Two hypothetical hay treatments defined as excellent and ideal preservation are also possible. Hay treated with an excellent preservative is assumed to have the same heating, DM loss, and nutritive changes during storage as dry hay (18% moisture). This reflects the goal of current preservatives. For an ideal preservative, all heating, loss, and nutritive change during storage are removed. Preservation at this level may never be possible, but it provides an ideal goal.

Three strategies can be used to apply preservatives defined as limited, moderate, and heavy use. Under limited use, if a plot of hay is dry enough for harvest as high-moisture hay (< 28% moisture), the model looks ahead to determine if rain is to occur during the remainder of that day or the next. The farmer (decision maker) is given a 60% probability of making the right decision on whether or not to bale the hay wet with a treatment (**Rotz et al., 1992**). Using this limited strategy, treated hay is baled when the probability is high for avoiding rain damage. Moderate use attempts to bale all hay as high-moisture hay. Some hay dries enough for stable storage without treatment (below 20% moisture content) while waiting for other plots to be baled and is not treated with a preservative. Heavy use of a preservative uses the same assumptions as moderate use except that the treatment is applied to all hay regardless of moisture content.

Silo Storage

Several ensiling options can be simulated with up to four silos for alfalfa and grass storage and two for corn silage. The silos can be bunker, top-unloaded tower or bottom-unloaded tower silos. In addition, forage can be ensiled in silage bags or as bale silage. Half of the alfalfa/grass silos can be designated for low-quality forage; the other two, for high-quality forage. Associated with each silo are its dimensions, capacity, initial cost, and permeability of the wall or cover. Structures containing similar quality forage are emptied over a 12-month period, and only one structure of each forage quality is open at a time. Because alfalfa/grass silage silos are commonly refilled within the harvest season, silo capacity is increased for later cuttings by the amount of alfalfa or grass silage used since an earlier cutting. With about 30 days between cuttings, a silo filled during a given harvest can hold an additional 1/12 of its capacity for each of the following cuttings.

Model Structure

A comprehensive silo model is used that includes five major phases of the ensiling process: preseal, effluent production, fermentation, infiltration, and feed-out (**Buckmaster et al., 1989a**). The preseal phase occurs before sealing. A silo is filled by plots (a plot is the material harvested in 3 hours). The first phase considers changes caused by aerobic respiration that occurs from the time a plot is placed into the silo until it is covered with another plot or, in the case of the last plot in the silo, until the silo is covered with plastic. Effluent production occurs when silage is very wet causing nutrient rich fluid to flow from the silo. Fermentation includes all nutritive changes that occur under anaerobic conditions. During the infiltration phase, oxygen penetrates the silo wall (tower silos) or the cover (bunker silos); this allows aerobic respiration in the stored material. During the last phase, feed-out, DM loss is due to aerobic respiration both in the exposed silage inside the silo and in the feed bunk.

The five phases are linked to simulate the entire ensiling process. This linkage is different for tower and bunker silos. There are also slight differences between top and bottom unloaded tower silos, because plots are removed from these silos in different orders.

In a top-unloaded tower silo, plots are numbered in the order that they are harvested and in the reverse order in which they are removed from the silo. Each of the five phases is simulated sequentially for each plot in the silo. The silage density during the preseal phase is the uncompacted density. It is assumed that the silo is filled prior to fermentation; therefore, the density during fermentation is higher and depends upon the position of the plot within the silo. The depth to the top of a given plot is computed using the mass and density of each plot above the given plot and the cross sectional area of the silo (**Buckmaster et al., 1989a**). The temperature of the ensiled crop as fermentation begins includes any temperature rise from this initial phase.

After fermentation is simulated for a given plot, infiltration is predicted based upon the permeability of the structure and the length of storage. The length of time each plot is in the silo is the time required to remove all of the material above a current plot plus half of the current plot. This time is determined from the feed-out rate, which is computed considering that all silos with a given forage type are emptied over a one year period. Feed-out is simulated following infiltration. The density of the exposed silage surface is the compacted density. Total DM loss from all phases cannot exceed the total respirable substrate available in the feed.

A complication in modeling a tower silo filled with hay-crop silage is that in many cases the silo is filled within one growing season. In a top-unloaded tower silo, refilling is modeled by increasing the length of time the original plots in the bottom of the silo are in the silo. Plots placed into the silo during refilling or plots replaced by the refill are treated identically. It is assumed that refilling does not change the density of the original plots in the bottom of the silo.

The bottom-unloaded tower silo is modeled similar to the top-unloaded silo; the difference is the length of time each plot remains in the silo. Because plots are removed in the same order that they are harvested, the length of time a given plot is in the silo is the time required to remove all plots below the given plot plus half of that plot. The effect of refilling a bottom-unloaded silo is an increase in the density of the original plots that remain in the silo. For plots removed prior to refilling, density remains the same as in a silo without refilling. For the remaining plots, infiltration losses are simulated before the refill using the original density of the plots; after refill a higher density is used, which depends on plot position within the silo (**Buckmaster et al., 1989a**).

In the bunker silo, the preseal phase is simulated for each plot as it is placed into the silo. Estimation of surface area is based on a 50% grade during filling. A bunker silo is not emptied one plot at a time; rather, vertical sections that contain material for several plots are removed. The plots, therefore, become indistinguishable once the silo is filled. Following preseal and fermentation, which are simulated for each plot, the moisture content and quality at any point in the silo is considered to be the average moisture content and quality of all material in the silo. Thus, before infiltration, the vertical sections each contain material of identical quantity and quality. The time that each vertical section remains in the silo is the amount of time required to remove all vertical sections in front of the current section.

For bunker silos, the initial silage density is related to the amount of packing performed on the silo. Initial density is a function of a packing factor that varies between 0 and 1 and the DM content of the silage at harvest. For alfalfa/grass silage, the packing factor (PF) is a function of the mass of the packing tractor, the packing time, and the amount of silage packed:

$$PF = \left[0.4\ (TMASS)\ (PTIME)\right] / TOTDM \qquad [7.9]$$

where $TMASS$ = tractor mass, kg
$PTIME$ = packing time, hr
$TOTDM$ = total silage DM packed, t

For corn silage, the relationship for determining the packing factor is doubled to reflect easier packing, but the packing factor is still limited to a maximum value of 1.

Silage bags and bale silage are simulated using the tower silo relationships, except that no refilling occurs. The dimensions of the silo are set to reflect those of a bag or bale. Oxygen permeability is set to that for sealed plastic (1.0 cm/h) rather than that for a silo structure (4.0 cm/hr).

Preseal Phase

Changes that occur before a plot is sealed from oxygen exposure are the result of plant respiration; they include DM loss, a change in DM content, and temperature rise. Proteolysis is assumed to be negligible until fermentation begins. During the preseal phase, oxygen infiltration through the silo wall is negligible compared with the infiltration into the open surface. Thus, infiltration is assumed to be vertically downward into the forage material.

The preseal portion of the silo model is a modification of the work of Pitt (**1986**). Respiration rate in forage material is a function of crop type, pH, temperature, and DM content. The oxygen concentration profile from the silage surface is estimated, and a profile of respiration rate is computed. From this, the average respiration rate over the depth of the plot is calculated (**Buckmaster et al., 1989a**). Dry matter loss is related to this average respiration rate and the duration of the preseal phase:

$$DML_p = \left[0.0299\ (MU)\ (T_e)\right] / DM \qquad [7.10]$$

where DML_p= total DM loss due to respiration during the preseal phase, fraction
MU = average respiration rate over the dept of the plot, cm3 O2/g silage-h
T_e = duration of preseal phase, days
DM = DM content of silage, fraction

The change in DM content during the preseal phase is estimated assuming that 108 g of water is produced for each 180 g of DM lost in respiration. Temperature rise during the preseal phase is computed with the assumption that all heat generated raises the temperature of the ensiled material (**Buckmaster et al., 1989a**). A lumped analysis is used; thus the plot is assumed to have uniform temperature.

All DM lost is respirable substrate (i.e., sugars and starch). Therefore, as DM is lost during the preseal phase, protein and fiber concentrations increase (**Buckmaster et al., 1989a**). These nutrient changes are determined using a form of equation 6.21 where the variable *a* is zero.

Effluent Production

Effluent production is a function of the initial DM content of the harvested silage and the length of the storage period. Effluent production normally only occurs when the silage has a DM content below 30% (moisture content greater than 70%). The volume of effluent produced by a plot of silage is a function of a maximum potential volume and the time the plot remains in the silo (**Rotz et al., 1993**). The average DM content and specific gravity of the effluent are 10% and 1.035 respectively. Therefore:

$$DML_e = \left[0.1035\ (VOLMAX)\ (FOFT)\right] / DMC \qquad [7.11]$$

where DML_e = silage DM lost in effluent, fraction of silage DM
$VOLMAX$ = maximum possible effluent production (Rotz et al., 1993), litre/t
$FOFT$ = fraction of effluent obtained in the given storage time (Rotz et al., 1993)
DMC = Initial DM concentration in the given plot of silage, fraction wet basis

The DM lost in the effluent is assumed to be 30% crude protein and all is assumed to be soluble non-protein nitrogen. Crude protein and non-protein nitrogen concentrations in the remaining silage are:

$$CP_f = \left[CP_i - 0.3DML_e\right] / \left[1\text{-}DML_e\right] \qquad [7.12]$$

$$NPN_f = \left[NPN_i\,(CP_i) - 0.3(DML_e)\right] / \left[CP_i - 0.3(DML_e)\right] \qquad [7.13]$$

where DML_e = DM lost in effluent, fraction of initial DM
CP_f = final crude protein concentration of silage, fraction of DM
CP_i = initial crude protein concentration of silage, fraction of DM
NPN_f = final non-protein nitrogen concentration of silage, fraction of total nitrogen
NPN_i = initial non-protein nitrogen concentration of silage, fraction of total nitrogen

No fiber is lost in the effluent, so the fiber concentration of the remaining silage increases with the loss of other DM (Equation 6.21 with a = 0).

Fermentation Phase

Functions that predict changes in forage due to fermentation and respiration of air trapped during ensiling were developed using the model of Pitt et al. (**1985**) as modified by Leibensperger and Pitt (**1987**). Numerous runs of their simulation model were used to develop a database of important quality changes for different initial temperatures, air to herbage ratios, and DM contents. Empirical functions were fit to the generated data. Simplifying the detailed model to empirical equations greatly decreased the execution time of this more comprehensive model without sacrificing accuracy in prediction.

Two of the major changes in the fermentation phase are DM loss and the breakdown or loss of hermicellulose. For alfalfa, the empirical relationships used to predict these changes are:

$$DML_f = 0.0156 - 0.0364\,(\mathrm{DM} - 0.20) \qquad [7.14]$$

$$\mathrm{HC} = 0.00609 + 0.0000546\,(\mathrm{T} - 5) + 0.02 \qquad [7.15]$$

where DML_f = DM lost during the fermentation phase, fraction
HC = hemicellulose broken down through acid and enzyme hydrolysis, fraction
T = silage temperature during fermentation, °C

For all other silage crops, the relationships are:

$$DML_f = 0.00864 - 0.0193\,(DM - 0.15) \qquad [7.16]$$

$$HC = 0.0367 + 0.000333\,(T) \qquad [7.17]$$

The functions developed to describe alfalfa fermentation are applicable for initial temperatures from 5 to 45°C, DM contents from 20% to 60%, and air to herbage volume ratios of 0.5 to 3.4 (**Buckmaster et al., 1989a**). Those for corn, grass, and small grain fermentation are applicable for initial temperatures from 0 to 40°C, DM contents from 15 to 60%, and air to herbage volume ratios from 1.0 to 2.0. Values for other initial characteristics and fermentation functions can be found in Buckmaster et al., (**1989a**).

Before infiltration is simulated for a given plot, the amount of DM in the plot is decreased and the associated fiber and protein contents are adjusted to reflect changes during fermentation. Fiber concentrations increase with the loss of DM (Equation 6.21). Some NDF is lost with the breakdown of hemicellulose, so the resulting NDF concentration is:

$$NDF_f = \left[NDF_i - HC\right] / \left[1\text{-}DML_f\right] \qquad [7.18]$$

where NDF_f = final NDF concentration, fraction of DM
NDF_i = initial NDF concentration, fraction of DM
DML_f = DM lost during fermentation, fraction of DM
HC = hemicellulose broken down during fermentation, fraction of DM

Crude protein concentration increases with the loss of other DM (Equation 6.21 with a = 0). The NPN content also increases as a function of crop type, silage temperature, and DM content (**Muck et al., 1996**).

Infiltration Phase

The infiltration model represents one-dimensional steady-state oxygen diffusion. In a tower silo this occurs radially inward through the walls and downward through the top plot. While in a bunker silo, oxygen diffusion moves downward through the cover. Dry matter loss due to oxygen infiltration is limited by oxygen and respirable substrate availability. The model is illustrated by the concept of a moving front (**Buckmaster et al., 1989a**). The only location of respiration activity is at the front. Outside or above the front, all respirable substrate is depleted; inside or below the front, oxygen infiltration has not occurred. It is assumed that oxygen is used in the respiration reaction as it reaches the moving front; thus, the respiration rate equals the rate at which oxygen reaches the front:

$$SL_i = 0.0628\ (U)\ (A_f) \qquad [7.19]$$

where SL_i = oxygen infiltration into silage
U = effective permeability of oxygen infiltration, cm/h
A_f = area of the moving front, m²

Since respiration resulting from oxygen infiltration occurs slowly, any heat generated is assumed to dissipate.

Oxygen must penetrate both the silo structure and some forage material to reach the front. The effective permeability for oxygen is determined by both the silo wall (tower) or cover (bunker) and any forage to the outside of (tower) or above (bunker) the moving front. Oxygen permeation and the resulting rate of DM loss are functions of the effective permeability, the density of oxygen, and the stoichiometry of the respiration reaction (**Buckmaster et al., 1989a**). The effective permeability is a function of the cover permeability, silage porosity, the position of the front and the diffusion parameter.

Movement of the front is modeled slightly different in a bunker silo. The bunker is divided into vertical sections with each section containing the amount of material removed during 10 days. The duration of this phase is different for each vertical section as determined from the feed-out rate.

All DM lost in the infiltration phase is respirable substrate, so the protein and fiber contents of the forage increase with this loss of non-protein and non-fiber constituents (Equation 6.21 with a = 0). These adjustments are made before the changes during feedout are predicted.

Feed-Out Phase

Dry matter loss during feed-out includes that occurring at the exposed silage face and that occurring in the feed bunk. Feed-out loss is defined as DM loss from respiration; feeding loss from handling or animal rejection is included in the feeding component.

The feed-out phase in the silo is similar to the preseal phase in that the surface is exposed to air and oxygen can diffuse into the forage. For a top-unloaded tower silo, diffusion is one-dimensional downward into the forage; in a bottom-unloaded tower silo, diffusion is one-dimensional upward into the forage; and in a bunker silo or silage bag, diffusion is one-dimensional from the opened end inward. Feed-out loss is modeled using the same procedure used for modeling preseal loss, but the density and other factors affecting respiration rate are different (**Buckmaster et al., 1989a**). Once the respiration rate profile during feed-out is determined, the in-silo loss is computed by considering the duration of exposure, which is inversely related to the rate silage is removed from the silo:

$$SL_{os} = \left[0.0299\ (MU)(TH)\right] / DF\ (DM) \qquad [7.20]$$

where SL_{os} = DM loss occurring in the silo during feed-out, fraction
TH = depth at which oxygen concentration gradient is zero, cm
DF = depth of forage fed each day, cm/day

During feedbunk exposure, the density of the crop is assumed to be its uncompacted density. The in-bunk loss is estimated by converting respiration rate in air to DM loss. Silage is assumed to lay in the feed bunk an average of three hours before it is consumed. The portion of the feed-out loss that occurs in the feed bunk (SL_{ob}) is modeled using equation 7.10 where Te is set at 0.125 days.

Total DM loss during feed-out (SL_{os}) is the sum of in-silo (SL_{os}) and in-bunk (SL_{ob}) losses. Again, because all DM lost is respirable substrate (non-protein and non-fiber constituents), the fiber and protein contents increase (Equation 6.21 with a = 0). Other nutrient concentrations including DM and NPN do not change during this phase.

Corn Silage Processing

Crop processing prior to storage affects the losses and nutritive changes that occur during storage. Crop processing can only occur with corn silage. Processing provides forage that is more easily compressed in the silo. Therefore, at a given pressure in the silo or given number of hours of packing in a bunker, the initial silage density is greater with processed forage compared to unprocessed. An average increase in the initial silage density of 10% is assumed for processed corn silage (**Rotz et al., 1999a**), so the density before settling occurs is increased by this amount.

The primary feed benefit from processing is an increase in the digestibility of the forage. This improvement in digestibility allows the animal to receive more energy from a unit of forage. The available energy from corn silage is a function of the neutral detergent fiber (NDF) concentration in the forage (**Rotz et al., 1999a**). As the crop matures, NDF content decreases and the predicted energy content increases. However as the crop approaches full maturity, corn kernels, cobs, and forage fiber become less easily digested. Whole kernels may pass through the animal undigested, and cobs may not be consumed. With lower digestibility, the animal does not receive all the energy contained in the silage. This effect is modeled by adding a second function that reduces available energy with increasing DM content. As the crop matures, a point occurs where available energy begins to decrease with maturity (**Rotz et al., 1999a**).

The effect of processing on forage fiber digestion is modeled by increasing the available energy predicted as a function of NDF content (**Rotz et al., 1999a**). This function is modified by increasing the net energy for lactation (NEL) obtained from the stover portion of the silage by 10%. This is done by subtracting the NEL of the grain portion from the NEL of the total silage to obtain the NEL from stover. The NEL content of the grain is assumed to be 2.0 Mcal/kg DM. The NEL of the stover is then increased 10% and added back with that of the grain portion to obtain the final available NEL of the total forage. This provides a greater increase in a less mature crop (lower grain content) with less effect in a more mature crop.

An additional effect of processing on more mature crop is modeled by adjusting the limit imposed by decreasing available energy with increasing DM content. When kernel processing is used and the DM function is limiting, the energy available is assumed to be the average of that predicted by the two functions (**Rotz et al., 1999a**). Therefore, use of processing does not eliminate the reduction in available energy imposed by the maturing crop, but this reduction is halved.

Processing may also reduce particle size. Corn silage is divided into two pools according to particle size (**Rotz et al., 1999a**). The large particle pool primarily consists of stover and the small particle pool is primarily grain. The effect of processing is modeled with two options. In the first option, processing is used with a relatively short chop length. In this case, the portion of the corn silage in the large particle pool is reduced 10%. In the other option, chop length is increased when processing is used. Under this scenario, no change is made in the particle size pools as a result of processing.

HERD AND FEEDING INFORMATION

Feeds and Feeding

Machinery Requirements and Resource Inputs

Simulation of feeding includes the use of machinery and the labor, fuel and electricity required to complete all feeding operations. The type of machines used and the resources required are primarily a function of the type of feeding system used. The user selects the type of feeding system for dry hay, silage, and grain feeding. Options for hay feeding include hand feeding of small bales, self (ad libitum) feeding of large bales, and grinding or chopping of bales for feeding in a total mixed ration. Silage and grain can be fed by hand, with a mobile mixer wagon, or with a stationary mixer and conveyor delivery system. Grain can also be fed with individual computerized grain feeders.

Feeding simulation begins by determining the type and number of machines required. For hand feeding, no machines are used. For ad libitum fed bales, the tractor specified for transport is used along with a transport device (probably a front mounted loader) to move the bales from storage to the feed rack. When hand feeding is specified for bale silage, the same transport machines are used to move the bales. For hay grinding and mixing, the equipment required includes a bale or tub grinder/chopper, a tractor to power this device, a feed mixer and the tractor used to power this mixer. When a mobile mixer is selected for silage and grain feeding, the tractor or skid-steer loader specified for feeding is used along with the mixer and the tractor used to drive the mixer. For a stationary mixer or computer feeder, only the stationary mixer or computer feeder is used. The model user specifies the number and size of each machine. When tower silos are used, an unloader for each silo is also included with the feeding equipment.

The total amount of each type of feed (hay, alfalfa/grass silage, grain crop silage, and grain concentrates) fed is determined. Feed use is the sum of the feeds fed to each animal group times the number of animals in each group totaled over the year. Prediction of the feed rations used for each animal group is described in the herd performance section below. Feed use includes all feeds produced on the farm and that purchased, but excludes any excess feed sold off the farm.

The amount of time required to feed each unit of feed is determined as a function of the type of feeding system. For hand feeding or ad libitum feeding of bales, a time requirement per unit of feed is assigned. Assigned values are 1.0 and 0.15 hour per tonne DM fed for hand and ad libitum feeding, respectively. For machine operations, the time required is the reciprocal of the machine's throughput capacity including any support time for loading and unloading where throughput capacity is determined in the machinery component (See the **Machinery Information** section). The total time for the operation is this time per unit of feed multiplied by the total amount of feed fed.

The time each machine is used is the time for each feeding operation (all feeds fed) totaled over the 365 days of the year. Labor, fuel, and electricity used are the total time for each feeding operation times the rate at which each resource is used. Rates for labor, fuel, and electrical use per hour of operation are determined in the machinery component (See the **Machinery Information** section). Totals over all feeding operations give the total feeding labor, fuel, and electrical requirements.

Feed Characteristics

Feed characteristics required to balance rations and predict feed intake include crude protein

(CP), rumen digestible protein (RDP), acid detergent insoluble protein (ADIP), net energy of lactation (NEL) or net energy of maintenance (NEM), and neutral detergent fiber (NDF). The total digestible nutrients (TDN), phosphorus (P), and potassium (K) concentrations are also used to predict manure excretion. Typical or average parameters for major feeds can be found in Rotz et al. (**1999a**). For forages, feed characteristics vary widely as influenced by growing, harvest, and storage conditions. Functions in the growth, harvest, and storage components predict forage CP, RDP, ADIP, and NDF concentrations.

To reduce the number of inputs from other components of the farm, forage NEL (Mcal/kg DM) and TDN (fraction of DM) contents are predicted from forage NDF and DM contents (fraction of DM):

$$NEL_{alfalfa} = 2.323 - 2.16\ (NDF_{alfalfa}) \qquad [8.1]$$

$$NEL_{corn\ silage} = 2.394 - 1.93\ (NDF_{corn\ silage}) \qquad [8.2]$$

$$= 2.536 - 2.71\ (DM_{corn\ silage}) \qquad [8.3]$$

$$NEL_{small\ grain\ silage} = 2.826 - 2.43\ (NDF_{small\ grain\ silage}) \qquad [8.4]$$

$$NEL_{grass} = 2.863 - 2.62\ (NDF_{grass}) \qquad [8.5]$$

$$TDN = (NEL + 0.12 / 2.45) \qquad [8.6]$$

The NEL of corn silage is the lesser of equations 8.2 and 8.3. This limits available NEL as the crop matures. Most functions are obtained from Mertens (**1987** and **1992**), but the corn DM and small grain functions are derived from published data for corn and small grain silages (**Adams, 1995** and **NRC, 1989**). For beef herds, NEM is used instead of NEL. The NEM concentration in each feed is determined by converting NEL content of the feed to TDN, then converting TDN content to metabolizable energy (ME), and finally converting ME to NEM (**NRC, 2000**).

Except for silages, the ruminal degradability of each feed is assigned a constant value (**Rotz et al., 1999a** and **NRC, 1989**). In all types of silage, protein degradability is determined from NPN (fraction of total N) content. All NPN and 50% of the true protein is assumed to be soluble and degraded in the rumen. Thus for silage i, the RDP (fraction of CP) is given by:

$$RDP_i = 0.5 + 0.5\ (NPN_i) \qquad [8.7]$$

Two limitations of the NRC (**NRC, 1989**) system were revised to create a more flexible ration formulation routine. The first limitation is intake prediction; the NRC system only provided the dry matter intake (DMI) required for an animal to obtain adequate NEL. A maximum forage intake implies that ruminal fill is at the maximum that the cow will tolerate and still maintain a target milk production. A theoretical fill unit (FU) is defined to represent the filling effects of forages and concentrates based on their NDF concentration, fraction of particles that are large or small, and filling factors for large and small particle NDF. The FU concentration in each feed is determined by:

$$FL_i = (FFL_i)\ (NDFL_i)\ (LP_i) + (FFS_i)\ (NDFS_i)\ (SP_i) \qquad [8.8]$$

where FFL_i = fill factor of large particles in feed i,

$NDFL_i$ = NDF concentration of large particles in feed i, fraction of DM)

LP_i= large particles (e.g. alfalfa stem or corn stover) in feed i, fraction of DM

FFS_i = fill factor of small particles in feed i,

$NDFS_i$= NDF concentration of small particles in feed i, fraction of DM

SP_i = small particles (e.g. alfalfa leaves or corn grain) in feed i, fraction of DM

$= 1.0 - LP_i$

NDF_i = NDF concentration in feed i, fraction of DM

$$= (NDFL_i)(LP_i) + (NDFS_i)(SP_i) \qquad [8.9]$$

Large and small particle fractions in forages are related to physical characteristics of the crop. For alfalfa, stems are defined as large, slow degrading particles that occupy more space in the rumen. The small particles are leaves that rapidly degrade in the rumen and thus have less filling effect. For corn and small grain silages, 85% of the non-grain plant material is defined to be large particles with the remainder of the plant being small particles. For grass forages, 70% of the crop is assumed to be large particles with the NDF concentrations in large and small particles being equal. For other forages, the proportion of large and small particles and their NDF concentrations vary with growing, harvest, and storage conditions. Except for corn silage processing (see description below), no attempt is made to relate particle size with harvest method or length-of-cut.

Fill factors serve as weighting factors for increasing or decreasing the effect that the NDF in feed particle size pools has on rumen fill. Values are assigned that are inversely related to the digestibility of those particles, i.e., a greater value represents a lower fiber digestibility and thus greater fill. Initial values were selected considering the relative fiber digestibilities of feed constituents with 1.0 being the average of all feeds. Large particles were defined to have over three times the filling effect of small particles in alfalfa and corn silage with less difference between the particle pools for grass, small grain, and pasture forages. Grain, high-moisture corn without cobs, and protein and fat supplements were assumed to be small particles with a fill factor similar to that of alfalfa leaves and the grain in corn silage. Initial values were tested and refined in the model. The final values selected (**Table 8.1**) give equivalent milk production using each forage in diets balanced to similar NDF concentrations.

The second limitation of the NRC system for formulating rations is related to the minimum fiber requirement. A minimum fiber level in the diet is recommended to prevent the NEL density from going too high, which results in health disorders and milk fat depression. Reducing the particle size of fiber can reduce or eliminate its ability to meet the minimum fiber requirement.

A roughage unit (RU) system is used to ensure that adequate forage is included in rations. In addition, there is the option of selecting rations that minimize forage use when forage is not available or when it is expensive. Roughage units are then used to define the minimum forage allowed in rations.

The RU system again considers particle size and the NDF concentration of feeds. The equation used to estimate RU for each feed is:

$$RU_i = (RFL_i)\,(NDFL_i)\,(LP_i) + (RFS_i)\,(NDFS_i)\,(SP_i) \qquad [8.10]$$

where RFL_i = roughage unit factor of large particles in feed i

RFS_i = roughage unit factor of small particles in feed i

Values for RFL and RFS are assigned to represent the relative physical effectiveness of the NDF in the two particle size pools. The effectiveness of NDF in long grass hay was assigned a value of 1.0, and chewing activity was used to estimate the relative physical effectiveness of the NDF in other forages. Large particles in all forages are assigned a roughage factor of 1.0. Factors for small particles are assigned so that the weighted average of the two particle pools provided values similar to the physically effective NDF values assigned by Mertens (**1997**).

Fill and roughage units vary with the characteristics of the feed. This is particularly true for forages where large particle content (stem or stover portion) and NDF concentration in those particles vary with growing, harvest, and storage conditions (See the **Harvest and Storage** sections). Typical FU and RU values for feeds can be found in Rotz et al. (**1999a**). Although fill and roughage factors may be influenced by crop maturity and harvest method, this is not considered in the present model. Assigned factors represent typical or normal conditions.

Fill and roughage units may also be affected by the use of corn silage processing. Processing provides more rapid digestion, and forage moves through the digestive tract a little faster stimulating greater intake. Fill units limit the physical intake of feed. As feed is made more digestible, the potential intake increases. Thus when processing is used, the fill factor for the large particle pool of corn silage is reduced 5%. This increases the potential intake according to the portion of corn silage in the diet.

For processed corn silage, the roughage factor of the large particle pool of the silage is not changed when a longer chop length is used along with processing, i.e. longer fiber offsets the effect of finer, more digestible particles. When processing is combined with a short chop length, the roughage factor is reduced 5%, and this increases the lower limit on the amount of forage required in the diet. The fill and roughage factors for the small particle pool are reduced in proportion to the predicted increase in NEL obtained by processing a dry crop. Therefore, for a relatively immature crop, these factors are not adjusted. As the crop matures, these factors are decreased in proportion to the increased NEL (increased digestibility) obtained by processing the grain portion of the forage. The combined effect of these adjustments is an increase of up to 4% in the average feed intake of lactating animals dependent upon the chop length used with processing, the amount of corn silage fed, and the production level of the animals.

Feeding Loss

Feeding loss consists of animal refusal and any feed lost between the storage location and the feed bunk during transport. Loss of each feed is related to the feeding method. With hand feeding, hay DM loss during the feeding operation is 5% of the hay DM fed. For hay fed ad libitum, DM loss in feeding is set equal to the average DM loss during storage. This provides feeding losses ranging from about 4% for hay stored inside to 16% and 10% for small and large round bales stored outside on soil, respectively. When hay is chopped and fed in a total mixed ration, loss is 3% of the hay DM. For silage and grain feeding, assigned values for feed DM loss are 4, 3, 2, and 1% for hand fed, mobile mixer, stationary mixer, and individual computer feeding systems, respectively. The major portion of this loss is assumed to end up in the manure produced on the farm.

For all feeds fed except dry hay, feeding loss is assumed to affect all feed constituents equally. Therefore, the nutrient concentration in feeds is not affected by the loss. For hay feeding loss, lost DM is assumed to be stem material. Since leaf and stem DM are tracked separately, this is modeled by subtracting the loss from the stem portion of the hay. With a greater concentration of NDF in stems, the feeding loss changes the particle size distribution and reduces the NDF concentration in the hay consumed. The intent is to model differences in the animal's ability to select weathered from unweathered hay and the resulting effects on feed requirements and animal performance. This effect is small except with the large feeding losses that occur with ad libitum feeding of large round bales stored without much protection from the weather.

Dairy Herd

A dairy herd consists of growing heifers, lactating cows, and non lactating cows. The model is organized in six sections. First, the characteristics of the major animal groups are established. Next, the feed characteristics are set and available feeds are allocated to the animal groups. Each group's requirements for fiber, energy, and protein are then determined, and a linear program is used to find the least cost, nutritionally balanced mix of feeds to meet these requirements. Finally, based upon the diet fed, the quantity and nutrient content of the manure produced is determined.

Dairy Animal and Herd Characteristics

The herd is described as six animal groups: young stock under one year old, heifers over one year old, three groups of lactating cows, and non lactating cows. There is flexibility in how the three groups of lactating cows are divided, but generally they represent early, mid, and late lactation cows. All cow groups are further subdivided between primiparous and multiparous animals with the portion of each set by the user as the replacement rate of the herd. The seven available animal types are large Holstein, average Holstein, small Holstein, Brown Swiss, Ayrshire, Guernsey, and Jersey.

Five characteristics are used to describe each animal group: potential milk yield, milk fat content, body weight (BW), change in BW, and fiber ingestive capacity. For cows, continuous functions are used to describe each characteristic over a full lactation (**Table 8.2**). A modified infinite Gamma function is used as the base model for each. This function has the following form:

$$Y = \left[A(w+s)^{b}\right] \Big/ \left[e^{[c(w+s)]}\right] \qquad [8.11]$$

where A = the intercept
w = week of lactation
s = shift factor (in weeks)
b = exponent of time
c = the exponential rate of change

Parameters b and c define the shape of the curve and parameter A determines the peak. A scaler is used to adjust these relationships for different animal breeds and sizes (**Rotz et al., 1999a**).

Although the feeding groups can be modified, the normal procedure is to assume that 16% of the cows are in early lactation, 23% in mid lactation, 46% in late lactation, and 15% are non lactating. Following a standard lactation cycle, this implies that the four groups represent weeks 0 to 9, weeks 10 to 22, weeks 23 to 48, and weeks 49 to 56, respectively. The animal characteristic functions are integrated over the appropriate weeks of the lactation cycle for a given group to determine the average characteristic over that period. The change in BW is the average daily change in BW over the period. Each characteristic of the group is then determined as the average of the primiparous and multiparous subgroups weighted by the number of animals in each subgroup. The herd is normally modeled with a 56 week lactation cycle, but feed intake and milk production are totaled for the calendar year.

Either a random or seasonal calving strategy can be selected by the model user. Seasonal calving places all cows on the same lactation cycle to better match their forage demand with the pasture forage available. Either spring or fall calving cycles can be used. For a spring cycle, all cows are assumed to calve in March and they are dry during January and February. With fall calving, lactation begins in October and ends in July. For random calving, the portions of the herd in early, mid and late lactation and the portion of non lactating cows remain the same throughout the year.

Dairy Feed Allocation

A feed allocation scheme is used to represent a producers approach to making the best use of homegrown feeds. This scheme uses decision rules to prioritize feed use. The feeds potentially available for feeding include any combination of: high-quality silage, low-quality silage, high-quality hay, low-quality hay, grain crop silage, high-moisture grain, and dry grain. Purchased feeds include corn grain, dry hay, a CP supplement, an RUP or oil seed supplement, and an animal or vegetable-based fat supplement. Because overfeeding of ingredients such as animal fat, blood meal, and meat and bone meal could result in unpalatable diets, user-specified limits prevent excessive inclusion of these feeds in rations. High-quality forage is that harvested with an NDF concentration less than a user-specified level. Depending upon the growing and harvest conditions, differences in the average nutrient concentrations between high- and low- quality forages may be small.

The preferred forage for lactating cows is a mix of grain crop silage, high-quality alfalfa/grass silage, and high-quality hay. For non lactating cows and growing heifers, preferred forages are grain crop silage, low-quality alfalfa/grass silage, and low-quality hay. Alternative forages are used when preferred forage stocks are depleted. If grain crop silage is not available, alfalfa or grass provides the forage. If high-quality hay or silage is preferred but unavailable, low-quality hay or silage is used and vice versa. When stocks of farm-produced forage are depleted, purchased hay is used.

A priority order for allocation is used to match forage quality with the animal group that best uses the available nutrients. Feeds are allocated first to animals with low nutrient requirements (non lactating cows and heifers) using low-quality forage. After that, the high-quality forage is allocated to the early lactation cows to maximize their production. Feeding the lower producing cows last allows low-quality forage to be used by animals with lower nutrient requirements when stocks of high-quality forage are depleted. Similarly, feeding younger heifers after non lactating cows and older heifers assures that, if a shortage of low-quality forage exists, animals with higher requirements receive the better feed.

The portion of each forage used in rations is based upon the amount of each forage type available and an estimate of the total forage requirement for the herd. Both available forage and forage requirement are modeled using fill units (FU). Total forage FU requirement for the herd is proportional to the sum of the maximum FU requirements of the individual animal groups:

$$AFR = \sum FR_j \ (FIC_j)\,(BW_j)\,(NA)\,(365) \qquad [8.12]$$

where AFR = annual forage requirement for the herd, FU/yr

FIC_j = fiber ingestive capacity for animal group j, FU/kg of BW/d

BW_j = average BW in animal group j, kg
FR_j= portion of the maximum FU that normally comes from forage for animal group j
NA= number of animals in the group

Values of FRj vary among animal groups and with the amount of forage used in diets. Average values for non lactating cows, older heifers, and young heifers are 0.80, 0.80, and 0.98, respectively. For maximum forage rations, values of FRj for early, mid and late lactation groups are 0.83, 0.90, and 0.93, respectively. For minimum forage rations, these values are 0.80, 0.68, and 0.57.

The objective in proportioning forage is to give first priority to pasture and second priority to silage. The lowest priority is given to dry hay because it is the easiest to sell. Total fill units available from each forage source are determined as the product of the available forage DM and the FU concentration in that forage. When available, grazed forage is used to meet as much of the annual forage requirement as possible. The portion of grazed forage permitted in the diet is limited to that available in the pasture when distributed among the grazed animal groups.

A portion of each forage is mixed to meet the remaining forage requirement set by the ratio of the FU available in that forage to the total FU of all available forages. After the portions of pasture and ensiled feeds in the ration of a given animal group are set, the remaining forage requirement is met with dry hay. This procedure maximizes the use of ensiled feeds, so that excess forage is normally dry hay. An additional option forces a user-specified, minimum amount of dry hay into rations even if it is not produced on the farm. This option enables the modeling of farms that use a preferred practice of feeding 10 to 15% of diet DM as hay.

Once a ration is formulated, the final step is to determine the number of animals in the group that can be fed that ration for a given time period from current feed stocks. The period is a full year for confined feeding systems, but a one-month period is used for grazing animals. If feedstocks do not allow all animals in the group to be fed the given ration for the full period, as many animals as possible are fed. Remaining animals of the group are fed rations balanced with alternate feeds. If milk production within the group is different because different rations are used, a weighted average milk production is computed for the group. Remaining feed quantities are updated each time a group of animals is fed.

Dairy Animal Nutrient Requirements

Rations for a representative animal of each animal group are formulated to meet four nutrient requirements: a minimum roughage requirement, an energy requirement, a minimum requirement of RDP, and a minimum requirement of RUP. The minimum roughage requirement stipulates that the total roughage units in the diet must meet or exceed 21% of the total ration DM (**Mertens, 1992** and **1997**). This assures that roughage in the formulated ration is adequate to maintain proper rumen function.

The energy and protein requirements for each animal group are determined using relationships from the Cornell Net Carbohydrate and Protein System, level 1 (**Fox et al., 2004**). The total net energy (NE) requirement is the sum of the requirements for maintenance, lactation, pregnancy, and growth. The maintenance energy requirement is determined as influenced by shrunk body weight (SBW), lactation, activity, and ambient temperature (**Fox et al., 2004**). The lactation effect on maintenance is determined using a thermal neutral maintenance requirement for fasting metabolism of 0.073 Mcal/day/SBW 0.75.

Activity is modeled as the sum of the daily requirements for standing, changing position, and distance traveled (**Fox et al., 2004**). The time spent standing is set at 12, 14, 16, and 18 h/d for confinement, half-day intensive grazing, full-day intensive grazing, and continuous grazing, respectively. Distances traveled for these four options are 0.5, 0.8, 1.0, and 2.0 km/d, respectively. A temperature effect and the resulting potential for heat stress are a function of the current and previous month's average temperature and the current relative humidity, wind speed, and hours of exposure to sun light (**Fox et al., 2004**). For simplicity, the relative humidity and wind speed are set at average values of 40% and 1.6 km/h, respectively. Exposure time is set at 0, 5, and 10 h/day for confinement, half-day, and full-day grazing systems. Cold stress effect is modeled considering an average hide thickness and hair coat (**Fox et al., 2004**), but this effect seldom occurs using temperatures averaged over a monthly time step.

Cows also include an energy requirement for lactation, and both cows and replacement heifers include a gestation requirement during pregnancy. Metabolizable energy requirement for lactation is proportional to milk yield as influenced by milk fat content (**Fox et al., 2004**). The gestation requirement is a function of the number of days pregnant and calf birth weight (**Fox et al., 2004**). Energy and protein requirements for lactation are increased by a lead factor to ensure that the requirements of a greater than average portion of the cows in each group are met. A lead factor of 12% is used for the early lactation group, and 7% is used for the mid and late lactation groups. Diets are formulated using these increased requirements, but feed consumption is determined to meet the original requirements.

Energy required for growth is a function of average daily gain (ADG) and equivalent empty body weight (**Fox et al., 2004**). To determine an equivalent empty body weight, a standard reference weight is assumed. This standard reference weight is 478 kg for cows and older replacement heifers and 462 kg for heifers less than 1 yr old.

Maintenance energy is based upon an animal in its third or higher lactation cycle. The total net energy requirement is adjusted by the multiple of maintenance of the animal group to model the efficiency of energy use as influenced by DM intake. The multiple of maintenance is the ratio of the total NE requirement to that needed for maintenance (**Table 8.3**). The total NE requirement is reduced by 4% for each multiple of maintenance less than three and increased by 4% for greater multiples of maintenance (**NRC, 1989**). Although increased intake actually affects the amount of energy extracted from the feed, this effect is included on the requirement side of the constraint equation to simplify the linear programming matrix (**Table 8.3**).

Finally, the NE requirement is increased to include an energy cost for excess protein in the diet. Each kilogram of excess protein requires 0.7 Mcal of NE to convert this protein to urea for excretion (**Tyrrell et al., 1970**). Excess protein is computed to include both RUP and RDP (**Table 8.3**). Excess RDP is that greater than the amount useful for making microbial CP (based on non-fat energy intake). Intake of RUP that causes total metabolizable protein to exceed the metabolizable protein requirement is considered excess.

The metabolizable protein requirement of each animal group is the sum of the maintenance, lactation, pregnancy, and growth requirements. The maintenance requirement is a function of SBW, lactation requirement is proportional to milk yield and milk protein content, gestation is a function of calf birth weight and days pregnant, and the growth requirement is related to ADG and the net energy required for growth (**Fox et al., 2004**). The metabolizable protein requirement is divided between RDP and RUP requirements. The RDP requirement is the microbial crude protein (MCP) requirement divided by 0.9 where MCP is defined as 0.13 times the digestible DM intake. Only energy coming from sources other than added fat is considered useful for making MCP. Added animal or vegetable fat helps meet the energy requirement, but this added energy does not yield bacterial cells.

The RUP requirement is the total metabolizable protein requirement minus the digestible microbial protein and the unavailable protein in the diet (**Table 8.3**). The digestible microbial protein is MCP multiplied by a conversion efficiency of 64% (**NRC, 1989**). Unavailable protein in the diet is set at 70% of the ADIP in forages and 40% of that in concentrates (**Weiss et al., 1992**). Because some of the ADIP of feeds is not included in the RUP, the ratio of digestible RUP to total RUP is set to 0.87 instead of the 0.8 recommended by the NRC (**1989**).

Mineral requirements considered in the model include P and K. The absorbable P requirement for each animal group is the sum of the requirements for maintenance, lactation, gestation, and growth (**NRC, 2001**). The maintenance requirement includes urine and fecal P where urine P is 2 mg P/kg of animal BW and fecal P is 1 g/kg of DM intake. For lactating cows, the lactation requirement is 0.9 g/kg of milk yield. The gestation requirement occurs when cows or heifers are over 190 days pregnant, and the gestation requirement is an exponential function of the number of days pregnant (**NRC, 2001**). The growth requirement for growing animals is a function of the animal SBW and ADG (**NRC, 2001**). The sum of the individual requirements provides the total absorbable P requirement. A user-defined adjustment factor is used to increase or decrease this total requirement for all animal groups if an adjustment is desired. The P in forages fed to cattle is assumed to be 64% absorbable and that in concentrates is 70% absorbable. An option is available to override this calcualted requirement with a value specified by the model user. The K requirement of each animal group is set at 1% of DM intake (**NRC, 1989**).

These requirements set the minimum P and K intakes of each animal group, and the P requirement is used to estimate the purchase of mineral supplements (**Rotz et al., 1999a**). Mineral supplements include phosphate, salt, and other minerals. Phosphate required is modeled as 5.3 times (assuming a 19% P concentration) the difference between the P requirement and the P contained in feeds summed over all animal groups. The P requirement can be adjusted by the user to be greater or less than that determined by the NRC (**2001**) relationships. Phosphorus in each feed is the user-specified P concentration times the DM fed. The quantity of salt and other minerals fed is modeled as 0.5% of the total feed DM consumed.

Dairy Linear Program and Constraint Equations

Animal diets and performance are modeled using a linear program that simultaneously solves five constraint equations in a manner that maximizes herd milk production with minimum cost rations. The constraints include a limit on ruminal fill and constraints for each of the four requirements described above. The ruminal fill limit is the product of the fiber ingestive capacity and the average animal weight for the given animal group (**Mertens, 1987**). Thus, the sum of the fill units of the feeds in the ration must be less than or equal to this maximum ingestive capacity (**Table 8.3**). The second constraint is the roughage requirement. As described above, the sum of the roughage units of all feeds in the diet must be greater than 21% of the ration DM (**Table 8.3**).

The third constraint equation is that the energy consumed must equal the energy requirement. An equality is used to ensure that an energy balance is maintained and that intake and feed budgets are accurate for each animal group. The total NE from all feeds in the ration minus the energy cost of excess dietary protein must equal the requirement (**Table 8.3**). The energy cost of excess protein places some feed characteristic terms on the requirement side of the equation. To simplify the linear programming matrix, the equation is rearranged so that all feed characteristics are on the left side of the constraint equation.

The last two constraints specify the minimum protein requirement in the ration. The RUP constraint requires that 87% of the sum of the RUP in all feeds must be greater than or equal to the RUP requirement (**Table 8.3**). The RDP constraint requires that the sum of the RDP contents of feeds plus the rumen influx protein (15% of feed CP) be greater than or equal to the rumen available protein requirement (**Table 8.3**).

The five constraint equations are simultaneously solved with the objective of minimizing ration cost. Ration cost is determined using relative prices of feed ingredients. For grain and concentrates, the relative price is the long-term average price set by the model user. For forages, the relative price is set to zero for maximum forage diets. With a low relative price, the model uses as much forage as possible in ration formulation. Another user-specified option allows a minimum forage diet for lactating animals. For this option and these animal groups, the price of forage is set high relative to concentrates forcing a minimum amount of forage in rations.

The constraint equations are solved for each of the six animal groups making up the herd. Each solution provides a ration that meets the minimum roughage, minimum protein, and energy requirements without exceeding the limit for intake. If a feasible solution is not found for early lactating animals, the milk production goal for the group is reduced by 0.5% and the procedure is repeated until a feasible solution is found. For later lactation groups, milk yield predicted by the functions of **Table 8.2** is reduced in proportion to the decrease found in early lactation. A set of feasible solutions for all animal groups, therefore, gives both balanced rations and a herd production level. In this case, milk production is the maximum that can be achieved considering the nutritional value of available forage and the type and amount of concentrates fed.

An option is available for balancing rations based upon crude protein content rather than protein fractions. With this option, the degradable protein constraint is replaced with a crude protein constraint. The feed protein available becomes the DM of each feed consumed times its protein content and the requirement becomes the set crude protein level times the total DM intake. An equality is used to force the fed protein to equal the set requirement. If a feasible solution is not found, a warning message is given. This indcates that the specified crude protein content is too low or too high to be met with the available feeds. The set crude protein content must be adjusted to allow a feasible solution.

For dairy operations, the average annual milk production of the herd is also converted to fat and protein corrected milk using a standard milk fat content of 4.0% and milk protein content of 3.3% (IDF, 2010). A correction factor is determined as:

$$FPCF = 0.2534 + 0.1226\,(MF) + 0.0776\,(MP) \qquad [8.13]$$

where $FPCF$ = fat and protein correction factor
MF = milk fat content, %
MP = milk protein content, %

Average milk fat content is a user defined parameter, and milk protein is defined as a function of the fat content:

$$MP = 1.7 + 0.4\,(MF) \qquad [8.14]$$

Annual milk production is multiplied by FPCF to obtain fat and protein corrected milk. In the U.S., milk is often corrected to 3.5% fat and 3.1% protein. Correcting to this lower milk solids content will reduce the footprint by 8%.

Dairy Manure DM and Nutrient Production

Manure DM production includes fecal DM, urine DM, bedding DM, and feed DM lost into manure. Fecal DM is the total quantities of all feeds consumed by each animal group multiplied by the fraction of indigestible nutrients (1 - TDN) of each feed. The TDN values are reduced 4% for the low production group and 8% for the medium and high production groups to account for the reductions in digestibility under multiple increases of intake over maintenance intake. Urine production (kg/day) is predicted as a function of DM intake, CP intake, and milk production (**Fox et al., 2004**):

$$URINE = (3.55 + 0.16(DMIA) + 6.73(CPIA) - 0.35(MILKA))SBW/454 \quad [8.15]$$

where $DMIA$ = DM intake per 454-kg animal unit, kg/day
$CPIA$ = CP intake per 454-kg animal unit, kg/day
$MILKA$ = milk production per 454-kg animal unit, kg/day

Urinary DM is set as 5.7% of total urine mass. Manure DM is increased by the amount of bedding used and by an additional 3% of the feed DM intake to account for feed lost into the manure. The quantity of wet manure is determined as manure DM divided by a user-specified value for manure DM content.

The nutrients in fresh manure are determined through a mass balance of the six animal groups. Manure nutrients excreted equals nutrient intake minus the nutrients contained in milk produced and animal tissue growth. Nitrogen intake is determined from the protein content of the feeds consumed (CP ÷ 6.25). Phosphorus and K intakes are set as the greater of the sum of that contained in feeds or the requirement of the animal group. For lactating animals, P supplementation above the quantities contained in feeds is often required; thus, P intake is normally based upon animal requirements. Potassium supplementation is normally not required, so K intake is that contained in consumed feeds. Fractions of the three nutrients contained in milk and body tissue leaving the farm are set as average values for the herd. Nutrient concentrations in milk are milk protein divided by 6.38 for N, 0.09% P, and 0.14% K. Concentrations in body tissue are 2.8% N, 0.72% P, and 0.20% K. Body tissue produced is based upon animal mass leaving the herd, not the change in body weight of individual animals during their annual cycle. Although these nutrient concentrations may vary with animal and feeding conditions, average herd values provide an acceptable level of detail for this model.

Manure N is partitioned between organic N and ammoniacal N. Organic N is assumed to come primarily from feces. Fecal N is fecal protein divided by 6.25 where fecal protein is the sum of the indigestible bacterial protein, the indigestible nucleic protein, the indigestible undegraded protein, and the metabolic fecal protein (**NRC, 1989**). Manure organic N also includes N from feed lost into manure and N contained in bedding. Feed loss is assumed to be 3% of the total N intake, and the N from organic bedding materials is 0.69% of the bedding DM.

Fecal N from the herd is the product of the excretions for each feeding group, the number of animals in the group, and the length of the feeding period summed over all animal groups. Urinary N excretion is then assumed to be the total N excreted by all animal groups minus the fecal N. All urine N is considered to be urea, ammonium, or another form that can readily transform to ammonia following deposition. Organic N is considered stable during manure handling, and ammonia N is susceptible to volatile loss.

Simulation of P loss requires that total manure P be divided between water-soluble and nonwater-soluble P components. The water soluble inorganic P is calculated using an empirical relationship with dietary P (**Dou et al., 2002**). An adequate lower limit for dietary P is about 3.3 g P/kg DM, corresponding to an inorganic soluble P concentration in excreted manure of 1.72 g P/kg DM (**Dou et al., 2002**). The model thus has a lower bound (Pi,min) for inorganic soluble P of 1.5 g P/kg fecal DM (dietary P concentration of 3.14 g P/kg DM), a concentration slightly less than the lowest expected concentration.

$$SP = max\ (P_{i,min}\ ,\ - 2.80 + 1.37\ P_d\ ) \qquad [8.16]$$

where SP = readily soluble inorganic P in feces, g P / kg fecal DM

P_d = dietary P concentration, g P/kg feed DM

$P_{i,min}$ = lower bound for inorganic soluble P

After determining the soluble inorganic P in manure, the remainder of the water-soluble portion is added to the soluble organic P pool. The insoluble P portion of the manure is assumed to be 70% inorganic and 30% organic.

Beef Herd

The beef herd can essentially consist of any amount or combination of cows, calves, growing cattle, and finishing cattle. This herd can be produced using a grazing strategy, feedlot, or a combination of the two. The model is organized in six sections to predict animal intake and performance. First, the characteristics of the animal groups making up the herd are established. Next, feed characteristics are set and available feeds are allocated to the animal groups. Each group's requirements for fiber, energy, and protein are then determined, and a linear program is used to find the least cost, nutritionally balanced mix of available feeds that can come closest to meeting these requirements. The established nutrient intake is then used to predict growth and condition each month of each simulated year. Finally, based upon the diet fed, the quantity and nutrient contents of the manure produced are determined.

Beef Animal and Herd Characteristics

The herd is described by some combination of six possible animal groups: cows, nursing calves, young heifers, yearling replacement heifers, stocker cattle, and finishing cattle. The cow group is a mix of primiparous and multiparous cows, and a weighted average of animal characteristics is used to describe a representative animal for ration balancing and estimation of feed utilization. Nursing calves receive at least a portion of their diet from their mother's milk. Calves remain in this group until they are at the user specified weaning age. At this age, they become young replacement heifers and/or stocker cattle. At one year of age, the young heifers transfer to the older heifer group. All females beyond those needed for replacement and all males are stockers where they remain until they reach 70% of their final shrunk body weight (FSBW). Animals of this size are moved to the finishing group until they reach FSBW.

The initial number of cows, replacement heifers, stocker cattle, and finishing cattle on the farm is set by the model user. For nursing calves, the number is set at 4% more than the number of cows to account for the probability of twins. When animals transition to the next age group or they are sold from the farm, their number is adjusted considering a mortality rate. Assigned mortality rates are 8% for nursing calves and 2% per year for all other animals. The age of all growing animals is set each month based upon the user-defined calving month.

Animal characteristics are described as a function of the animal breed. Seven breeds are predefined: Holstein, Simmental, Limousin, Short horn, Hereford, Charlais, and Angus. The user can modify these characteristics, or define another breed or cross breed. The primary characteristics used to define a breed are the mature cow shrunk body weight (CSBW), peak milk yield, calf birth weight, the genetic influence on maintenance energy requirement, the genetic influence on fiber ingestive capacity, and the genetic influence on body composition rate. Typical values for these characteristics are listed in **Table 8.4** for the primary breeds.

Shrunk body weight (SBW) and average daily rate of gain (ADG) are primary characteristics used to describe growing animals. Target weights are initially set for each growing animal group at each month of their life cycle. For replacement heifers and all animals prior to weaning, this weight goal is a function of age:

$$SBW = CSBW\,(1\text{-}e^{-k(AGE)}) \qquad [8.15]$$

where k = maturity rate, per d
AGE = animal age, d

A maturity rate of 0.0019 d-1 was used to allow heifers to attain a proper weight for calving (80% of CSBW) at 2 yr of age. For stocker cattle, a linear growth rate is assumed where the post weaning ADG is the difference between their target weight entering the finishing stage (70% of FSBW) and their weaning weight divided by the days available for growth. This available time is set by the user as the backgrounding period. The ADG goal during finishing is also set by the user. An initial rate of gain is determined for the first month with this target gain reduced 10% each month until FSBW is reached. The initial gain is set to provide the ADG over the finishing period requested by the user. If feed quality allows, this target ADG is met. If the feeds fed limit ADG, a lower ADG is used and the length of the finishing period is extended.

For growing animals, this target weight relationship sets the potential rate of gain for each month. If an implant treatment is used for stocker or finishing cattle, this potential rate of gain is increased 10%, and the target FSBW is increased 5%. If the feed quality fed in a given month inhibits this potential growth rate, the highest possible rate is established. When feed quality improves in future months, compensatory gain allows the animal group to move back toward its target weight.

Cow target weights are set assuming a BCS of 5.5. At this condition, the SBW of primiparous animals is set at 80% of the breed's CSBW and that of multiparous animals is 91% of CSBW. When available feeds cause a negative energy balance for the cow group, weight loss occurs. This weight loss is regained in future months if the energy balance improves.

Milk production for primiparous and multiparous cows is a function of the time in lactation and the peak milk yield (**Fox et al., 2004**):

$$MY = {}^{n}\!/_{a\, e^{kn}} \qquad [8.16]$$

where MY = milk yield during week n of the lactation cycle, kg/d
a = 1. / (P k e)
P = peak milk yield during the lactation, kg/d
k = shape parameter = 1. / 8.5

Breed specific values for peak milk production, milk fat content, and milk protein content are included in Table 8.4. Milk production of primiparous cows is set at 74% of that of mature cows and production in the second lactation is 88% of that in later lactations (**Fox et al., 2004**).

A fiber ingestive capacity (FIC) is determined for each animal group at each month. FIC is used to set a limit on the fiber intake that can occur (**Rotz et al., 1999a**). This ingestive capacity is the sum of the capacity as affected by body leanness and lactation (**Tess and Kolstad, 2000**):

$$FIC = FIC_f + FIC_l \;/\; SBW \qquad [8.17]$$

where FIC = fiber ingestive capacity, % SBW/day
FIC_f = F (LN) (0.0148 + (0.0066 (ALN)(LN) / ALN))
FIC_l = 0.122 (MY)
LN = current lean (no fat) body mass, kg
ALN = adult lean (no fat) body mass, kg
= 0.8 (0.891) (FSBW)

The factor F represents the effect of carcass leanness, which is limited to a maximum of 1.0:

$$F = 0.8 + 0.2\,(0.36 - 0.0377\,(BCS)) \;/\; 0.16 \qquad [8.18]$$

where BCS = body condition score, 9 point scale.

The FIC is then adjusted to include effects for ionophore and implant treatments. Implants allow a 10% increase in FIC while ionophore treatments provide a 3 to 6% decrease. Finally, FIC is multiplied by an adjustment factor that is set by the model user as a breed characteristic to allow for genetic influences (**Table 8.4**).

Beef Feed Allocation

A feed allocation scheme is used to represent a producers approach to making the best use of homegrown feeds. This scheme uses decision rules to prioritize feed use. The feeds potentially available for feeding include any combination of pasture, high-quality silage, low-quality silage, high-quality hay, low-quality hay, grain crop silage, high-moisture grain, and dry grain. Purchased feeds include grain, dry hay, a CP supplement, a rumen undegradable protein (RUP) or oil seed supplement, and an animal or vegetable-based fat supplement. Because over feeding of some feed ingredients may result in unpalatable diets, user-specified limits prevent excessive inclusion of supplemental feeds in rations. High-quality forage is that harvested with an NDF concentration less than a user-specified level (See the **Forage Harvest** section).

When an animal group is grazed, the preferred forage is always pasture. If ample pasture is not available to meet the needs of the grazing animal groups, each group is supplemented with at least one other forage. If grain-crop silage is available to a given animal group, this will be one of the forages fed; otherwise, it will be excluded from the forage mix. The next priority is given to grass or alfalfa silage with the lowest priority given to dry hay because it is the easiest to sell. Lower priority forages are used when preferred forage stocks are depleted.

A priority order for allocation is used to match forage quality with the animal groups that best use the available nutrients. Feeds are allocated first to cows, if any are maintained on the farm. The next group fed is nursing calves followed by young heifers, older heifers, stocker cattle, and finally finishing cattle. High-quality forage (grass or alfalfa hay or silage) is the preferred forage for feeding calves and finishing cattle (unless pasture is used) to maximize their production. Lower quality forage is normally fed to cows and stockers. These animals can be maintained with lower quality forage, and if they lose condition from low quality feed, they can recover more easily than other animal groups. If high-quality hay or silage is preferred but unavailable, low-quality hay or silage is used and vice versa. When stocks of farm-produced forage are depleted, purchased hay is used.

The portion of each forage used in rations is based upon the amount of each available and an estimate of the total forage requirement for the herd. These are quantified in total units of net energy for maintenance NEM. Thus, the amount of forage required is estimated as the total NEM requirement summed over all months of the year and all animal groups on the farm. The one exception is for finishing cattle fed a high grain diet. For this group, the forage demand is estimated as 10% of their total NEM requirement. Total units available from each forage source are determined as the product of the available DM and the NEM concentration in that forage.

When pasture is available, grazed forage is used to meet as much of the annual forage requirement as possible. The portion of grazed forage permitted in the diet is limited to that available in the pasture when distributed among the grazed animal groups. If pasture is available to meet the entire forage requirement of all grazing animals for a given month, then this is the only forage fed to these animal groups. When pasture does not meet the full requirement, additional forage is obtained from conserved or bought forage. This supplemental forage is distributed across animal groups as long as supplies last.

The portion of each forage type mixed to meet the supplemental forage requirement is set by the ratio of the total NEM available in that forage to the total NEM of all available forages. If adequate amounts of silage are available to meet the remaining forage requirement, then a mix of available silages is used. After the portions of pasture and ensiled feeds in the ration of a given animal group are set, any remaining forage requirement is met with dry hay. This procedure maximizes the use of ensiled feeds, so that excess forage is normally dry hay.

Allocation of feeds to nursing calves requires additional rules. During the calves first two months, energy and protein requirements are completely met through the mother's milk. After two months of age, the calf begins to supplement its diet with other available feeds (primarily forage) to meet its requirements. The amount of supplemental feed consumed increases each month until the calf is weaned. The forage allocated to this group follows the same allocation rules followed for other animal groups. When pasture is available, it is used. If pasture is not available, high-quality forage is used.

Once a ration is formulated for a given animal group and month, the final step is to determine the number of animals in the group that can be fed that ration from current feed stocks. If these feed stocks do not allow all animals in the group to be fed the given ration for the full month, as many animals as possible are fed. Remaining animals of the group are fed rations balanced with alternate feeds. If ADG within the group is different because different rations are used, a weighted ADG is computed for the group. Remaining feed quantities are updated each time a group of animals is fed.

Beef Animal Nutrient Requirements

Diets for a representative animal of each animal group are formulated to meet four nutrient requirements: a minimum roughage requirement, an energy requirement, a minimum requirement of rumen degradable protein (RDP), and a minimum requirement of RUP. The minimum roughage requirement stipulates that the total roughage units in the diet must meet or exceed 20% of the total ration DM (**Mertens, 1992** and **1997**). For finishing cattle fed a high grain diet, this minimum roughage requirement is reduced to 8% (**NRC, 2000**). This assures that roughage in the formulated ration is adequate to maintain proper ruminal function with at least 20% of the finishing diet DM coming from forage.

The energy and protein requirements for each animal group are determined using relationships from the Cornell Net Carbohydrate and Protein System, level 1 (**Fox et al., 2004**). The energy requirement is the sum of the requirements for maintenance, lactation, pregnancy, and growth. For lactating cows, energy can also be available from weight loss. The maintenance energy requirement is determined as influenced by lactation, activity, and ambient temperature (**Fox et al., 2004**). The lactation effect is determined using a thermal neutral maintenance requirement for fasting metabolism of 0.07 Mcal/day/SWB0.75, but this requirement can be adjusted using an adjustment factor entered as a breed characteristic (**Table 8.4**).

Activity is modeled as the sum of the daily requirements for standing, changing position, and distance traveled (**Fox et al., 2004**). Time spent standing is set at 12, 14, 16, and 18 h/d for confinement, half-day intensive grazing, full-day intensive grazing, and continuous grazing, respectively. Distances traveled for these four options are 0.5, 0.8, 1.0, and 1.2 km/d, respectively. A temperature effect and the resulting potential for heat stress are a function of the current and previous month's average temperature and the current relative humidity, wind speed, and hours of exposure to sun light (**Fox et al., 2004**). For simplicity, the relative humidity and wind speed are set at average values of 40% and 1.6 km/h, respectively. Exposure time is set at 0, 5, and 10 h/day for confinement, half-day, and full-day grazing systems. Cold stress effect is modeled considering an average hide thickness and hair coat (**Fox et al., 2004**), but this effect seldom occurs using temperatures averaged over a monthly time step.

Cows also include an energy requirement for lactation, and both cows and replacement heifers include a gestation requirement during pregnancy. Metabolizable energy requirement for lactation is proportional to milk yield as influenced by milk fat content (**Fox et al., 2004**). The gestation requirement is a function of the number of days pregnant and calf birth weight (**Fox et al., 2004**).

Energy required for growth is a function of ADG and equivalent empty body weight (**Fox et al., 2004**). To determine an equivalent empty body weight, a standard reference weight is assumed. This standard reference weight is 478 kg for replacement heifers and 462 kg for all other growing animals. Cows in early lactation are allowed to lose weight to maintain production. Energy received from mobilized reserves is a function of weight loss and condition score (**Fox et al., 2004**).

Finally, the net energy requirement is increased to include an energy cost for excess protein in the diet. Our model implementation required a different approach for the calculation of urea cost than that used by Fox et al. (**2004**). Each kilogram of excess protein was assumed to require 0.7 Mcal of net energy to convert this protein to urea for excretion (**Tyrrell et al., 1970**). Excess protein includes both RUP and RDP (**Table 8.5**). Excess RDP is that greater than the amount useful for making microbial CP (based on non-fat energy intake). Intake of RUP that causes total metabolizable protein to exceed the metabolizable protein requirement is considered excess.

The metabolizable protein requirement of each animal group is the sum of the maintenance, lactation, pregnancy, and growth requirements. The maintenance requirement is a function of SBW, lactation requirement is proportional to milk yield and milk protein content, gestation is a function of calf birth weight and days pregnant, and the growth requirement is related to ADG and the net energy required for growth (**Fox et al., 2004**). The metabolizable protein requirement includes RDP and RUP requirements. The RDP requirement is the microbial crude protein (MCP) requirement divided by 0.9, where MCP is defined as 13% of the diet TDN excluding TDN from added fat sources (**NRC, 2000**). The RUP requirement is the total metabolizable protein requirement minus 64% of the MCP requirement.

Mineral requirements considered in the model include P and K. The P requirement (g P/d) for each animal group is the sum of the daily requirements for maintenance, lactation, gestation, and growth (**NRC, 2000**). The daily maintenance requirement is 0.016 g P/kg of SBW. For lactating cows, the lactation requirement is 0.9 g P/kg of MY. The daily gestation requirement is 7.6 g P/kg of fetal weight gain over the last 90 d of pregnancy, and the growth requirement is 0.039 g P/g of protein gain. The sum of the requirements is divided by an absorption coefficient of 0.68. The K requirement of each animal group is set at 0.6% of DM intake (**NRC, 2000**; **Fox et al., 2004**). These requirements set the minimum P and K intakes of each animal group, and the P requirement is used to estimate the purchase of mineral supplements (see Dairy Section above).

Beef Ration Balancing and Performance Prediction

Ration balancing and performance prediction is accomplished through an iterative solution where a linear program is used to determine a ration that meets the nutrient requirements. Intake is energy driven, but is potentially limited by physical fill. Constraints on the ration include physical fill, effective fiber or roughage, energy, degradable protein, and undegradable protein.

An iterative determination of intake begins with an estimate of the NEM concentration of the final diet. For most animal groups, fed a predominately forage diet, NEM of the final diet is estimated as the NEM concentration in the forage or forage mix fed to the given animal group. If the group is finishing cattle fed a high grain diet, the diet NEM is estimated assuming that 90% of the diet energy will come from available grain with the remaining 10% from forage.

Based upon the diet NEM, diet concentrations of net energy for gain (NEG) and metabolizable energy (ME) are estimated. Over the range of realistic beef ration energy concentrations ($0.8 < NEM < 2.5$ MCal/kg), NEG and ME are linearly related to NEM. The following functions were fit to data generated by calculating NEG and NEM over a range in diet ME concentrations (**NRC, 2000**).

$$NEG = 0.907\,(NEM) - 0.458 \qquad r^2 > 0.999 \qquad [8.19]$$

$$ME = 1.095\,(NEM) + 0.751 \qquad r^2 > 0.999 \qquad [8.20]$$

Total DM intake for the animal group is the sum of the DM intake for maintenance and that for gain. The DM intake required for maintenance is the net energy of maintenance requirement divided by the estimated NEM of the diet. The DM intake required for gain is the net energy required to meet the ADG goal divided by the NEG of the diet.

After DM intake and the associated energy concentrations are established, a linear program is used to balance the ration. Five constraint equations are solved in a manner that maximizes herd production with minimum cost rations (**Table 8.5**). Constraints include ruminal fill and the effective fiber, energy, RDP, and RUP requirements. The ruminal fill limit is the product of FIC and SBW for a given animal group (**Mertens, 1987**). Thus, the sum of the fill units of all feeds in the ration must be less than or equal to this maximum ingestive capacity. Fill units are the NDF concentration of feeds adjusted for particle size and fiber digestibility effects (see Feed Section above).

An effective fiber constraint assures that diets formulated contain adequate amounts of roughage. The sum of the roughage units of all feeds in the diet must exceed the minimum roughage requirement (**Table 8.5**). The roughage unit content of each feed is the NDF concentration adjusted to represent differences due to fiber digestibility and the size distribution of feed particles.

The energy constraint requires the energy consumed to equal the energy requirement. Thus, the total NEM from all feeds in the ration must equal the requirement plus the energy cost of excess dietary protein (**Table 8.5**). The energy cost of excess protein places some feed characteristic terms on the requirement side of the equation. To simplify the linear programming matrix, the equation is rearranged so that all feed characteristics are on the left side of the constraint equation.

The last two constraints specify the minimum protein requirement in the ration. The RUP constraint requires that 87% of the sum of the RUP in all feeds must be greater than or equal to the total metabolizable protein requirement minus the microbial CP production (**Table 8.5**). The RDP constraint requires that the sum of the RDP contents of feeds plus the rumen influx protein (15% of feed CP) be greater than or equal to the rumen available protein requirement (**Table 8.5**).

The five constraint equations are simultaneously solved with the objective of minimizing ration cost. Ration cost is determined using relative prices of feed ingredients. For grain and concentrates, the relative price is the long-term average price set by the model user. For forages, the relative price is set to zero for maximum forage diets. With a low relative price, the model uses as much forage as possible in ration formulation. Another user-specified option allows a minimum forage diet for finishing cattle. For this option, the price of forage is set high relative to concentrates forcing a minimum amount of forage in rations.

The constraint equations are solved by the linear program to provide a ration that meets the minimum roughage, minimum protein, and energy requirements without exceeding the limits on intake. If a feasible solution is not found for growing animals, the ADG goal for the group is reduced by 5% and the procedure is repeated until a feasible solution is found. If a feasible solution is not found for lactating cows, their loss in body weight (and resulting condition score) is increased by 50 g/day and the procedure is repeated until their energy need is offset by energy obtained from mobilized reserves.

The solution from the ration-balancing linear program provides a better estimate of the energy concentrations in the diet and the DM intake. If the DM intake obtained based upon the formulated diet is not within 1% of the initial estimate, a new set of requirements is determined based upon the new estimated DM intake. This iterative process is repeated until the difference between estimated and final DM intakes is less than 1%.

A final iteration is taken when the user specifies that minimal grain should be fed. If grain is included in the feasible solution found, then animal gain is further reduced and another feasible ration is determined. This procedure is continued until a ration is obtained without using grain or until a lower limit on gain is reached. This lower limit is set at 10% of the initial potential gain. At this point, grain is allowed in the ration to prevent adverse long-term effects on animal health. When the gain is reduced on a given month, the potential gain for following months is increased accordingly to allow compensatory gain to bring the animal back toward its ideal weight goal. Therefore, a set of feasible solutions on a given month of the year gives balanced rations, feed intakes, and weight changes for all animal groups. This solution makes good use of available feeds while maintaining a suitable production level.

Beef Growth and Condition

The ADG determined for each group of growing cattle on a given month is used to determine the SBW and condition of that group for the next month. For cows, a loss in body reserves reduces their weight and condition for the following month. Weight for the next month is the current weight plus the weight change over the month (ADG times 30.4 d).

Body composition and BCS of each animal group are predicted using the composition model of Williams and Jenkins (**1998**). Their model is implemented with the following assumptions or simplifications: 1) the stage of maturity for transition from growing cattle to mature cattle is 70% of FSBW rather than floating with the rate variable, 2) a 30 d time step is used, 3) the lag term for effect of nutrition is set equal to average daily gain, 4) calves are assumed to be born at a condition score of 3, and 5) replacement heifers gain at rates to achieve 60% of CSBW at breeding age (15 months) and 80% of CSBW at calving (24 months) (**NRC, 2000**). Fat free weight (FFW) of each animal group is described as a function of maturity where the monthly change in FFW is influenced by a genetic effect on body composition rate (**Williams and Jenkins, 1998**; **Table 8.4**). During months when ADG is greater than the change in FFW, BCS increases. Likewise, when ADG is less than the change in FFW, BCS decreases.

When growing animals progress to a suitable age or sufficient BW, they transition to the next age group. The animal characteristics entering the next group are set equal to those completing the current group. At this point, the number of animals bought or sold is determined. If the number of animals specified for the next age group is greater than the number in the current group after deducting mortality loss, then the difference is purchased. If the number specified for the next group is less than the current number minus loss, the difference is sold. If all animals entering a group are purchased, their characteristics are set assuming an ideal weight and condition. The number, month of the year, SBW, and BCS of the animals bought or sold are tracked for use in determining the cost of purchased animals and the income from animal sales.

Beef Manure DM and Nutrient Production

Manure DM production is the sum of the dry matters from feces, urine, bedding, and feed lost into manure. Fecal DM is the total quantity of all feeds consumed by each animal group multiplied by the fraction of indigestible nutrients (1 - TDN) of each feed. Urine production is determined using equation 8.13 as described above for dairy cattle. Urinary DM is set as 5.7% of total urine. Additional manure DM includes any bedding DM used and 3% of the feed DM intake (excluding pasture) to account for feed lost into the manure during confinement feeding.

The nutrients in fresh manure are determined for each simulated month through a mass balance of the six animal groups. Manure nutrients tracked are N, P and K. The quantity of each nutrient excreted is the nutrient intake minus the nutrients contained in animal tissue growth and that excreted in milk. Nitrogen intake is determined from the protein content of the feeds consumed (CP ÷ 6.25). Phosphorus and K intakes are set as the greater of the sum of that contained in feeds consumed or the requirement of the animal group. Fractions of the three nutrients in milk and body tissue are set as average values for the herd. Milk N is determined from the milk protein content, which is related to the breed. Remaining nutrient concentrations are 0.09% P and 0.14% K for milk and 2.8% N, 0.72% P, and 0.20% K for body tissue. Body tissue produced is based upon animal mass exported from the herd (dead or alive) minus that imported. This provides a more accurate long-term balance then tracking the change in body weight of individual animals during each month of their annual cycle. Manure also includes P and K from bedding material and feed lost into the manure. That from lost feed is set at 3% of the total intake of each nutrient, and organic bedding materials are assumed to contain 0.06% P and 2.4% K.

Manure N is partitioned between organic N and ammoniacal N. Organic N is assumed to come primarily from feces. Fecal N is fecal protein divided by 6.25 where fecal protein is the sum of the undigested bacterial protein, the undigested feed protein, and the metabolic fecal protein (**NRC, 1989**; **Fox et al., 2004**). Undigested bacterial protein is defined as 26% of the microbial crude protein (MCP, **Table 8.5**) produced in the rumen. Undigested feed protein includes all ADIP consumed in the animal diet plus 13% of the remaining RUP (Diet RUP minus ADIP). Metabolic fecal protein is 9% of the indigestible DM consumed (**NRC, 1989**). Manure organic N also includes N from feed lost into manure, N contained in bedding, and the N in scruff loss of hair and other tissue from animals. Feed loss is assumed to be 3% of the total N intake, and the N from organic bedding materials is 0.69% of the bedding DM. Scruff loss of protein (SPA) is a function of the body weight in each animal group (**Fox et al., 2004**):

$$SPA = 0.0002\ (SBW)^{0.6} / 0.67 \qquad [8.21]$$

Fecal and scruff N from the herd is the product of the excretions for each feeding group, the number of animals in the group, and the length of the feeding period (30.4 d) summed over all animal groups. Urinary N excretion is then assumed to be the total N excreted by all animal groups minus the fecal and scruff N. Fecal and scruff N is assumed to be organic N, and all remaining N (urine N) is considered to be urea, ammonium or another form that can readily transform to ammonia following deposition. Organic N is considered stable during manure handling, and ammonia N is susceptible to volatile loss.

Simulation of P loss requires that total manure P be divided into organic and nonorganic water-soluble and nonwater-soluble P components. The portion of the total excreted P in each of these four pools is determined as described above for dairy cattle.

Table 8.1 - Feed Fill and Rouhage Factors

Fill and roughage factors assigned to large and small particle pools of each feed type.

	Fill Factors		Roughage Factors	
	Large Particles	Small Particles	Large Particles	Small Particles
Alfalfa hay and silage	1.35	0.4	1.0	0.6
Grass hay and silage	1.50	0.8	1.0	0.8
Pasture	1.40	0.5	1.0	0.7
Corn silage	1.45	0.4	1.0	0.7
Small grain silage	1.55	0.6	1.0	0.8
Grain and concentrates	---	0.4	---	0.4

Table 8.2- Dairy Cow Characteristics

Functions used to describe dairy cow characteristics through a 56 wk lactation cycle.

Characteristics	Animal Type	Function
Milk Yield, kg/d	Primiparous cows	$MY_1(w^{0.178})(e^{-0.021w})$
	Multiparous cows	$MY_2(w^{0.2218})(e^{-0.034w})$
Milk Fat, %	Primiparous cows or Multiparous cows	$MF(w-0.24)(e^{0.016w})$
Body weight, kg	Primiparous cows	$BW_1(w+1.71)^{-0.0730}[e^{0.00869(w+1.71)}]$
	Multiparous cows	$BW_2(w+1.57)-0.0803[e^{0.00720(w+1.71)}]$
Fiber ingestive capacity *FU*/(kg of *BW*)/d	Primiparous cows	$FIC_1(w+0.857)0.360[e^{-0.0186(w+0.857)}]$
	Multiparous cows	$FIC_2(w+3.000)^{0.588}[e^{-0.0277(w+3.00)}]$

[1]*MY* = milk yield parameter, *MF* = milk fat content parameter, *BW* = body weight parameter, *FIC* = fiber ingestive capacity parameter, w = week in the lactation cycle, 1 to 56, and *FU* = fill units.

Table 8.3- Dairy Ration Constraints

Constraints and associated equations used to develop dairy animal rations.

Constraint Equations		
Physical fill	$\sum xi\ (FUi)$	$\leq$ FICj (BWj)
Effective fiber	$\sum$ xi (RUi-0.21)	≥ 0
Energy requirement	$\sum$ xi (NEi)	= [NEDj + 0.7 (ECPj)] AMMj
Rumen degradable protein	$\sum$ xi (CPi) (RPDi + 0.15)	$\geq$ MCPi / 0.9
Rumen undegradable protein	$\sum$ xi 0.87 (AUPi)	$\geq$ MPRj - 0.64 (MCPi)

Associated Equations	
Adjustment for multiple of maintenance	*AMMj* = 0.92 / [1-0.04 (NERj / NEMj - 1)
Available undegraded protein	*AUP*i =CPi [1-RPDi - UFi (ADIPi)]
Microbial crude protein	*MCP*j = 0.13 (TDNDj)(DMIj)
Excess protein	*ECP*j = $\sum$ xi (CPi) [RPDi + 0.15 + 0.87 (1 - RPDi - UFi (ADIPi)]- 0.7 MPRj + 0.47 (MCPj)]

ADIPi = acid detergent insoluble protein concentration in feed i, fraction of CP

AMMj = adjustment factor for multiple of maintenance in lactating animal group j

AUPi = available RUP in feed i, fraction of DM

BWj = body weight of animal group j, kg

CPi = CP concentration in feed i, fraction of DM

RPDi = rumen degradability of protein in feed i, fraction of CP

DMI = DMI estimate which resolves NEm intake with NEm and NEg requirements, kg/d

ECPj = excess protein consumption, kg/d

FICj = fiber ingestive capacity, kg NDF/kg SBW/d

FUi = fill units (NDF adjusted for particle size and digestibility; Rotz et al., 1999a) of feed i, fraction of DM

MCPj = microbial crude protein production in animal group j, kg/d

MPRj = metabolizable protein requirement of animal group j, kg/d

NEi = NEm concentration in feed i, MCal/kg DM

NEMD = diet NEm which resolves NEm intake with NEm and NEg requirements, MCal/kg DM

NEMj = net energy requirement for maintenance of animal group j, MCal

NERj = net energy requirement of animal group j, MCal

RUi = roughage units (NDF adjusted for particle size and digestibility; Rotz et al., 1999a) of feed i, fraction of DM

TDNDj = total digestible nutrient concentration of the diet, fraction of DM

UFi = unavailable fraction of ADIP (0.7 for forages and 0.4 for concentrates).

xi = amount of feed i in the diet, kg DM/d

Table 8.4- Beef Breed Parameters

Breed dependent parameters and suggested values for beef animals.

				Breed			
Parameter Description	**Holstein**	**Simmental**	**Limousin**	**Shorthorn**	**Hereford**	**Charlois**	**Angus**
Final shrunken body weight for mature steers (28%) body fat, kg	700	760	620	560	620	814	560
Peak milk production of mature cows, kg/d	15.0	12.0	9.0	8.5	7.0	9.0	8.0
Milk fat content, %	3.5	4.0	4.0	4.0	4.0	4.0	4.0
Milk protein content, %	3.3	3.8	3.8	3.8	3.8	3.8	3.8
Calf birth weight, kg	43	39	37	37	36	39	31
Genetic effect on thermal neutral maintenance energy requirement	1.2	1.2	1.0	1.0	1.0	1.0	1.0
Genetic effect on fiber ingestive capacity	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Genetic effect on body composition rate	8.0	7.2	6.0	6.3	7.5	7.5	6.0

Genetic parameter (theta) developed by Williams and Jenkins, 1998.

Table 8.5- Beef Ration Constraints

Constraints of the linear program used to balance beef rations.

Constraint Equations		
Physical fill	$\sum$ xi (*FUi*)	< (*FIC*)(*SBW*)
Effective fiber	$\sum$ xi (*RUi*)	$\geq$ (*EF*)(*DMI*)
Energy requirement	$\sum$ xi (*NEMi*)	= (*NEMD*) (DMI) + 0.7 (*EP*)
Rumen Degradable Protein	$\sum$ xi (*CPi*) (*DEGRi* + 0.15)	$\geq$ *MCP* / 0.9
Rumen Undegradable Protein	$\sum$ xi (*CPi*) (1-*DEGRi* -*UPi*)	> *MPR* -0.64 (*MCP*)
Associated Equations		
Excess Protein	*EP*	= $\sum$ xi (*CPi*) (*DEGRi* + 0.15 + 0.87 (1 - *DEGRi* - *UP*)) -*MPR*+0.47 (*MCP*)
Microbial Crude Protein	*MCP*	= 0.13 (*TDND*) (*DMI*)
Total Digestible Nutrients of Diet	*TDND*	= 0.31 (*NEMD*) + 0.2

xi = amount of feed i in the diet, kg *DM*/d

DMI = DMI estimate which resolves NEm intake with NEm and NEg requirements, kg/d

NEMi = net energy requirement for maintenance of animal group j, MCal

NEMD = diet NEm which resolves NEm intake with NEm and NEg requirements, MCal/kg *DM*

EPi = excess protein consumption, kg/d

CPi = crude protein concentration in feed i, fraction of *DM*

DEGRi= rumen degradability of protein in feed i, fraction of *CP*

UPi = unavailable protein in feed i, fraction of *CP*

MCP = microbial crude protein production, kg/d

MPR = metabolizable protein requirement, kg/d

TDND = total digestible nutrient concentration of the diet, fraction of *DM*

FUi = fill units (NDF adjusted for particle size and digestibility of feed i, fraction of *DM*

RUi = roughage units (NDF adjusted for particle size and digestibility of feed i, fraction of *DM*

FIC = fiber ingestive capacity, kg NDF/kg SBW/d

SBW = shrunken body weight, kg

EF = effective fiber requirement, fraction of diet

DM = 0.08 for finishing cattle on high concentrate diet, 0.20 otherwise

MANURE AND NUTRIENT INFORMATION

The manure component describes a variety of options in manure handling including methods of manure collection, storage, transport, and application. Collection methods include hand scraping, a gutter cleaner or alley scraper, a tractor mounted scraper or loader with a ramp, and a collection pit and slurry pump. Storage methods include a stack for dry manure, a cement pad and buck wall for short-term storage of semi-solid material, tanks for slurry storage, and an earthen retention pond for liquid manure. Transport and application is done with tractor-drawn or truck-mounted spreaders with or without a nurse tank, and manure is spread on field surfaces, injected into the soil, or irrigated.

The model allows the user to specify up to two manure collection methods used on the farm. For each collection method, the user must assign appropriate inputs that include manure type, storage method, and machinery for field application of manure.

Manure Handling

The quantity and nutrient content of the manure produced by the animals on the farm is a function of the feeds fed as described in the **Herd and Feeding** section above. In each manure collection method, the total quantity of manure handled is a function of the amount and type of bedding used, the amount of water contained in the manure, and the percentage of total manure handled (assigned by the user). Bedding options include manure solids, straw, sawdust, and sand. For each collection method, the user can select the bedding type and specify the amount of bedding used per mature animal in the herd. The quantity of bedding used is determined by calculating the number of animal units on the farm with the mass of an animal unit being the average mass of a mature cow in the herd. This animal mass varies with the animal breed selected. The number of animal units thus reflects the total animal mass on the farm (including young stock) expressed in units of mature animals. Bedding use is the product of mature animal units and the use per animal unit.

The quantity of wet manure handled is determined from total manure *DM* and the user selected manure type. Manure types are dry, solid, semisolid, slurry, and liquid. Total manure *DM* includes that excreted by animals plus that of bedding and feed lost into the manure. Total manure handled is manure *DM* handled divided by *DM* content. Although *DM* content can be adjusted, preset values are 70, 20, 13, 8, and 5% for dry, solid, semisolid, slurry, and liquid manures, respectively. Dry manure is manure removed from open lots, which is typically very dry when removed. Solid manure is that from packed beds, and semi-solid represents fresh manure plus bedding. Slurry manure typically includes milking facility wastewater and additional water from rain runoff from animal holding areas. For liquid manure, additional water from rain or other sources such as flush water is assumed and a liquid/solid separator may be used.

Two different manure handling systems can be used on a simulated farm. The first, designated as the primary system, would normally be the system handling most of the manure. If a secondary system is used, a designated portion of the total manure dry matter is handled with this system and the remainder is handled in the primary system. Manure nutrients entering the two systems are split in proportion to the excreted dry matter handled by each. Both systems are simulated through the same processes except that an anaerobic digester can only be associated with the primary system.

Scraping and Hauling

Manure is collected in the barn or housing area by manual scraping, a gutter cleaner, alley scraper, or a tractor mounted scraper or loader. With slurry and liquid manure systems, a pumping operation can also be used to move the manure into storage or a transport vehicle. Transport and application of manure is done with semi-solid or slurry type spreaders, a tank with injectors that deposits the manure beneath the surface, or an irrigation system.

Throughput capacity and the fuel, electricity, and labor use rates for each operation are determined in the **Machinery** component. Hauling cycle times are a function of loading and unloading rates, transport speeds, and distance hauled. Power requirements for the various operations are estimated using the procedure of Rotz and Muhtar (**1992**). For collection, a power requirement of 8 kW is assigned for scraping with a power requirement of 0.13 kW-h/t for pumping slurry. Surface application of manure requires 0.2 kW-h/t for spreading plus the power required to overcome the rolling resistance of the spreader load. For subsurface injection, an additional 12 kW per injection unit is required. From these power requirements, fuel and electricity use rates are determined for each operation.

The type, number, and size of machines used for manure handling are set by the user through the manure handling system and machines selected. It is the responsibility of the user to select appropriate equipment to perform the work required. To maintain flexibility in the use of the model, no constraints are placed on machinery selection. If the equipment selected is too small for the required work, warning messages can occur indicating that spring or fall operations were not completed. If this occurs for a number of years, larger manure handling and/or tillage equipment may be needed.

The time for loading, transport, and applying a load of manure are determined based upon the hauling capacity of the transport device and the throughput capacities of the loading, transport, and spreading operations. This provides the time required to cycle through the transport and unloading of one load of manure. The number of loads that can be hauled and spread during a day is the time available that day divided by the single load time. The time available on a given day is limited to that set by the user for the maximum time worked each day on tillage and planting operations. The time available may also be reduced if another field operation is competing for the same labor on a given day.

The model user selects the manure collection equipment used. This equipment can be a gutter cleaner or electrical powered scraper, a tractor or skid-steer loader and scraper, or a flush system. Again the throughput capacity and the fuel, electricity, and labor use rates are determined for the selected equipment in the machinery component. The amount of time each machine is used is determined as the quantity of manure handled divided by the throughput capacity of the equipment.

At the completion of all manure handling operations, the totals of all machinery and resources used are determined. The total number of hours each machine is operated is summed, and the total use for manure operations is maintained along with the total use of each machine summed over all farm operations. Fuel, electricity, and labor uses are also totaled based upon the loading, transport, and spreading times and the rate requirements of each operation determined in the **Machinery** component. If custom hire is used for manure hauling and application, the same processes are simulated, but machinery, fuel, electricity, and labor use and costs are ignored for these operations. Instead, the total hours required for manure hauling and application is determined as a basis for calculating a custom cost.

Costs of manure collection and application are determined from the predicted hours of machine use and labor, fuel, and electricity used. As discussed in the **Economics** section, an annual machinery cost is determined by depreciating the initial cost over the designated machine life and adding 0.5% of the initial cost to cover the annual costs of insurance and taxes. Annual repair and maintenance costs are determined from the hours of machine use. Repair and maintenance factors assumed for most manure equipment are 0.16 (RF1) and 1.6 (RF2) with a wear-out life of 2000 h, but these can be adjusted by the model user. Costs for each machine are allocated between manure and other farm operations according to the time used for manure handling compared to other uses.

Separation and Extraction

Manure treatment technologies for separation and extraction of nutrients can be modeled to represent nutrients removed from the farm. When substantial amounts of feed are imported to the farm, large amounts of excess nutrients must be exported from the farm to use nutrients most efficiently and maintain a long-term balance. A centrifuge is sometimes used to extract P from liquid manure. Other new technologies based upon dissolved air floatation, evaporation, and ultrafiltration techniques are being explored. This technology can be represented as a manure handling process using a general and flexible model. As with other manure handling equipment, the user specifies the initial cost, repair and maintenance factors, throughput capacity and power requirement for the operation. The annual use of the equipment is determined using the throughput capacity and the quantity of manure processed. The power source is normally electricity where electricity use is determined assuming an average 70% load on the motor power specified. The manure volume and nutrients removed reduces that stored and applied on the farm.

Manure Storage

Manure storage options include long-term storage in an aboveground steel tank, a belowground concrete tank, or a clay- or plastic-lined earthen retention pond. Essentially any storage size can be selected by setting an average diameter and depth for the structure. The type and size of storage selected controls the amount of manure that can be stored, the cost of manure storage, and it influences the amount of volatile nitrogen loss that occurs from storage.

Storage options include none, six-month, and twelve-month storage. Without storage, manure must be hauled each day. This option can also be used to represent short-term storage on a slab or in a small pit. With a six-month storage, manure is emptied twice each year in the spring and fall. For twelve-month storage, it is emptied once a year in the spring. For either of the two long-term storage options, the manure produced during that period of time each year is compared to the storage capacity. If the storage is too small to hold the manure produced, the simulation continues but a warning message is given that the user should consider increasing the storage size.

When manure is stored in a concrete or steel tank, the manure can be added to the top or bottom of the tank. Top loading represents scraping or pumping of the manure onto the top surface; whereas, bottom loading represents the pumping of manure into the bottom. With bottom loading, a crust forms across the manure surface. This crust helps seal the surface, reducing volatile nitrogen loss from the storage facility.

Application

The model user sets the portion of the total manure applied to each crop on the farm. The sum of these portions cannot exceed 100% and should equal 100%. The amount of manure applied to each crop is the portion of the total manure applied to that crop times the total amount of manure handled on an annual basis. Manure deposited during grazing is applied to the grazed crop, and this portion is not included in the value for total manure handled, i.e. the manure handled is the total produced minus that deposited during grazing. The amount applied during grazing is determined by the animal groups on pasture and the time those animals spend in the pasture. When all animals are maintained on pasture year around, about 85% of the total manure produced is deposited during grazing. For seasonal grazing, this value is about 40%.

The manure application rate for a given crop is the manure applied to that crop divided by the land area designated for that crop. Manure nutrients applied to the crop are the manure *DM* applied times the concentration of each nutrient in the manure *DM*. Nitrogen concentrations are those determined after losses during collection, storage, and application are subtracted.

Manure application is simulated on a daily time step. For daily hauling (or short-term storage) of manure, hauling and application occur each day. When a storage facility is emptied, manure is applied on a given day when manure is available for application, the day is suitable for fieldwork, and there is not a higher priority field operation being performed. A given day is suitable for fieldwork when the soil moisture level is below a critical level (See the **Tillage and Planting** section). Manure hauling and application occur each suitable day until the storage is emptied. The amount applied each day is the number of loads spread each day (see above) times the load size. On a given parcel of land, manure application must be complete before tillage operations can occur to incorporate the manure and prepare a seedbed.

Criteria for manure application through irrigation are slightly different. The amount of manure handled each day is based upon the throughput capacity of the irrigation equipment as set by the user. When the manure is pumped long distances, an auxiliary pump can be used to increase the throughput capacity of the system. Manure can be applied on any given day when application is required, regardless of the soil and weather conditions.

Nutrient Balance

All nutrient flows onto, within, and off the farm are tracked to determine a whole farm nutrient balance. Nutrients are primarily imported onto the farm through *N* fixation by legumes, fertilizer, and nutrients in purchased feeds. Nutrient levels in purchased feeds are set by the user where *N* concentration is protein content divided by 6.25. A small amount of *N* is also imported through rainfall. Nutrients are exported off the farm through the losses described above and in the milk, animals, and feeds sold off the farm. Nutrient levels in milk and meat are those given above in the **Herd and Feeding** section. Losses of *N* and *P* are predicted as described above. Loss of *K* between the animal and the crop is set at 5% of that applied to fields in manure or fertilizer.

Over the long term, *N* does not accumulate in the soil. Therefore, as excess *N* increases on the farm, *N* losses increase to maintain a balance. However, *P* and *K* minerals can accumulate in the soil. The accumulation of each is determined by subtracting the total exports from the imports and dividing this result by the total farm area. This predicts the whole farm balance of each of these nutrients assuming that over the long term these nutrients are uniformly distributed over all available land.

Nutrient removals by each crop are estimated to track the flow of nutrients within the farm and to predict the nutrients in feeds sold. Soil nutrient removal by a given crop is the crop area times the harvested yield times the concentration of the nutrient in the material harvested. Nitrogen concentration in forage crops (alfalfa, grass, corn silage, and small grain silage) is the harvested protein concentration divided by 6.25. Nitrogen concentrations in grain crops and the *P* and *K* concentrations in all harvested crops are set to typical values, i.e. protein/6.25, *P*, and *K* contents assumed for crops produced (See the **Crop and Soil** section). The total *N* available to crops on a given year is the total of that available from fertilizer, fixation by legumes, rain, and manure after the volatile losses during collection, storage and application are subtracted.

Manure Import and Export

Manure can be brought on to the farm or carried off the farm. This affects the nutrient balance of the farm, but in most cases does not have much effect on the economics of the farm due to the assumptions made on manure handling. When manure is imported, it is assumed that the supplier of the manure provides the equipment, fuel, and labor to spread the manure on the farm. Thus the manure brought onto the farm does not have any additional cost to the farm owner. This means that the farm owner provides a service to the manure producer by supplying land for disposal of the manure, but the farm can obtain benefit from the use of the added nutrients. These conditions hold whether the farm is for crop production only or if it has an animal component that is producing manure as well.

When fresh manure is exported, the assumption is made that the farm owner has the equipment or pays for the cost of transporting the manure off the farm and applying it on another farm. Thus, that portion of the nutrients are removed from the farm, but the equipment requirements and handling costs are essentially the same as if the manure were applied to the cropland of the simulated farm. The only difference will be in the assigned distance the manure is hauled. When manure is exported in the form of separated solids or compost, the amount of manure handled is influenced, which reduces the spreading costs. Costs for composting are not included in the farm economic analysis.

Nutrient Import

When manure is carried onto the farm, the amount of manure imported and the *DM* and nutrient contents of that manure are provided by the model user. The amount of manure *DM* applied to the cropland is the sum of that produced on the farm and that imported. Likewise, the total quantities of *N*, *P*, and *K* applied are the sum of that produced and that imported. The portion of the manure nutrients applied to each crop on the farm is the same as that specified for farm produced manure.

The flow, transformation, and loss of the added manure nutrients follows the same relationships used for the farm-produced manure. The manure carried onto the farm has volatile *N* losses following field application, but losses that occur in the barn or during storage and handling are not included. These losses have occurred before the manure is brought onto the farm, which should be considered when setting the *N* content of the imported manure. The *N* volatilization rate following field application is set at the same rate as that for manure produced on the farm. This is a function of the volatile (ammoniacal) *N* content of the manure and the time between spreading and incorporation of the manure (see the **Nitrogen Loss** section above). The fraction of *N* that is in a volatile form is set as the weighted average of that imported and that produced on the farm. Phosphorus and *K* losses occur only in runoff, and the losses from imported manure are predicted using the same relationships as farm-produced manure (see the **Phosphorus Loss** section above). Thus *P* and *K* losses increase in proportion to the amount of each applied.

Nutrient Export

Manure nutrients can leave the farm as fresh manure, separated solids, compost or extracted nutrients. Similar but somewhat different relationships are used to model the effect of each type of export. The manure *DM* exported is set as a portion of the total manure *DM* produced on the farm. This can be 0 to 100% of the manure solids produced.

When the export is fresh manure, the nutrients removed are the nutrient contents of the manure following storage (or following barn scraping if no storage exists) times the manure *DM* removed from the farm. The *N* content is that determined after volatile losses occur in the barn and during storage (if manure storage is used). The *P* and *K* contents are that in manure excreted by the animals (See the **Herd and Feeding** section). For the portion of the manure exported from the farm, the *N*, *P*, and *K* losses that would occur following land application are eliminated.

When separated manure solids are removed from the farm, the nutrient removal is the *DM* removed times the nutrient contents of the removed solids. By default in the program, the *N*, *P*, and *K* contents in organic bedding material (straw or sawdust) are set at 1.4, 0.3, and 0.4%, respectively (**Chastain et al., 2001**; **Meyer, 1997**). With sand bedding, fewer nutrients are retained in the solids, so the *N*, *P*, and *K* contents are set at 0.8, 0.15, and 0.4% respectively (**Van Horn et al., 1991**; **Harrison, unpublished data**). The nutrient contents of the removed solids can also be set in the farm parameter file. When values are set, the default values in the program are overwritten by the user specified values.

The amount of manure handled on the farm and the nutrients in the remaining manure are adjusted according to the solids removed. It is assumed that the manure solids removed contain about 40% *DM*. The amount of manure applied to the farm cropland is the total produced minus the solids removed and the moisture contained in those solids. The *DM* content of the remaining manure is the original *DM* minus that exported divided by the total quantity of manure remaining. Thus the amount of manure handled during field application is reduced, and the costs for spreading that manure are reduced accordingly. Nutrients remaining in the manure on the farm following separation are that in manure received from the barn minus that leaving in separated solids. Nutrient losses during storage and following land application are reduced in proportion to the amount removed.

Another option is to remove manure and nutrients in the form of compost. The manure removed reduces the amount of manure stored and applied to cropland thus reducing the manure application costs. When a portion of the manure is exported as compost, the nutrient content of the manure removed is that following composting. The process-based model of the composting process and the resulting predicted losses is described in the **Manure Composting** section. The portion removed reduces soil accumulation and *N, P* and *K* losses following field application in proportion to that removed.

The remaining option is the use of equipment such as a centrifuge to extract nutrients from the manure for export off the farm. The user sets the portion of each of the major nutrients in the manure prior to processing that are extracted and removed. As with the other exports, the portion removed reduces soil accumulation and *N, P* and *K* losses following field application in proportion to that removed.

If equipment is used for manure separation, compost turning or extraction, equipment use and the cost of owning and operating that equipment can be included with other machinery operations (See the **Manure Handling** and **Production Cost**s sections). Initial costs and other economic parameters for the manure handling equipment must be specified as part of the machinery operations.

Anaerobic Digestion

Anaerobic digestion of manure on farms, particularly dairy farms, is becoming more common. The major incentives are energy recovery, odor reduction, and reductions in greenhouse gas emissions. In an anaerobic digester, volatile solids in manure are decomposed by microorganisms in a warm anaerobic environment to produce biogas. Biogas generally contains about 60% methane (the main component of natural gas) and 40% carbon dioxide on a volumetric basis. Biogas can be burned to create heat or used as stationary engine fuel, normally to power generators for creating electricity. Burning of the biogas converts methane to carbon dioxide, a less potent greenhouse gas. The energy produced is primarily used on the farm, but it can also be sold to power and natural gas companies for resale as "green" energy. The anaerobic digester is modeled in three major components: energy production, energy use, and effects on manure.

Energy production

Biogas is produced through the microbial degradation of volatile solids in the manure. The rate of volatile solids flow into the digester is determined from the manure dry matter produced and loaded into the digester and the volatile solids content of that dry matter:

$$Q_{vs} = C_{vs}\ Q_m \qquad [9.1]$$

where

Q_{vs} = flow rate of volatile solids into digester, kg/d

C_{vs} = volatile solids concentration in manure influent, fraction

Q_m= loading rate of manure dry matter, kg/d

The manure loading rate is the amount of manure excreted and collected from barns (See the **Manure and Nutrient Production** section). The volatile solids content of the manure is primarily a function of the animal groups that produced the manure (see **Table 13.3**).

The amount of methane produced is a function of an assigned productivity and a conversion efficiency:

$$CH4 = Q_{vs}\ (E_{vs})\ (CH4_{yld}) / 100 \qquad [9.2]$$

where

$CH4$ = methane production rate, kg/d

E_{vs} = efficiency of volatile solids conversion, %

$CH4_{yld}$ = methane productivity per unit of volatile solids destroyed, kg CH_4/kg VS

The methane productivity from volatile solids is dependent on characteristics of the manure, and is not expected to vary substantially. The methane productivity is set at 0.35 kg CH_4/kg VS, based on predicted and measured values reported by **Hill (1984)** and measured values given in **Converse et al. (1977)** and **Moller et al. (2007).** Over all studies, reported values range from 0.23 to 0.39 kg CH_4/kg VS. The conversion efficiency is a user defined characteristic of the digester, and may range from about 20% to 45% for dairy manure, with typical values close to 30% (**Converse, 1977; Hill, 1984; Moller et al., 2004**). A similar relationship is used to predict carbon dioxide production where the productivity is 0.9 kg CO_2/kg VS. In practice, carbon dioxide productivity also varies. Values calculated from the data in **Converse et al. (1977)** range from 0.74 to 0.98 kg/kg, but this parameter has only a small effect on greenhouse gas emissions.

The power available in the biogas produced is a function of the energy content (lower heating value) of methane:

$$P_{bg} = E_{CH4} (1 - L_{BG} / 100) (CH4) / 3.6 \quad [9.3]$$

where

P_{bg} = power available in the biogas produced, kW-h/d

E_{CH4} = lower heating value of methane, 50 MJ/kg CH_4 (**Masters, 2004**)

L_{BG} = biogas leakage rate, %

3.6 = conversion from MJ to kW-h

The biogas leakage rate is assigned by the model user; a typical value is 1% (**EPA, 1999**).

Biogas use

The total power in the biogas produced can be used to heat water in a boiler, generate electricity, or burned in a flare. The amount used to heat water is set by the model user as a portion of the total available:

$$P_{BLR} = BLR_{use} (P_{bg}) / 100 \quad [9.4]$$

where

P_{BLR} = biogas power used in the boiler, kw-h/d

BLR_{use} = portion of biogas used to heat water, %

All remaining biogas power is available to generate electricity. Electricity production is a function of the efficiency of electrical generation and the capacity of the generator. The amount of electricity produced each day is limited by either the capacity of the generator and the time it is operating or the amount of biogas available:

$$ELECT = \min (24 F_{run} (CAP_g), \; E_g (P_{bg} - P_{BLR}) / 100) \quad [9.5]$$

where

$ELECT$ = electricity produced, kW-h/d

F_{run} = portion of time engine-generator sets are running, %

CAP_g = electric generation capacity, kW

E_g = efficiency of electric generation, %

The portion of time the engine-generator sets are running, the generation capacity, and the generation efficiency are all set by the model user to represent the characteristics of the system modeled. The efficiency of the engine-generator varies with the type and age of the equipment used, but will generally be about 25%. The goal is to keep the engine-generator sets running most of the time, but maintenance, repairs, and other shut downs reduce this time.

Any remaining biogas that is not used for electric generation and water heating is burned in a flare. The power disposed of in the flare (P_{flr}) is determined as:

$$P_{flr} = P_{bg} - P_{BLR} - ELECT / (E_g / 100) \qquad [9.6]$$

Burning the methane converts the lost carbon to carbon dioxide, which reduces the global warming potential of the emission (see the **Methane Emission** section). This power represents a loss of energy, and thus should be minimized.

Effects on manure effluent

A major benefit from anaerobic digestion of manure is a reduction in the volatile solids content in the effluent. The effluent is normally stored in a tank or basin, the same as that used to store raw manure without digestion. Because of the reduction in volatile solids, the odor and methane produced from this storage is less than that occurring from untreated manure.

The effluent dry matter leaving the digester is reduced to account for volatile solids converted to methane and carbon dioxide:

$$Q_e = Q_m - E_{vs} (Q_{vs}) \qquad [9.7]$$

where

Q_e = digester effluent dry matter entering long term storage, kg/d

The volatile solids leaving the digester are determined as the amount entering minus that decomposed in the digester. Total volatile solids can be separated into degradable and slow degrading or non degradable fractions. The more degradable volatile solids in the effluent are determined as:

$$VS_d = (B_o / E_{CH4pot} - E_{vs}) Q_{vs} \qquad [9.8]$$

where

VS_d = degradable volatile solids in effluent, kg/d

B_o = achievable emission of methane during anaerobic digestion, g/kg VS

E_{CH4pot} = potential methane productivity during storage of the manure, g/kg VS

The achievable emission of methane and potential methane productivity are assigned characteristics of the raw manure; typical assigned values are 0.2 and 0.48, respectively (**Sommer et al., 2004**; see the **Methane Emission** section). The slow degrading or non degradable volatile solids in the effluent are determined as:

$$VS_{nd} = (1 - B_o / E_{CH4pot}) \, Q_{vs} \quad [9.9]$$

where

VS_{nd} = nondegradable volatile solids in effluent, kg/d

The remaining volatile solids in the manure control the methane emission rate of the stored digester effluent (see the **Methane Emission** section).

The digestion process also affects the nitrogen fractions in the manure. A portion of the organic N in the raw manure is decomposed to TAN. Based upon data collected by **Gooch et al. (2007)**, the amount of TAN in effluent entering long term storage is modeled as 15% greater than that entering the digester. This increase in TAN potentially increases the ammonia emissions from the storage and field applied effluent (see the **Ammonia Emissions** section).

Manure Composting

A routine is used to simulate either a static stack or turned windrow of manure. This compost model simulates processes occurring during the biological decomposition and stabilization of organic matter and the resulting C and N gaseous emissions. These processes include organic C and N microbial decomposition (mineralization), C and N microbial consumption (immobilization), microbial respiration, NH_3 volatilization, nitrification, denitrification, leaching, runoff, and CH_4 fermentation and oxidation. Because of their influence on composting, environmental conditions within the stack or windrow, such as moisture content, temperature, aeration, and oxygen availability, and compost material properties, such as particle density and bulk density, are also modeled (**Figure 9.1**). Important equations used are summarized in **Table 9.1**. A more complete description of the model, refinement of simulation settings, and model evaluation are documented in **Bonifacio et al. (2016a, 2016b)**.

Two simulation profiles are used: (1) a triangular profile, which represents the shape of an actual windrow (**Figure 9.2a**), and (2) the equivalent soil profile, which is rectangular-shaped (**Figure 9.2b**) as used in modeling croplands and open lots. To simplify the model, dimensions of these two profiles are held constant. Based on published values, the height and width of the triangular profile are set to 1.5 and 3.5 m, respectively. The length is computed as a function of the amount of manure and any added material. The profile is divided into two equal parts (**Figure 9.2a**): the inner half, which is triangular-shaped with a height and width of 1.06 and 2.48 m, respectively, and the outer half. This simulation profile is used when modeling aeration within, evaporation from the surface, and heat transfer between the inner and outer halves of the profile. With this set-up, two sets of conditions (i.e., temperature, moisture, and C and N contents) are simulated for each half.

Model routines developed for cropland and open lots (see **Environmental Information, Nitrous oxide** section) are adapted to represent several N processes (nitrification, denitrification, leaching, and runoff) for stacks and windrows. A soil equivalent profile is used when modeling these processes. This profile is also divided into two equal layers, each 33.4 cm deep and 3.9 m wide (**Figure 9.2b**). The 33.4 cm depth is the thickness of the outer half of the original profile (**Figure 9.2a**) whereas the 3.9-m width is based on this depth and half of the original profile's cross-sectional area (~1.31 m^2). The outer layer is divided into four sublayers with depths of 3.0, 4.5, and 7.5 cm for the three uppermost layers.

Moisture content

The moisture component simulates the processes of precipitation infiltration, runoff, saturated and unsaturated flows, and evaporation. Relationships used to simulate infiltration, runoff, and saturated flows are those used for soils (see **Crop and Soil Information**). A different parameter in simulating unsaturated flows and a new model for evaporation are implemented to better represent stack or windrow conditions. In simulating unsaturated flows, the hydraulic conductivity (K_{hc}) of cattle manure is used. From data of **Sutitarnnontr et al. (2014),** K_{hc} is computed as a function of moisture content (Eq. 9.10). Three stack or windrow configurations are considered: open, roofed, and covered. In simulating evaporation losses for these configurations, particularly for the absence of solar radiation, a new evaporation model is used (see next section).

Parameters required to model moisture content include porosity, field capacity, and saturation moisture content. Saturation is assumed to equal total porosity (PO_{total}), which is a function of dry bulk density (ρ_{dry}) and particle density (ρ_p) (see equation 4 of **Richard et al., 2002**). Field capacity is determined as half of saturation. At the start of composting, ρ_p is initialized at 1,370 kg/m^3 (**Das and Keener, 1997**); whereas, initial ρ_{dry} is approximated from initial amounts of manure (i.e., organic + inorganic) and added material, and their corresponding bulk densities. The bulk density for manure organic and inorganic components is set to 175 kg/m^3 based on data of **Larney and Olson (2006)** and **Hao et al. (2001).** The density of added material is based on the type selected, with default settings of 135, 135, and 237 kg/m^3 for straw, cornstalks, and sawdust, respectively (**AAFRD, 2005; Rynk et al., 1992**). Stack or windrow physical properties, such as ρ_p and ρ_{dry}, change during the simulation as amounts of manure organic and inorganic components decrease while the amount of composted components increases.

Total moisture loss is influenced by changes in water retention characteristics during composting. The raw, uncomposted material can potentially lose all its moisture through unsaturated flow (i.e., to adjacent layers) and evaporation. On the other hand, to represent higher water retention characteristics, the composted material can retain moisture equivalent to 60% of its water holding capacity; below this level, no water is lost through unsaturated flows and evaporation. The moisture content in each layer is limited to a minimum of 15% (wet-basis) to prevent infinite concentrations. For turned windrows, turning evenly redistributes moisture throughout the profile.

Evaporation

Moisture evaporation from stacks or windrows can occur through surface drying and aeration. The potential rate of surface evaporation (E_{sur}) is a function of a water mass transfer coefficient in the gas phase ($K_{g,w}$) and the moisture concentration gradient between the surface and ambient air (**Black et al., 2013**) (see Eq. 11.33 of the **Animal Housing Emissions** section). The $K_{g,w}$ is calculated from a 10-m height effective air velocity and Schmidt number using a relationship derived from data of **Mackay and Yeun (1983)** (Eq. 9.11). Effective air velocity is set to ambient air velocity for open conditions, half the ambient air velocity when a roof is used, and 0 m/s (i.e., no surface evaporation) with a cover. Using relationships based on **MAC (2011)**, ambient air moisture concentration is estimated from ambient relative humidity (*RH*); whereas, air moisture concentration at the surface assumes a saturated (100% *RH*) air layer. Ambient *RH* is approximated from meteorological inputs (i.e., daily maximum and minimum temperatures, precipitation, wind speed, and solar radiation) and the number of preceding consecutive days without rain using equation 9.12, which was derived using measurements taken at a cattle feedlot in Kansas (**Bonifacio et al., 2011**).

In calculating the potential rate of evaporation due to aeration (E_{aer}) (Eq. 9.13), air flow through the stack or windrow is modeled in three stages: (1) from ambient air to the outer half, (2) from the outer half to the inner half, and (3) from the inner half to the outer half. For each stage, initial ($MC_{aer,in}$) and final ($MC_{aer,out}$) moisture concentrations of air as it flows through the profile are calculated following the same procedure explained above. In calculating $MC_{aer,out}$, air exiting each half of the stack or windrow is assumed to be at the temperature of that material and saturated. For the first two stages in which the temperature of air flowing through the profile increases, evaporation occurs because more water is required for air to be saturated at a higher temperature (i.e., $MC_{aer,in} < MC_{aer,out}$). For the last stage where air temperature decreases as air flows from the inner to outer half, condensation is modeled (i.e., $MC_{aer,in} > MC_{aer,out}$).

The overall potential evaporation rate is the sum of E_{sur}, E_{aer} for the outer half (stage 1), and E_{aer} for the inner half (stages 2 and 3). However, predicted actual evaporation rate is either equal to or less than the overall potential evaporation rate. Aside from the 15% lower limit for moisture content (wet-basis), a maximum evaporation loss is set equal to the amount of water present in the uppermost 15 cm.

Temperature

Composting has two major phases: active composting and curing (**AAFRD, 2005**). Each phase can be further divided into two stages in terms of temperature and microbial activity. For the active composting phase, there are mesophilic and thermophilic stages and for curing, mesophilic and maturation stages (**Cooperband, 2002; Ghazifard et al., 2001**). Compost temperature is primarily dependent on simulated microbial activity and the stack or windrow conditions of moisture content, aeration, and remaining material. Temperature prediction involves simulation of: (1) heat generation through microbial activity, (2) heat loss through evaporation and convection, and (3) heat conduction between outer and inner halves.

Similar to bedded pack barns (see **Environmental Information, Nitrous oxide** section), relationships for calculating heat generation (Eq. 9.14) and heat evaporation loss (Eq. 9.15) are adapted from **Cekmecelioglu et al. (2005).** The amount of C respired needed to calculate heat generation (i.e., C_{CO2} in Eq. 9.14) is based on simulated microbial activity (see C and N Processes section). Heat convection loss is calculated following **Liang et al. (2004)** (Eq. 9.16). Heat conduction between the outer and inner halves is a function of their temperature difference and thermal conductivity (k_w) (Eq. 9.17), with k_w calculated from the overall moisture content of the composting material using a relationship from **Sutitarnnontr et al. (2014).**

To simulate turning, the temperature of the whole windrow is set to that of ambient air. Based on findings from previous cattle manure compost studies (**Robin et al., 2002; Robinzon et al. 2000**), no heat evaporation loss from the inner windrow is modeled until its temperature reaches 40°C, the defined starting temperature for the active thermophilic stage.

Oxygen and aeration

As an aerobic process, composting requires a continuous and sufficient supply of oxygen for microbial consumption. Depending on the type of composting, oxygen can be provided through natural convection and mechanical aeration for static piles and natural convection and turning for turned windrows. The routine simulating air entering the stack or windrow is composed of two components. The first component is for the amount of air added through turning, which we assume is equal to the volume of air-filled pore space (V_{afps}) calculated as the product of the volume and air-filled porosity (PO_{air}). The value of PO_{air} is a function of ρ_{dry} and moisture content (**Richard et al., 2002).**

The second component is for the air added through natural convection driven by a temperature gradient. This component is adapted from aeration models by **Richard et al. (2004)** and **Yu et al. (2008)** for cylindrical composting bioreactors. In addition to those made by **Yu et al. (2008),** additional assumptions were applied when modeling air flow through the windrow profile: (1) both ambient air enters and exhaust air exits at any given point on the outer surface, (2) air flow direction has no effect on processes such as water evaporation and heat convection, and (3) air velocity throughout the pile is constant. Based on the simulation profile used (**Figure 9.2a**), the volume of air passing through the inner half is driven by the temperature gradient between the outer and inner halves. Total air passing through the outer half is driven by the temperature gradient between the outer half and ambient air plus the inner aeration. For each half, daily aeration (V_{aer}) is a function of PO_{air}, surface area (A_w), compost material permeability (K_p), air density and viscosity (i.e., both held constant), and the temperature gradient (Eq. 9.18) (**Yu et al., 2008**). The value of A_w is a function of the length of the stack or windrow. The K_p is a function of PO_{air}, effective particle size (d_p), and the Ergun viscous component constant (A) is approximated using figure 6 of **Richard et al. (2004).** Through refinement using Larney and Olson (2006) data, A is set to 60. With changes in ρ_p and ρ_{dry} and their effects on PO_{air} simulated (see Compost Physical Properties section), effects of compaction on aeration is not included.

The amount of oxygen added is computed from the simulated air volume (i.e., V_{aer} for turning, V_{afps} for aeration) and temperature (i.e., compost temperature for turning, ambient air temperature for aeration) using the Ideal Gas Law. In the calculations, an atmospheric air molecular weight of 28.85 kg/kmol and an oxygen weight fraction of 0.23 are used. With V_{aer} (Eq. 9.18) much greater than V_{afps}, most of the oxygen in the stack or windrow is simulated through natural convection rather than turning.

Microbial decomposition, consumption, and respiration

Figure 9.3 illustrates the association and integration of the different C and N processes simulated for compost stacks or windrows. Modeling of each process and tracking of different C and N forms are performed for each defined layer (i.e., four upper sublayers and one lower layer) using the equivalent soil profile (**Figure 9.2b**). Organic, mineralized, and microbial C and N forms are evenly redistributed throughout the profile when turning occurs.

Relationships for simulating microbial decomposition, microbial consumption, and respiration for stacks and windrows were adapted from numerical studies on composting by **Cekmecelioglu et al. (2005)** and **Liang et al. (2004).** For each layer, organic C required for microbial decomposition is from both manure and added material while N is from manure. The different organic C forms in both manure and added material are discussed in the Compost Physical Properties section below. The total amount of organic C that decomposes within a day (C_{decomp}) is a function of the total organic C available (manure C + added material C), microbial decomposition rate (K_{decomp}) (i.e., assuming the same rate for manure and added material), a moisture content factor ($F_{m,decomp}$), and an anaerobicity factor (anaerobicity factor (anaerobicity factor ($F_{anaerob}$) (Eq. 9.19). The $F_{m,decomp}$, which has a value from 0.0 to 1.0, is based on **Liang et al. (2004).** Also ranging from 0.0 to 1.0, $F_{anaerob}$ is based on the oxygen concentration correction factor presented by **Richard et al. (2006)** with the half-saturation constant for oxygen set to 0.02 (**Haug, 1993**).

Patterned after the multi-factorial kinetic model derived by **Richard (1997),** K_{decomp} is a function of maximum decomposition rate ($K_{d,max}$), decomposition rate for the slow fraction ($K_{d,slow}$), number of days from the start of composting or last turning event (t), lag time in days (τ), and a first-order decay coefficient (k_{decay}) (Eq. 9.20). Both $K_{d,max}$ and $K_{d,slow}$ are calculated using the model by **Haug (1993)** modified to have a maximum growth rate of microorganisms, and thus maximum decomposition, at 60^{o}C (Eq. 9.21). The $K_{d,slow}$ is calculated using the compost temperature (T_w in equation 9.21) while $K_{d,max}$ uses the temperature for maximum decomposition (60 ^{o}C). Through refinement (**Bonifacio et al., 2016b**), τ is set to 2 days, k_{decay} to 0.10 per day, and x_1 (in Eq. 9.21) to 2.37×10^{-3} (dimensionless).

Manure organic N that decomposes within a day (N_{decomp}) is calculated from the manure component of C_{decomp}. As applied to open lot and bedded pack barn models, a manure carbon-to-nitrogen (C/N) ratio of 15 is used. Aside from N_{decomp}, other forms of N available for microbial consumption are ammonium N (NH_4^+-N) and nitrate N (NO_3^--N). Through refinement using data by Larney and Olson (2006), which indicated low NO_3^--N profiles for both static stacks and turned windrows throughout composting, NO_3^--N is treated as the primary N source over N_{decomp} and NH_4^+-N. Evaluation also showed that whichever N (i.e., N_{decomp} or NH_4^+-N) follows NO_3^--N as the next N source is not critical.

Two important parameters in composting are the N availability and the C/N ratio requirement ($(C/N)_{req}$) for composting microorganisms. There are two major decomposition scenarios with respect to N availability: with and without organic N. In the first scenario, C decomposition is not limited by N availability and there is always N_{decomp} being added to the NH_4^+-N pool depending on NO_3^--N available and $(C/N)_{req}$. In the second scenario, C decomposition is controlled by the total mineralized N (NO_3^--N, NH_4^+-N) present and $(C/N)_{req}$. If not enough mineralized N is available, C decomposition is limited, with organic C from the dry material as the last to decompose.

The $(C/N)_{req}$ for mesophilic (< 40°C) and thermophilic (≥ 40°C) stages of composting are set to 25 and 50, respectively (**Shaffer et al., 1991; Horwath and Elliot, 1996**). Some of the decomposed C becomes part of microbial biomass with the rest respired as CO_2. Assuming a *C/N* ratio of 6 for microbial biomass (Williamson et al., 2003), 88% and 76% of C decomposed during thermophilic and mesophilic stages of composting, respectively, are converted to CO_2 through microbial respiration. Per mole of CO_2 formed, 0.8 mole of oxygen is consumed (**Richard et al., 2006**) and 0.9 mole of water is generated (**Stombaugh and Nokes, 1996**).

Nitrification, denitrification, nitrate movement, and nitrogen runoff

Similar to cropland and animal housing (open lots and bedded pack barns), simulation of nitrification, denitrification, and leaching for stacks and windrows are based on **DayCent (2007)** and nitrogen runoff on the Soil and Water Assessment Tool (SWAT) (**Neitsch et al., 2005**). Through refinement (**Bonifacio et al., 2016a and 2016b**), several changes were made to adapt the routines for stacks and windrow. For nitrification, the maximum fraction of available total ammoniacal N (TAN = NH_4^+-N + NH_3-N) that can be nitrified each day (K_{max}) is set to 0.27. Temperature effect on nitrification (F_{temp}) is calculated using a Poisson density equation. Compared to that for soils (**DayCent, 2007**), F_{temp} for composting was adjusted to have a wider range of temperature with higher nitrification rates. This enables the model to simulate a continuous decrease in NH_4^+-N concentration even at temperatures greater than 30°C. Also, if a layer enters the anaerobic phase (i.e., oxygen concentration after microbial decomposition < 5%; **AAFRD, 2005**), nitrification ceases in that layer.

Two revisions were made in implementing the denitrification model for compost, with the modified form given by equation 9.22. The first revision was to neglect the factor representing C availability ($F_d(CO_2)$ in equation 2 of **Del Grosso et al. (2000**) as *C* would always be in excess (i.e., *C/N* > 20). With predicted air flow (Eq. 9.18) and oxygen availability, the second revision was to replace the moisture-based factor in the original model with an oxygen-based factor ($F_{d,O2}$, Eq. 9.22), defined as 1.0 minus $F_{anaerob}$. With this parameter, denitrification rate is a function of oxygen availability, with the highest rate for anaerobic conditions and negligible for ambient-level oxygen conditions.

The NO_3^--N leaching model (Eqs. 13.51 to 13.53) for cropland and animal housing is implemented for compost stacks or windrows with the following conditions: (1) an impermeable working surface is assumed so no NO_3^--N leaches into the soil below, and (2) the outer windrow is treated as four sublayers; whereas, the inner is one layer when representing NO_3^--N movement within the profile.

Similar to modeling runoff from croplands, NO_3^--N runoff for stacks and windrows is simulated using relationships from the Soil and Water Assessment Tool (SWAT) (**Neitsch et al., 2005**). However, organic N runoff is currently not modeled and prediction of NH_4^+-N runoff is not feasible.

Ammonia volatilization

Ammonia (NH_3) is exhausted to the atmosphere through aeration and turning. As in the numerical model of **Liang et al. (2004),** NH_3 emission rate due to aeration is a function of the Henry's law constant for NH_3 (H), the difference in aqueous phase NH_3 concentrations between adjacent outer ($C_{NH3,out}$) and inner ($C_{NH3,in}$) layers, and hourly aeration rate (V_{aer}/24) (Eq. 9.23). Calculation of NH_3 emission is done on an hourly time step and for each layer (**Figure 9.2b**). Parameters H and C_{NH3} are calculated using Eqs. 11.8 and 11.15, respectively. In calculating C_{NH3}, pH of compost material is constant at 8.0 based on measurements by **Larney and Olson (2006).** Hourly aeration passing through each simulated layer is dependent on its position in the profile where the outermost sublayer of the outer half has the highest aeration and the inner half has the lowest aeration (see Oxygen and Aeration section). The NH_3 emission rate due to turning is computed in a similar way except that the volume of air-filled pores is used instead of hourly aeration (Eq. 9.24) and calculation is done on a per turning basis. Similar to other NH_3 sources (see **Environmental Information, Ammonia Emission** section), ambient air NH_3 concentration is assumed negligible. As in open lots, steady-state conditions are applied. Effects of NH_4^+-N sorption, however, are neglected due to lack of appropriate values for parameters such as the sorption linear partitioning coefficient for compost materials.

Methane emissions

During composting, CH_4 may form under anaerobic conditions due to fermentation of available C. In our model, C lost as CH_4 can only come from CO_2-C. This assumption is used to agree with trends reported by **Hao et al. (2001)** for both static and turned windrows. Two processes associated with CH_4 emission are simulated for each layer on a daily time-step: CH_4 fermentation, which converts CO_2-C to CH_4-C, and CH_4 oxidation, which oxidizes CH_4-C to CO_2-C (**Figure 9.3**). The CH_4-C fermentation rate is a function of the amount of CO_2-C, the maximum fraction of CO_2-C that can be converted to CH_4-C (K_{CH4}), and a temperature factor ($F_{t,ferm}$) (Eq. 9.25). The $F_{t,ferm}$ is calculated using relationships from Manure-DNDC, with the maximum production rate at 30°C (**Li et al., 2012**). The K_{CH4} is set to 0.075 (**Bonifacio et al., 2016b**). The CH_4-C oxidation rate is a function of available CH_4-C, and factors for moisture content ($F_{m,CH4}$), temperature ($F_{t,oxid}$), oxygen concentration ($F_{anaerob}$), and air velocity within the pile (F_{vel}) (Eq. 9.26). Values for $F_{m,CH4}$ and $F_{t,oxid}$ are computed using relationships from **Parton et al. (1996)**, revised to have the highest CH_4 oxidation at a dry-basis moisture content of 15% and within a 25 to 30°C temperature range (**Stein and Hettiaratchi, 2001**). As mentioned, $F_{anaerob}$ is computed following **Richard et al. (2006).** Using the measured CH_4-C emission data of **Hao et al. (2001),** an equation for F_{vel} was developed based on air velocities simulated by the model (i.e., calculated from V_{aer} and PO_{air}). Based on F_{vel}, 99% of CH_4-C is available for oxidation at air velocities equal to or less than 0.2 m/h (0.06 mm/s) while no CH_4-C is oxidized at air velocities equal to or greater than 0.5 m/h (0.14 mm/s).

Compost physical properties

Simulation of changes in physical properties of the compost material are calculated on a daily basis. The ρ_p is calculated as a function of percentages of raw and composted components, with individual particle densities of 1,370 kg/m^3 for raw material (**Das and Keener, 1997**) and 2,300 kg/m^3 for composted material (**Weindorf and Wittie, 2003**) (Eq. 9.27). Similarly, ρ_{dry} is adjusted to account for conversion of some raw materials to microbial biomass. The following assumptions are applied for microbial biomass: (1) a molecular formula of $C_6H_{11}O_2N$ (**Kling, 2010**) and (2) use of 2,300 kg/m^3 in approximating its contribution to total volume.

Aside from simulating raw material conversion to microbial biomass, calculation of both ρ_p and ρ_{dry} requires simulation of dry matter losses. Total dry matter loss is the sum of C, N, H, and O losses. Other losses (e.g., sulfide, phosphorus) are assumed to be negligible. Calculation for C and N losses is based on predicted gaseous emissions.

For H and O, estimation of corresponding losses is more complex. Instead of tracking all H and O present in the stack or windrow (i.e., H and O from rain and added and generated water; O from aeration), only that in the manure and dry material are needed to predict dry matter losses. The amounts of dry matter H and O lost during composting are approximated from C_{decomp}. The percentage losses of H and O for different organic C compounds (for both thermophilic and mesophilic stages) are presented in Table 9.2. The types of organic C compounds included in the simulation (i.e., manure characterization by **Liao et al., 2007**), and the sequence of C consumption (**Epstein, 1997**) are as follows: sugar, starch, protein, hemicellulose, cellulose, and lignin. The H and O percentage losses in Table 9.2 are based on decomposition reactions derived using the assumed molecular formula for microbial biomass ($C_6H_{11}O_2N$) and percentages of C_{decomp} respired during the thermophilic (85%) and mesophilic (76%) stages of composting. Also, among the organic C compounds simulated, only protein contains N (Table 9.2). Through refinement using data by **Larney and Olson (2006),** a 25% protein N loss setting, equivalent to 75% conversion of protein N to microbial N, is assumed in the simulation.

Table 9.1- Model equations

Equation	No.
$K_{hc} = \frac{e^{-1752(WB)^6+5884(WB)^5-8098(WB)^4+5864(WB)^3-2380(WB)^2+540(WB)-61}}{24\times3600\times100}$	9.10
$K_{g,w} = \left(0.00684e^{0.08794 WS_{air}}\right)S_c^{-0.67}$	9.11
$RH = \min\begin{bmatrix}100.0\ ,95.13 - 1.62T_{avg} - 0.51T_{max} + 2.07T_{min} + 0.33P_{rain} \\ -0.82WS - 0.49SR - 0.41D_{norain}\end{bmatrix}$	9.12
$E_{aer} = \left(MC_{aer,out} - MC_{aer,in}\right)V_{aer}$	9.13
$H_g = h_c C_{CO_2} A_{eqs}$	9.14
$H_{evap} = h_{fg} E_{tot}$	9.15
$H_{conv} = \frac{V_{aer}\rho_{aer}\left[\left(c_w\left\{w_{out}T_{out} - w_{in}T_{in}\right\}\right) + \left(c_a\left\{T_{out} - T_{in}\right\}\right)\right]}{1000}$	9.16
$H_{cond} = \frac{k_w\left(T_2 - T_3\right)A_{w,2}}{L_{cond}}$	9.17
$V_{aer} = A_w PO_{air} K_p\left(\frac{\rho_{aer}}{\mu_{aer}}\right)g\left(1 - \frac{T_{w,l-1}}{T_{w,l}}\right)\times3600\times24 \qquad \& \ l=2\ to\ 3, T_{w,1} = T_{air}$	9.18
$C_{decomp} = \left(C_{man} + C_{drymat}\right)K_{decomp}F_{m,decomp}F_{anaerob}$	9.19
$K_{decomp} = \left(K_{d,\max} - K_{d,slow}\right)e^{\left\|k_{decay}(t-\tau)\right\|} + K_{d,slow}$	9.20
$K_{d,slow}, K_{d,\max} = x_1\left(1.066^{(T_w-10)} - 1.21^{(T_w-50)}\right)$	9.21
$EF_{d,N} = F_{d,NO_3}F_{d,O_2}$	9.22
$J_{NH_3,aer} = \left(\frac{V_{aer}}{24}\right)\left(\frac{C_{NH_3,out} - C_{NH_3,in}}{H}\right)$	9.23
$J_{NH_3,turn} = V_{FAS}\left(\frac{C_{NH_3}}{H}\right)$	9.24
$J_{CH_4,ferm} = K_{CH_4}C_{CO_2}F_{t,ferm}$	9.25
$J_{CH_4,oxid} = C_{CH_4}F_{m,CH_4}F_{t,oxid}F_{anaerob}\left(1 - F_{vel}\right)$	9.26
$\rho_p = \frac{\left(1{,}370\times\left(M_{mo} + M_{mi} + M_{dm}\right)\right) + \left(2{,}300\times M_{cm}\right)}{\left(M_{mo} + M_{mi} + M_{dm} + M_{cm}\right)}$	9.27

Term	Definition
A_{eqs}	= area based on the equivalent soil profile (m^2)
A_{w2}	= area of contact between outer and inner windrows based on the windrow profile (m^2)
c_a	= specific heat capacity of dry air (1.006 kJ/kg dry air per °C)
c_w	= specific heat capacity of water (4.18 kJ/kg H_2O per °C)
C_{decomp}	= amount of organic C that can be composted within the day (kg C/d)
C_{drymat}	= available dry material organic C (kg C)
C_{man}	= available manure organic C (kg C)
C_{CO_2}	= amount of C respired (kg C/d)
C_{CH_4}	= amount of CH_4 available (kg C/d)
C_{NH_3}	= NH_3 concentration in aqueous phase for simulated layer (kg/m)
$C_{NH3,in}$, $C_{NH3,out}$	= NH_3 concentration in aqueous phase for adjacent inner and outer layers, respectively (kg/m)
$D_{no\ rain}$	= number of preceding consecutive days without rain (d)
E_{aer}	= potential evaporation rate due to aeration (kg H_2O/d)
E_{tot}	= total evaporation rate (kg H_2O/d)
$EF_{d,N}$	= total denitrification N loss per unit mass of windrow (µg N/g soil per d)
$F_{anaerob}$	= effect of presence of anaerobic conditions on microbial decomposition (dimensionless, 0.0 to 1.0)
F_{d,NO_3}	= total denitrification N loss as a function of nitrate concentration (µg N/g soil per d)
F_{d,O_2}	= effect of oxygen on denitrification (dimensionless, 0.0 to 1.0)
F_{m,CH_4}	= effect of moisture on CH_4 oxidation (dimensionless, 0.0 to 1.0)
$F_{m,decomp}$	= effect of moisture on microbial decomposition (dimensionless, 0.0 to 1.0)
$F_{t,ferm}$	= effect of temperature on CH_4 production (dimensionless, 0.0 to 1.0)
$F_{t,oxid}$	= effect of temperature on CH_4 oxidation (dimensionless, 0.0 to 1.0)
F_{vel}	= effect of velocity on CH_4 oxidation (dimensionless, 0.0 to 1.0)
g	= acceleration due to gravity (9.8 m/s^2)
h_c	= C oxidation specific heating value (20 MJ/kg C)
h_{fg}	= latent heat of evaporation (2.37 MJ/kg H_2O)
H	= Henry's law constant (dimensionless)
H_{conv}	= heat loss through convection (MJ)
H_{evap}	= heat loss through evaporation (MJ)
H_g	= heat generated through microbial activity (MJ)
$J_{CH_4,ferm}$	= daily production rate of CH_4 due to fermentation (kg C/d)
$J_{CH_4,oxid}$	= daily oxidation rate of CH_4 (kg C/d)
$J_{NH3,aer}$	= hourly NH_3 emission rate due to aeration (kg N/h)
$J_{NH_3,turn}$	= hourly NH_3 emission rate due to turning (kg N/d)
k_{decay}	= first-order decaying coefficient (per d)
k_w	= windrow thermal conductivity (MJ/h/m per °C)
K_{CH_4}	= maximum fraction of CO_2-C that can be converted to CH_4-C within a day (per d)
$K_{d,max}$	= maximum microbial decomposition rate (per d)
$K_{d,slow}$	= microbial decomposition rate for slowly decomposing components (per d)
K_{decomp}	= effective microbial decomposition rate (per d)
K_{gw}	= water mass transfer coefficient in gas phase (m/s)
K_{hc}	= cattle manure hydraulic conductivity (m/s)
K_v	= compost permeability (m^2)
L_{cond}	= average distance for conduction between outer and inner windrows (0.81 m)
M_{cm}	= amount of composted windrow material (kg)
M_{dm}	= amount of raw dry material (kg)
M_{mi}	= amount of raw manure inorganic matter (kg)
M_{mo}	= amount of raw manure organic matter (kg)
$MC_{aer,in}$, $MC_{aer,out}$	= moisture concentration of incoming and outgoing air flows, respectively (kg H_2O/m^3 dry air)
P_{rain}	= amount of daily precipitation (mm)
RH	= ambient air relative humidity (%)
S_c	= Schmidt number (dimensionless)
SR	= daily solar radiation (MJ/m^2)
t	= days from the start of composting or last turning (per d)
T_{air}, T_{avg}	= daily average ambient air temperature (K)
T_{in}, T_{out}	= initial and final temperatures for air flowing through the windrow layer, respectively (°C)
T_{max}	= daily maximum ambient air temperature (K)
T_{min}	= daily minimum ambient air temperature (K)
T_w	= temperature of the layer simulated (°C); set to 60 °C in computing the maximum microbial decomposition
T_2, T_1	= temperatures of outer and inner windrows, respectively (°C)
V_{aer}	= daily total aeration volumetric flowrate (m^3/d)
V_{FAS}	= volume of air-filled pores (m^3)
W_{in}, W_{out}	= initial and final humidity ratios for air flowing through the windrow, respectively (kg H_2O/kg dry air)
WB	= moisture content, wet-based for layer simulated (fraction, 0.0 to 1.0)
WS	= daily average air velocity at 10-m height (m/s)
WS_{ef}	= effective air velocity at 10-m height (m/s)
x_1	= effectiveness of the microbial decomposition rate (dimensionless)
ρ_{aer}	= density of air flowing through the windrow (kg/m^3)
ρ_{dm}	= density of dry material (kg/m^3)
ρ_{dry}	= windrow dry bulk density (kg/m^3)
ρ_m	= density of manure organic and inorganic contents (kg/m^3)
ρ_v	= effective particle density of windrow material (kg/m^3)
μ_{aer}	= air viscosity (kg/m/s)
τ	= lag time before reaching maximum decomposition (per d)

Table 9.2 - Simulation settings

Simulation settings for the different organic carbon (C) compounds in cattle manure and bedding material: molecular formula, initial percentages, and corresponding organic hydrogen (H) and oxygen (O) losses.

Component	Percentage in total organic C		Organic C compound	Molecular formula	Initial percentage in the component[b]		H, O losses during decomposition (%)	
	Manure	Bedding[a]			Manure	Bedding	Thermophilic ($\geq$ 40°C)	Mesophilic (< 40°C)
Non-lignin	86%	-	Sugar	$C_6H_{12}O_6$	2%	0%	87%, 95%	78%, 92%
			Starch	$C_6H_{10}O_5$	2%	0%	84%, 94%	74%, 90%
			Protein	$C_6H_{13}O_2N_{1.5}$[c]	28%	5%	5%, 0%[d]	5%, 0%[d]
			Hemicellulose	$C_5H_8O_4$	24%	37.5%	83%, 94%	73%, 90%
			Cellulose	$C_6H_{10}O_5$	44%	57.5%	84%, 94%	74%, 90%
Lignin	14%	-	Lignin	$C_{11}H_{14}O_4$	100%	100%	78%, 86%	65%, 78%

[a] Percentages of non-lignin and lignin components for bedding are based on the type of bedding selected.

[b] Values based on Liao et al. (2007).

[c] Molecular formula for protein based on amino acid Leucine ($C_6H_{13}O_2N$), with N adjusted to meet the assumed manure *C/N* of 15.

[d] The H and O percentage losses for protein based on assumption that 25% of its N is not consumed during microbial decomposition.

Figure 9.1 - Model flow for a compost windrow

Model flow in the simulation of a compost windrow.

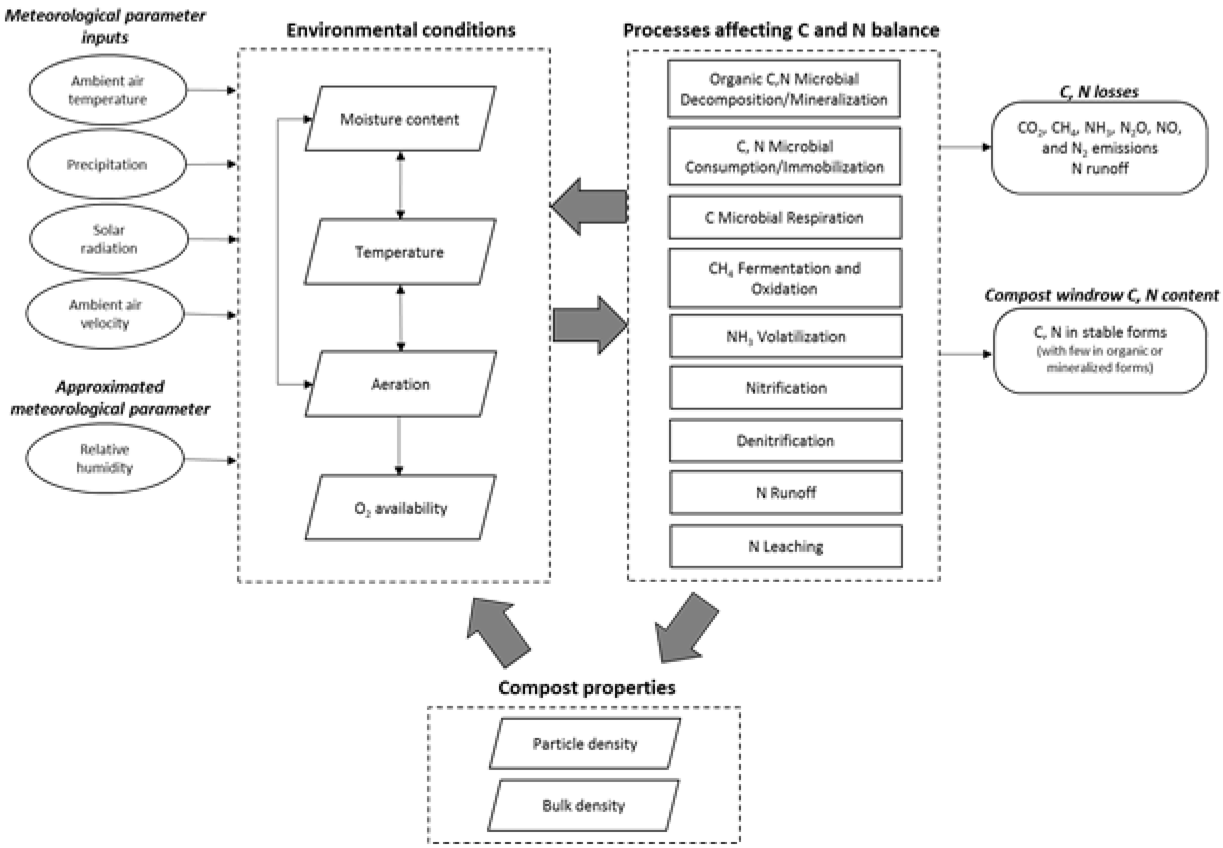


Figure 9.2 - Compost Simulation Profiles

Simulation profiles used to represent a compost stack or windrow: (a) windrow profile and (b) equivalent soil profile.

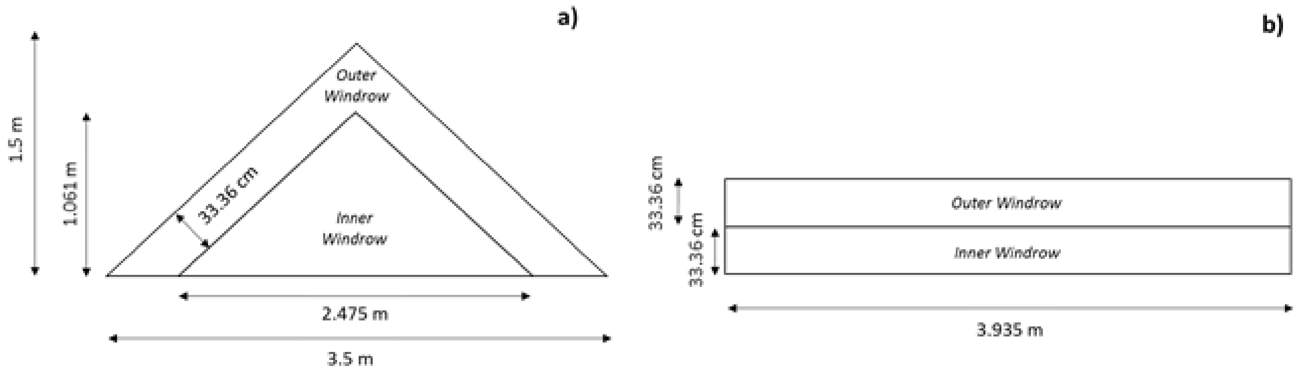
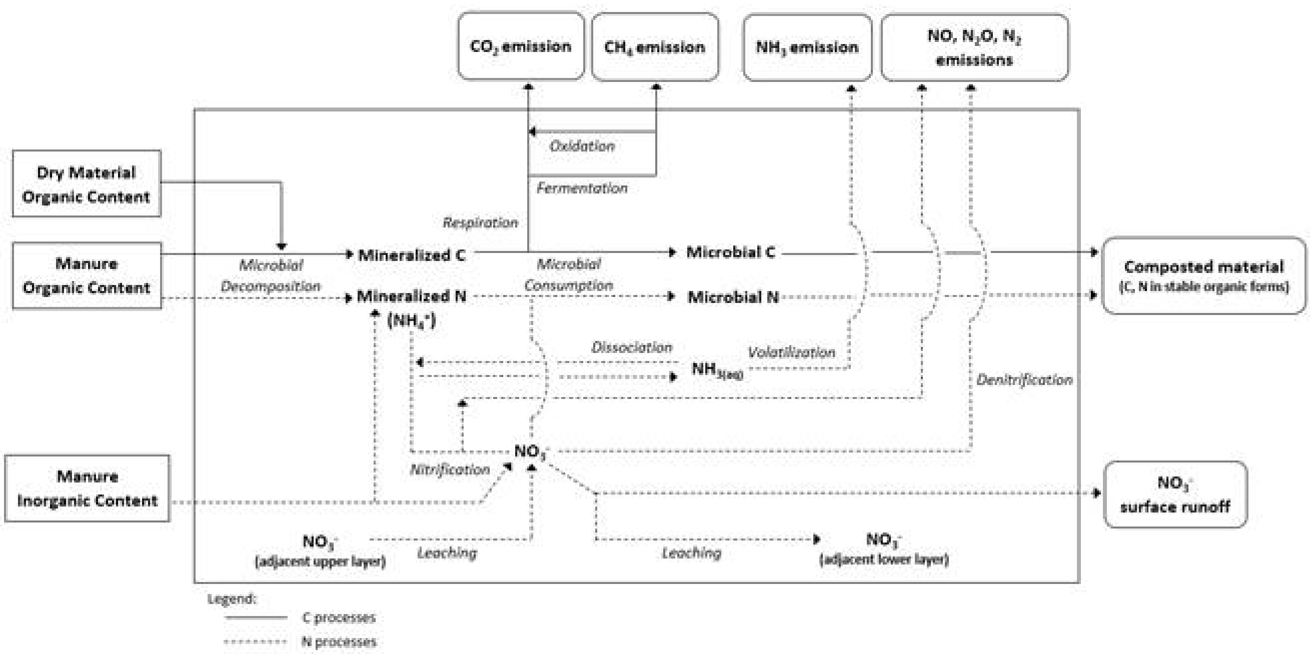


Figure 9.3 - Compost carbon (C) and nitrogen (N) flows

Flow of carbon (C) and nitrogen (N) through processes as simulated for compost windrows.



ENVIRONMENTAL INFORMATION

Simulated environmental impacts of the farm include volatile, leaching and denitrification losses of *N*, volatile loss of hydrogen sulfide (H_2S), surface runoff and leaching of *P*, and greenhouse gas emissions of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). Ammonia (NH_3), and hydrogen sulfide emissions come from manure sources including the barn floor, manure storage and field applied manure. Major sources of methane include enteric fermentation and long term manure storage with minor sources being the barn floor, field applied manure, and feces deposited by grazing animals. Carbon dioxide sources include plant respiration, animal respiration, and microbial respiration in the soil and stored manure. Nitrous oxide is a product of nitrification and denitrification processes in the soil and these processes can also occur in the crust on a slurry manure storage creating substantial loss. Each of these losses can lead to different environmental concerns. A comprehensive evaluation of production systems is obtained by considering the potential effects of all nutrient losses and emissions.

Phosphorous Loss

The *P* cycle is a complex process consisting of various chemical forms and transformations of *P*. These processes are modeled using relationships from the Erosion-Productivity Impact Calculator (*EPIC*) (**Williams, 1995**; **Jones et al., 1984**) and the Soil and Water Assessment Tool (*SWAT*) (**Arnold et al., 1998**; **Neitsch et al., 2002**) with modifications by **Vadas et al. (2004)** and **Vadas et al. (2005)** to better represent surface processes. The major components include surface and soil *P* pools and the transformation and flows that link these pools (**Sedorovich et al., 2007**).

Surface Phosphorus

When simulating livestock farming systems, surface application of manure is an important process. In previous models (**Williams 1995**; **Arnold et al., 1998**) munincorporated surface applications of manure and fertilizer are added directly to either the organic or inorganic soil *P* pools, depending on the source. This does not include loss directly from the *P* source on the surface and therefore underestimates the amount of *P* lost in runoff. Field data have shown that *P* loss directly from a surface application of manure can be significant when rain occurs soon after application. A surface *P* model proposed by **Vadas (2006)**, **Vadas et al., (2005),** and **Vadas (2007)**is used to simulate surface processes.

Four surface *P* pools are used to model surface applications and soil interactions (**Vadas, 2006<**). These pools represent water-extractable inorganic (MW_{ip}) and organic (MW_{op}) *P* and non-water-extractable inorganic (MT_{ip}) and organic (MT_{op}) *P* (**Figure 10.1**). Surface processes include surface application, runoff, and transformation along with soil-surface interactions through infiltration and tillage. Additions to the surface P pools occur through surface application of manure. The freely draining portion of applied manure with a high moisture content infiltrates into the soil immediately after application (process 1 in **Figure 10.1**). The remaining *P* is proportioned into the four soil pools based on the application method and characteristics of the applied manure.

After *P* is added to the surface pools, it can be released from both water-extractable pools (MW_{ip} and MW_{op}) during a rainfall event. The amount of inorganic *P* released from the surface pools by rainfall, P_{rel} [kg P], is a function of the water-to-manure ratio and the water-extractable inorganic P on the surface (**Vadas, 2006**).

$$P_{rel} = 1.2\left[W / W+73.1 \right] MW_{ip} \qquad [10.8]$$

where W = water-to-manure ratio, cm^3 water/g dry manure
MW_{ip} = water-extractable inorganic P on the surface, kg P

The concentration of inorganic P released from the surface pools by rainfall, P_{conc} is the mass of P released, P_{rel}, divided by the total volume of precipitation (i.e., the product of precipitation depth and land area).

If runoff occurs from a rain event, a portion of the inorganic P concentration enters the runoff water and is lost from the system (process 2 in **Figure 10.1**). The P lost, P_{runoff} [kg P/ha], is the product of the runoff depth, the concentration of inorganic P released from the surface pools, and a P distribution factor:

$$P_{runoff} = Q\,(P_{dist})\,(P_{conc})\,/\,100 \qquad [10.9]$$

where Q = runoff depth, mm
P_{conc} = concentration of inorganic P released from the surface pools, mg P/L
P_{dist} = P distribution factor, dimensionless factor ranging from 0 to 1

The P distribution factor is empirically modeled as a function of the runoff depth per unit of precipitation depth **(Vadas et al., (2007)).**

$$P_{dist} = 0.89\left[Q / PD \right]^{0.37} \qquad [10.10]$$

where PD = precipitation depth, mm

Runoff is calculated using the U.S. Soil Conservation Service (SCS) runoff curve number method. With this method, the amount of runoff is related to the amount of precipitation and the moisture content in the top 45 cm of the soil profile (see **Crop and Soil** section).

The remaining water-extractable P, or the total amount released if there is no runoff, infiltrates into the soil and enters the appropriate soil P pools (process 3 in **Figure 10.1**). The water-extractable inorganic P is added to the upper soil layer pool of labile P, and the water-extractable organic P is added to the upper layer organic P pool. Infiltration of P following surface application and prior to rainfall is set at 60, 50, 20 and 0% for liquid (< 7%, DM), slurry (7 to 12%, DM), semi-solid (12 to

20% DM) and solid manure (>20% DM), respectively **(Vadas, 2006).**

The final surface process is the decomposition of the non-water-extractable P, MT_{ip} and MT_{op}, into water-extractable P, MW_{ip} and MW_{op} (process 4 in **Figure 10.1**. The mass of P decomposed, P_{decom} [kg P/d], is determined using the following equation:

$$P_{decom} = Rate\,(P_{mass}) \qquad [10.11]$$

where $Rate$ = product of a dynamic rate factor, 1/d
P_{mass} = mass of P on the surface, [kg P]

The dynamic rate factor is the product of three dimensionless factors representing the effects of ambient temperature, manure moisture content, and the age of the manure on the surface (**Vadas et al. , 2007**). The decomposed organic and inorganic P is subtracted from their respective surface pools. This decomposed P is added to the water-extractable surface pools with 25% of the decomposed organic P added to the organic pool and 75% added to the inorganic pool (**Vadas et al. , 2007**).

For subsurface application of manure or fertilizer, the surface pools are essentially bypassed with inorganic and organic P components added directly to the appropriate soil pools. Subsurface injection of manure is modeled assuming 95% infiltration, which places the remaining 5% of the applied P in surface pools. Subsurface applied inorganic fertilizer is added to the labile pool of the second soil layer.

Inorganic Soil Phosphorus

The inorganic soil *P* component of the model is based on relationships from EPIC (**Williams, 1995**; **Jones et al., 1984**) and SWAT (**Arnold et al., 1998**; **Neitsch et al., 2002**) with modifications to simulate rapid adsorption and desorption as suggested by **Vadas et al., (2006)**. Three inorganic soil *P* pools are simulated: labile (P_{il}), active (P_{ia}), and stable (P_{is}) *P* (**Figure 10.2**). The P_{il} pool is the P in solution and weakly sorbed to soil particles. This labile P is readily desorbed and thus provides the amount available for crop uptake and runoff loss. The P_{ia} pool is the non-labile P in balance with the labile pool. The P_{is} pool is the P that is least susceptible to plant uptake and runoff loss and that which is in balance with the active pool.

Inorganic pool processes include the transfer of P between the labile and active pools, which represents rapid adsorption and desorption. Rapid adsorption maintains the dynamic equilibrium between the labile and active P pools, and rapid desorption represents the opposite process. Similarly, the movement of P between the active and stable pools represents slow adsorption and desorption. Phosphorus is also taken from the labile pool through crop uptake, runoff, and leaching loss.

The rate of P movement from the inorganic labile pool, P_{il}, to the inorganic active pool, P_{ia} is a function of a dynamic rate factor and the expected P distribution between the two soil reservoirs, P_{Bal}, which is a function of a P sorption factor (**Vadas et al., 2006**).

$$R_{ia} = K_{ia}\,(P_{bal}) \qquad [10.12]$$

$$K_{ia} = a\ (time) \qquad [10.13]$$

where $P_{Bal} = P_{il} - P_{ia} \left[P_{sp} / (1 - P_{sp}) \right]$ [10.14]

K_{ia} = dynamic rate factor, 1/d
P_{Bal} = P distribution between the two soil reservoirs, kg P/ha
time = time since an imbalance occurred between the pools, d
P_{il} = inorganic labile pool, kg P/ha
P_{ia} = inorganic active pool, kg P/ha
P_{sp} = sorption factor, dimensionless.

The dynamic rate factor is a function of the number of days since an imbalance occurred between the pools (**Vadas et al. 2006**). Slow adsorption and desorption are similarly defined, but they occur between the active P pool and the stable P pool. The rate of P movement [R_{as}, kg P/ha/d] from P_{ia} to the inorganic stable P pool, P_{is}, is a function of a rate constant based on soil characteristics, K_{as}, and P_{is} (**Vadas et al. 2007**):

$$R_{as} = K_{as}\,(4P_{ia} - P_{is}) \qquad [10.15]$$

where R_{as}= rate of movement from to the inorganic
K_{as} = rate constant, 1/d
P_{is} = inorganic stable P pool, kg P/ha

An important process simulated for the inorganic pools is the loss of P from the upper soil layer through runoff. Using the theory of an extraction coefficient, labile P is withdrawn from the soil reservoir and enters runoff. The mass of soluble P lost in runoff, P_{sol} [kg P/ha], is a function of the runoff depth Q [m], the extraction coefficient, soil depth, and soil bulk density.

$$P_{sol} = \left[P_{il}\,(Q)\,(C_{extr}) \;/\; D_{layer}\,(r_{BD}) \right] \qquad [10.16]$$

where C_{extr} = extraction coefficient, Mg/m^3
D_{layer} = depth of the soil layer, m
ρ_{BD} = bulk density of the soil, Mg/m^3

Models such as EPIC and SWAT use extraction coefficients that are specific to soil type, hydrological conditions, land uses, and other conditions. However, **Vadas et al. (2005)** found a strong relationship between soil P and runoff dissolved P for a variety of soil types and hydrology, which suggests that a single extraction coefficient can be used to simulate the loss of P in runoff under various conditions. Thus, a single extraction coefficient (C_{extr} = 0.005 Mg/m^3) is used in the soil P model.

A portion of the soil P is removed through crop uptake. Uptake is a function of the difference between the optimal P concentration for a given crop and the actual concentration in the simulated plant material (**Jones et al., 1984**). The P uptake of the crop on each simulated day is subtracted from the labile P pools within the soil profile. Uptake is weighted to draw primarily from the upper three soil layers where most of the soil P is located.

Leaching loss of soil *P* through the soil profile is normally relatively small and unimportant, but it can occur. A relatively simple relationship is used to predict this loss based upon the work of **Vadas (2001).** The total soil *P* leached from the root zone of the crop on any given day is the sum of that leached from the top soil (top three soil layers) and subsoil (bottom layer). Soil P leached from each of these layers, P_{lch} [kg/ha/d], is a function of the *P* concentration in the leachate, the amount of leachate occurring on that day, the depth of the soil layer, and the depth of the root zone in the soil profile:

$$P_{lch} = 0.01\ (C_{lp})(L_s)\left[D_{layer} / D_{soil}\right] \qquad [10.17]$$

where P_{lch} = soil *P* leached from layer, kg/ha
C_{lp} = concentration of *P* in leachate from soil layer, mg/kg
L_s = amount of leachate flowing from soil layer, mm
D_{soil} = depth of root zone in soil, m

Concentration of *P* in leachate is exponentially related to the inorganic labile *P* in the soil layer (P_{il}) (**Vadas, 2001**):

$$C_{lp} = e^{(P_{il} - EQ_i) / EQ_i} \qquad [10.18]$$

where EQ_i = intercept of logarithmic relationship between sorbed P and solution P
EQ_s = slope of logarithmic relationship between sorbed P and solution P

EQ_i and EQ_s are determined using empirical relationships with soil clay content (m_c) derived from the data of **Vadas (2001)**.

$$EQ_s = 1.49\ (m_c) + 6.18 \qquad [10.19]$$

$$EQ_i = 4.89\ (EQ_s) - 6.51 \qquad [10.20]$$

The amount of leachate is predicted on a daily time step based upon soil moisture content and other soil characteristics (see **Crop and soil** section).

Organic Soil Phosphorus

The organic soil *P* component is based on published equations from EPIC (**Jones et al., 1984**) and SWAT (**Neitsch et al., 2002**) with no further modifications. Two organic *P* pools are simulated: residue *P* (P_{or}) and stable *P* (P_{os}) (**Figure 10.3**). The P_{or} pool represents organic *P* in residue and microbial biomass. The P_{os} pool represents organic *P* in a more stable, less available form.

Organic soil transformations consist of mineralization and immobilization. Mineralization involves the net conversion of organic P (both P_{or} and P_{os}) to inorganic labile P (P_{il}). Immobilization is the reverse process, with P moving from P_{il} to P_{or}. The two organic P pools also interact, with a fraction of organic P in crop residue (P_{or}) becoming less available and moving to the stable P pool (P_{os}).

The net mineralization from both organic P pools, R_p [kg P/ha/d], is a function of the rate of mineralization of P from decaying organic matter, the rate of P mineralization from stable organic matter, and the rate of P immobilization by decomposing organic matter.

$$R_p = 0.8\ R_{pr} + R_{pos} - R_{upr} \qquad [10.21]$$

where R_{pr} = rate of mineralization from decaying organic matter, kg P/ha/d
R_{pos} = rate of mineralization from stable organic matter, kg P/ha/d
R_{upr} = rate of immobilization by decomposing organic matter, kg P/ha/d

As documented by **Jones et al., (1984)** R_{pr} is a function of a rate constant for decomposition of decaying organic matter, moisture and temperature constants, and the C/N and C/P ratios. R_{pos} is a function of a rate constant for decomposition of stable organic matter and the moisture and temperature constants, and R_{upr} is a function of the rate of organic matter decomposition and the microbial P concentration.

$$R_{pr} = K_{or}\ P_{or}\ (F_{ot}\ F_{om})^{1/2} \min(F_{cn}, F_{cp}) \qquad [10.22]$$

$$R_{pos} = K_{os}\ P_{os} \min(F_{om}, F_{ot}) \qquad [10.23]$$

$$R_{upr} = 0.16\ R_{or} \left[P_m / O_m \right] \qquad [10.24]$$

where K_{or} = rate constant for decomposition of decaying organic matter, 1/d
F_{om} = moisture factor, dimensionless
F_{ot} = temperature factor, dimensionless
F_{cn} = C/N ratio factor, dimensionless
F_{cp} = C/P ratio factor, dimensionless
K_{os} = rate constant for decomposition of stable organic matter, 1/d
R_{or} = rate of organic matter decomposition, kg OM/ha/d
P_m/O_m = microbial P concentration, kg P/kg OM

Sediment Phosphorus and Erosion

Sediment P loss is simulated using enrichment ratios to predict bioavailable and labile P losses as functions of erosion sediment loss (**Sharpley, 1985**). On any day when erosion occurs, enrichment ratios are determined for both bioavailable and labile P as exponential functions of the amount of sediment loss that occurs that day (**Sharpley, 1985**). Bioavailable P loss in sediment is the product of the sediment loss, the bioavailable P concentration in the upper soil layer, and the enrichment ratio. Bioavailable P is the sum of the active and stable inorganic and organic pools in the upper soil layer. Similarly, the labile P loss is the product of the sediment loss, the inorganic labile P concentration in the upper soil layer, and the labile P enrichment ratio. The sum of the bioavailable and labile P losses provides a total sediment P loss.

Erosion sediment loss is predicted using the Modified Universal Soil Loss Equation (MUSLE). Sediment loss through erosion on a given day is predicted by:

$$sed = 11.8\,(Q_{surf}\ q_{peak}\ A_{hru})^{0.56}\,(K)(L)(S)(C)(P) \qquad [10.25]$$

where Q_{surf} = daily runoff depth, mm

q_{peak} = peak runoff, m^3/s

A_{hru} = field area analyzed, m

K = soil erodibility factor

L = slope length factor

S = slope steepness factor

C = cover management factor

P = support practice factor

The soil erodibility factor is determined using relationships published by **Williams (1995)** where K is the product of four dimensionless empirical factors: $f_{c\text{-}sand}$, a factor that gives low values for soils with a high percentage of coarse sand; $f_{clay\text{-}silt}$, a factor that gives low values for soils with high clay to silt ratios; f_{orgC}, a factor that gives low values for soils with high organic carbon content; and $f_{hi\text{-}sand}$, a factor that gives low values for soils with very high sand content. These four factors are functions of the sand, silt, clay, and organic carbon contents of the surface soil as documented by **Williams (1995)** and **Neitsch et al., (2002)**:

$$f_{c\text{-}sand} = 0.2 + 0.3\exp\left[-0.256\, m_s\left(1 - \left(m_{silt}/100\right)\right)\right] \qquad [10.26]$$

$$f_{clay\text{-}silt} = \left[m_{silt}/(m_c + m_{silt})\right]^{0.3} \qquad [10.27]$$

$$f_{orgC} = 1 - \left[0.25\, orgC / \left(orgC + \exp(3.72 - 2.95\, orgC)\right)\right] \qquad [10.28]$$

$$f_{hi\text{-}sand} = 1 - \left[\left(0.7\left[1 - (m_s/100)\right]\right) / \left(\left[1 - (m_s/100)\right] + \exp\left[-5.51 + 22.9\left(1 - (m_s/100)\right)\right]\right)\right] \qquad [10.29]$$

where m_s = sand content, %

m_{silt} = silt content, %

m_c = clay content, %

orgC = organic carbon content, %

The method published in **Renard et al (1996)** is used to calculate *L*, *S*, and *C*. The current version of IFSM does not have a mechanism to simulate support practices and thus the support practice factor *P* is set to a default value of one.

Figure 10.1 - Surface P Pools

Surface P pools and processes

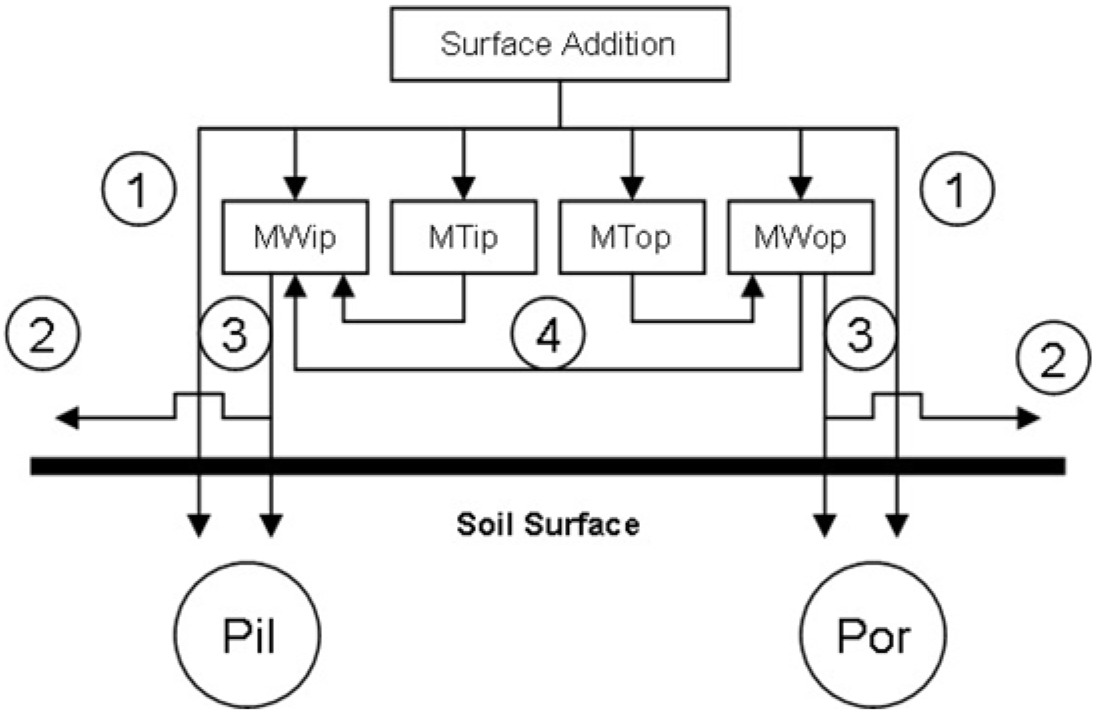


Figure 10.2 - Inorganic Soil P Pools

Inorganic soil *P* pools and processes.

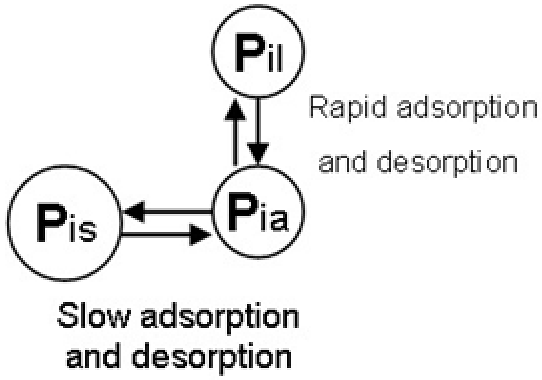
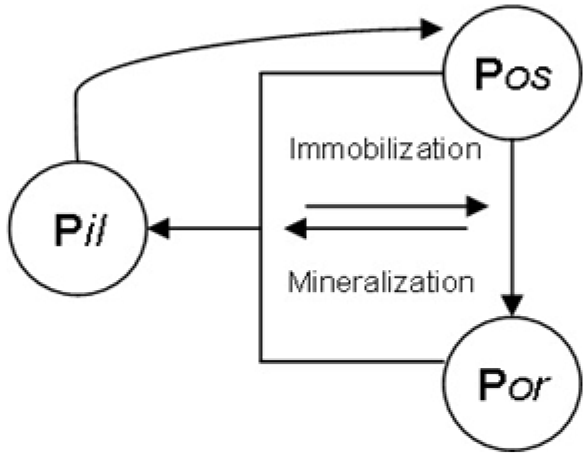


Figure 10.3 - Organic Soil P Pools

Organic soil *P* pools and processes.



Ammonia Emission

Total manure *N* consists of organic *N* and ammoniacal *N* (See the **Herd and Feeding** section) where ammoniacal *N* is readily transformed and volatilized as ammonia during manure handling. The primary source of ammoniacal *N* is urinary *N*, but a portion of the fecal *N* also can transform to an ammoniacal form during extended storage periods.

Nitrogen is lost through ammonia volatilization, leaching, and denitrification processes. Leaching and denitrification losses occur after the manure *N* is incorporated into the soil. Mineralization, nitrification, denitrification, and leaching processes are simulated on a daily time step dependent upon soil and climate conditions as described in the **Crop and Soil** section above. Only ammonia volatilization losses are discussed in this section.

Research over the past century has developed a good understanding of how volatile compounds in solution form, migrate, react, and ultimately volatilize to the atmosphere. Mathematical models have been developed and validated that accurately represent these processes. Through adaptation of these relationships, emissions such as ammonia from manure can be predicted for livestock farming systems. Predicted emissions from each important source are summed to determine the total farm emission.

Formation and Emission Processes

Total manure *N* consists of organic *N* and ammoniacal *N* (See the **Dairy and Beef Herd** sections) where only the ammoniacal form is readily volatilized during manure handling. Immediately upon excretion, about 95% of cattle manure *N* is in an organic form (**Muck, 1982**). Depending on how the cattle are fed, about 40-50% of this organic *N* is in the form of urea excreted in urine (**Rotz, 2004**). Excess protein *N* fed to cattle generally ends up in the urine, increasing the concentration of urea in the manure mixture of feces and urine. The primary source of ammoniacal N in manure is through the transformation of urea by the urease enzyme present in the feces. A portion of the organic fecal N can also transform to ammoniacal N during extended storage periods.

Immediately following excretion, ammonia emission from a manure surface involves five important processes: urea hydrolysis, dissociation, diffusion, aqueous-gas partitioning, and mass transport away from the manure surface to the atmosphere. Immediately following excretion, urea comes in contact with urease enzymes present in feces or on floor and soil surfaces. Enzymatic hydrolysis quickly decomposes the urea to aqueous un-ionized ammonia, NH_3 (aq), as shown in Reaction (11.1) (**Mobley and Hausinger, 1989**).

$$CO\,(NH_2)_2 + 2H_2O \rightarrow 2NH_3 + H_2CO_3 \qquad [11.1]$$

In solution, $NH_3\ (aq)$ exists in equilibrium with ammonium, NH_4^+, as shown in Reaction (11.2).

$$NH_4^+ \leftrightarrow NH_3\ (aq) + H^+ \qquad [11.2]$$

The sum of $NH_3\ (aq)$ and NH_4^+ is referred to as total ammoniacal *N* (*TAN*).

The rate of urea hydrolysis is dependent on temperature, pH, and the concentration of urea in the manure solution. **Muck (1982)** found that over 95% of the urea in dairy cattle manure decomposed within 6 h of excretion at 30°C and within 24 h at 10°C. Therefore, up to 50% of the total *N* excreted (all of the urea *N*) can be transformed to *TAN* in the housing facility when manure is removed once a day or less frequently. **Muck (1982)** found that Michaelis-Menten kinetics provided a good model to describe the degradation of urea by the urease present in feces. The maximum reaction velocity (V_{max}) and the Michaelis-Menten coefficient (K_{mc}) increased with temperature between 10 and 40°C, and the activity decreased linearly on both sides of a pH range of 6.8 to 7.6. Since the pH of fresh cattle manure normally falls within an optimum range for urease activity (**Sommer et al, 2006**), pH has little influence in this model.

The transformation of urea to *TAN* is modeled on an hourly time step as a function of temperature and urea concentration in manure (**Muck, 1982**):

$$RUC = V_{max}\, C_U / (K_{mc} + C_U) \qquad [11.3]$$

where

RUC= rate of urea transformation to *TAN* via Eq. (1), kg/m^3-h

C_U = urea concentration in urine, kg/m^3

V_{max}= maximum rate of urea conversion, kg *N*/m^3 wet feces-h

$$= 3.915 \times 10^9\, e^{-6463/T} \qquad [11.4]$$

K_{mc}= Michaelis-Menten coefficient, kg *N*/m^3 mixture

$$= 3.371 \times 10^8\, e^{(-5914/T)} \qquad [11.5]$$

T = temperature, K

The distribution of *TAN* between ammonia (NH_3) and ammonium (NH_4^+) in a solution such as manure, i.e. *TAN* dissociation, can be modeled using thermodynamic equilibrium principles (**Stumm and Morgan, 1996**). The ammonia fraction of *TAN* in a manure solution is a function of pH and a dissociation constant (K_a) that increases exponentially with temperature (Montes et al., 2009):

$$F = 1 / (1 + 10^{-pH} / K_a) \qquad [11.6]$$

where

$$K_a = 10^{(0.05\, -\, 2788/T)} \qquad [11.7]$$

pH = surface pH of manure or urine

Therefore, ammonia formation is very sensitive to pH and temperature. Below pH 8, a one unit increase in pH increases the ammonia fraction by about an order of magnitude, and this fraction approximately doubles with each 10°C increase in temperature. As the ammonia fraction in a solution increases, the potential emission rate increases.

Henry's Law relates the ammonia in a solution to that in a gas phase equilibrium with the solution. The Henry's Law constant, defined as the ratio of ammonia concentration in a solution in equilibrium with gaseous ammonia concentration in air, is exponentially related to temperature. A number of equations have been used to represent this relationship with a wide range in predicted values (**Montes et al., 2009; Ni, 1999**). A model developed by **Montes et al. (2009)** based upon thermodynamic principles is used:

$$H = (T/0.2138) \times 10^{(1825/T - 6.123)} \qquad [11.8]$$

where

H = Henry's Law constant for ammonia, dimensionless aqueous:gas.

Because ammonia concentration is so sensitive to pH, knowing the pH at the surface of the manure is critical for accurate prediction of emission rate. Surface pH is difficult to measure and model. When manure is exposed to air, dissolved carbon dioxide is released more rapidly than ammonia due to a lower solubility. The rapid loss of carbon dioxide leads to an increase in manure surface pH, while the pH of the bulk of the manure remains relatively constant (**Montes et al., 2009; Sommer et al., 2006; Blanes-Vidal et al., 2009**). Measurements and model predictions of manure pH suggest that surface pH may be on the order of 0.5 to more than 1.0 pH unit greater than the bulk pH (**Chaoui et al., 2009; Ni et al., 2009; Blanes-Vidal et al., 2009; Montes et al., 2009**). The magnitude of the pH increase is expected to depend on solution chemistry, manure depth, and environmental properties. On a barn floor with constant animal movement, there is continuous mixing of the manure so the surface pH likely varies across a manure covered floor surface.

Equations 11.7 and 11.8 represent ammonia formation in an infinitely dilute solution. For a substance such as manure, ions in the solution affect the equilibrium of NH_3 and NH_4^+ and thus the overall emission rate. In this mixed electrolyte solution, the interaction with other ions affects chemical activity. This effect can be estimated from the concentrations of these species in solution multiplied by their corresponding activity coefficients where the activity coefficients are a function of ionic strength (**Montes et al., 2009**). Ionic strength in cattle manure depends on manure composition and DM content, but is fixed at 0.35 in our model (**Chaoui et al. 2009**), which gives an activity coefficient of 0.74 for NH_4^+, based on the Davies equation (**Montes et al., 2009**). Since NH_3 has no charge, its activity coefficient will be close to 1.0. To account activity corrections, K_a from equation 11.7 is multiplied by 0.74.

The movement of ammonia away from the manure surface into the surrounding atmosphere is described in the model using a mass transfer coefficient (Eq. 11.14). The rate of transfer is a function of the air velocity over the surface, temperature of the manure and air, and the geometry of the surface in relation to air movement (**Montes et al., 2009**). A number of empirical relationships have been used to predict ammonia transfer from manure (**Ni, 1999**), but most are based on conditions different from that of a flat manure covered surface (**Montes et al., 2009**).

Principles are again well established for deriving the mass transfer coefficient based upon a two film model and the properties of the emitted compound and air as the transfer media (**Montes et al., 2009**). In our model, the mass transfer coefficient is a function of the air friction velocity and the Schmidt number (**Mackay and Yeun, 1983**):

$$K_g = 0.001 + 0.0462\ U\,(SC^{-0.67}) \qquad [11.9]$$

where

K_g = mass transfer coefficient through gaseous layer, m/s

U = air friction velocity near surface, m/s

$= 0.02\ V_a^{1.5}$ [11.10]

V_a= ambient air velocity measured at standard anemometer height of 10 m

SC= Schmidt number (**Perry et al., 1997**), dimensionless

From the review by **Ni (1999),** the mass transfer coefficient through the liquid film layer (K_l) is modeled as:

$$K_l = 1.417 \times 10^{-12}\ T^4 \quad [11.11]$$

This coefficient has relatively little effect on the mass transfer of ammonia.

A remaining process that must be considered is mass transfer of *TAN* within the bulk material below the liquid film. For manure in a thin layer, such as on a free stall barn floor, this process is assumed to not limit emission and is thus neglected. In a large volume of manure such as in a storage tank, aqueous phase mass transfer within the tank becomes important. As the ammonia is emitted, there is a drop in the concentration of *TAN* at the surface. This forms a gradient in concentration from the bulk material to the surface, and the *TAN* migrates from the high concentration at lower depths toward the lower concentration at the surface. The rate of this migration is dependent on the distance *TAN* migrates and the degree of mixing of the manure. With no mixing, *TAN* will move by diffusion only, leading to a low rate of migration. With mixing due to manure addition, wind, or temperature gradients, migration is more accurately described as convection, and can be much greater than that by diffusion (**Cussler, 1997**). This effect is modeled as a resistance to mass transfer which is the sum of the resistance movement through the manure and the resistance of any cover material over the manure:

$$R_m = R_s + R_c \quad [11.12]$$

where

R_m = resistance to mass transfer, s/m

R_s = resistance to mass transfer through the manure, s/m

R_c = resistance to mass transfer through a storage cover, s/m

The overall mass transfer coefficient is the reciprocal of the sum of the three resistances to mass transfer:

$$K = 1 / (H / K_g + 1/K_l + R_m) \quad [11.13]$$

The hourly rate of emission is then a function of the overall mass transfer rate and the difference in ammonia concentration between the manure and surrounding atmosphere (**Datta, 2002**):

$$J = 3600\ K (C_m - H (C_a)) \quad [11.14]$$

where

J = ammonia flux, kg/m^2-s

C_m = concentration of ammonia in manure, kg/m^3

C_a = concentration of ammonia in ambient air, kg/m^3

Ammonia concentration in the ambient air is assumed to be negligible, and is thus set to zero. The ammonia concentration in the manure is calculated from the bulk *TAN* concentration and *F* from Eq. 11.6.

$$C_m = F \times C_{TAN} \quad [11.15]$$

where

C_{TAN} = concentration of *TAN* in the manure solution, kg/m^3

By linking models for the emission processes, emission rates are predicted for each of the major ammonia sources on farms. The four sources are housing facilities, manure storage, field applied manure, and direct deposits on pasture. The principles and relationships described above are used to predict emissions from each with some differences as described below.

Animal Housing

Housing facilities include free stall barns, tie stall barns, open lots, and bedded pack barns. For predicting emissions from free stall and tie stall facilities, manure is represented as a thin layer with a uniform concentration of *TAN* below the liquid film, where diffusion is neglected. Urea hydrolysis is an important part of this emission source, where the excreted urea is converted to *TAN*. Emission is then predicted through an integrated model of the dissociation, aqueous-gas equilibrium, and mass transfer processes using equations 11.6 to 11.15. For open lot and bedded pack facilities, a more complex model is used that considers fresh and non fresh manure surfaces.

Free Stall and Tie Stall Barns

A major difference among housing facilities is the area soiled by the manure. As manure is spread over more area, the ammonia emission rate per animal increases. Exposed manure surface area is set considering typical designs for cattle housing. The soiled areas assigned to tie stall and free stall facilities are 1.2 and 3.5 m^2 per cow (or finishing beef animal), respectively. For growing animals, the areas are 1.0 and 2.5 m^2 per head. These areas are fixed for the duration of a simulation.

The mass of *N* on the floor of the housing facility is a function of the time animals spend in the facility, the amount excreted, the manure removal rate, and rates of urea hydrolysis and ammonia emission. These processes occur simultaneously in our model with a fixed time step of one hour. During the day, urea *N* accumulates in proportion to time and the excretion rate. When animals spend a portion of their time on pasture, the amount of manure deposited in the housing facility is proportional to their time in that facility. Urine and fecal production and *N* excretion are functions of animal size, feed intake, protein intake, and milk production (See the **Dairy Herd** section). The amount of urea *N* excreted is set at 70% of the total urine *N* plus 9% of the fecal *N* with 1% of the urine *N* excreted as ammoniacal *N* (**Bristow et al., 1992, Rotz, 2004**). All remaining *N* is in a more stable organic form that does not affect emissions from the housing facility. Removal rate is a function of housing type. Removal factors, or the fraction of the manure removed are 0.98, 0.98 and 0.9 for tie stall, flushed free stall, and scraped free stall facilities, respectively. The portion not removed remains on the exposed surface where emissions can continue. As the urea accumulates, the rate of urea N conversion to TAN is determined using equation 11.3, and the TAN emission rate is predicted using equations 11.6 to 11.15. Emission rates are determined separately for the lactating cow and growing animal facilities due to differences in manure excretion, composition, and management.

When manure is removed by flushing, three parameters are adjusted to account for differences compared to scraped manure. Following a scraping operation, a very thin layer of manure is spread over the surface. This causes increased carbon dioxide emission, which increases surface pH. Following flushing, a cleaner and wetter floor surface follows that removes this effect on surface pH. This is modeled by setting the surface pH equal to that of the bulk manure pH for the first hour following flushing. As noted above, the removal factor is also increased to 0.98 to represent a cleaner floor immediately following removal. The third factor is that the urinary N deposited following flushing is diluted by increasing the volume of solution on the floor by 20%.

Important parameters for predicting housing emissions are temperature, air velocity, and manure pH. For naturally ventilated facilities, temperature is set to that of the ambient air. For enclosed, mechanically ventilated barns, air temperature in the barn is modified as a function of the ambient air temperature:

$$T = \max(-5.0, 0.63\, T_a + 6.0) \quad [11.16]$$

where
T_a = ambient air temperature, ^oC

Hourly temperatures are estimated from daily maximum and minimum temperatures using a hyperbolic tangent fitting algorithm (**USAF, 1991**):

$$T_a = H_x(T_{max} - T_{min})/2 + (T_{max} + T_{min})/2 \quad [11.17]$$

where>

$$H_x = -\tanh((H + 3.5)/3.5) \quad \text{for } H \leq 4 \quad [11.18]$$

$$H_x = \tanh((H - 9.5)/2.5) \quad \text{for } 4 < H \leq 14$$

$$H_x = -\tanh((H - 21.5)/3.5) \quad \text{for } H > 14$$

H = hour of the day from 1 to 24

For naturally ventilated barns, air velocity is set at half the ambient wind speed. For mechanically ventilated barns, the air velocity in the barn (V_a) is determined as a function of ambient temperature with an increase in ventilation rate as temperature increases:

$$V_a = \max(0.3, 0.1\, T_a) \quad [11.19]$$

where
V_a = air velocity in barn, m/s

As described above, manure pH is influenced by the characteristics of the manure and environmental conditions. The pH of excreted cattle manure is about 7 for feces and 8 for urine. The mixture has a pH of about 7.5, which is assumed to be the bulk pH of the manure laying on the floor.

Since the ammonia concentration at the surface controls emission rate, the pH at the surface is most important. Based upon experimental data (**Chaoui et al., 2009; Ni et al., 2009; Blanes-Vidal et al., 2009**), the surface pH for manure in all housing facilities is set 0.7 units greater than the average bulk pH of the excreted manure to represent the effect of CO_2 formation and emission on pH.

Hourly emissions from each animal facility are totaled to obtain a daily emission. For barns where manure is removed on a daily basis, the mass of *TAN* removed is all urea and ammoniacal *N* in the excreted manure minus the *TAN* emitted during the day. This provides the mass placed into storage or that applied to fields through a daily application strategy.

Open Lot Facilities

For open lot facilities, the exposed manure surface area is based on typical animal densities for dairy and beef operations. Animal densities of 60.0 and 25.0 m^2 per head are assigned to represent the surface areas for dairy and beef open lot facilities, respectively. These areas are fixed for the duration of a simulation.

The mass of *N* on the open lot is a function of the amount of urine excreted, the time spent by animals on open lots, and manure pack conditions, such as moisture content and the amount of organic matter present (see **Nitrous Oxide** section). For open lots, effects of processes such as urine infiltration and ammonium adsorption on ammonia emissions are considered. These processes are modeled simultaneously on an hourly time step.

Manure harvesting is normally done after several months of operation on open lots. As an example, manure harvesting at beef feedyards is performed at the end of each feeding cycle, which can last for 180 days. Until the manure pack is harvested, organic forms of *N* in the urine excreted can undergo decomposition to other forms of *N* that can transform into ammoniacal *N* (**Bristow et al., 1992**). Depending on soil/manure temperature, open lots have the capacity to hydrolyze all urea *N* due to urease activities in both fresh and non-fresh manure areas. As stated previously, over 95% of urea decomposes within 6 h at 30°C and within 24 h at 10°C (**Muck,1982**). Assuming a manure N content of 7,000 mg N/kg feces for cattle manure (**Lorimor et al., 2000**), an expression was derived for estimating the fraction of urine *N* (urea *N*, ammoniacal *N* and other organic *N*) excreted on open lots that can hydrolyze within 24 h:

$$F_{ur} = min\ (1, 0.4232 \text{ x } e^{0.0901 T_{s,avg}}) \qquad [11.20]$$

where

F_{ur} = fraction of urine *N* that hydrolyzed, 0.0 to 1.0

$T_{s,avg}$ = daily average manure temperature, °C

Applying equation 11.20, all urine *N* hydrolyzes within 24 h at manure temperatures above 10°C. Below 10°C, the fraction of urine *N* that hydrolyzes within 24 h decreases exponentially with manure temperature. The daily average manure temperature is just the average of daily maximum and minimum manure temperatures approximated using relationships presented by **Parton (1984)**.

When excreted on the open lot, a portion of the urine infiltrates the manure pack while the remaining stays on or near the surface and becomes available for ammonia volatilization. The degree of urine infiltration depends on the moisture content of the manure pack. A dry manure pack has the capacity to hold more moisture and thus leads to higher infiltration; whereas, a wet manure pack won't be able to absorb additional moisture and thus will reduce infiltration. The fraction of urine infiltrating into the manure pack (*IR*) is computed as a function of the runoff curve number (*CN*):

$$IR = 1 - CN/100 \quad [11.21]$$

For open lots, *CN* is computed daily and estimated from the initial abstraction of the manure pack (**USDA, 2005**). As initial abstraction is the amount of moisture needed to exceed field capacity (**Dahlke et al., 2012**), the initial abstraction (I_a) for the manure pack on open lots is:

$$I_a = max(0, \ FC - MC)\ D \quad [11.22]$$

where

FC = field capacity of the manure pack, cm H_2O/cm soil

MC = water content of the manure pack, cm H_2O/cm soil

D = depth of the manure pack, 5 cm

CN is calculated from I_a using:

$$CN = 36.486\ I_a^{\ 2} - 89.571\ I_a + 96.895 \quad [11.23]$$

regression equation derived using I_a - *CN* values presented in Table 2-4 of the Engineering Field Handbook (**USDA, 2012**).

The moisture content of the manure pack is predicted using the soil water model used for cropland soils, which is based on ;relationships described by **Jones and Kiniry (1986)** (see **Soil** section). The open lot soil profile is modeled in four layers, with the first 3 upper layers of 3.0 (surface), 4.5 and 7.5 cm depths representing the manure pack and a fourth layer with a 100 cm depth representing the underlying soil layer. Modifications were made on some constants and expressions to adapt the soil water model to open lots. In calculating the total porosity for open lots, a particle density of 1.89 g/cm^3 (**Pepple et al., 2011**) and bulk density of 1.7 g/cm^3 (**Mielke et al., 1974**) are used. Permanent wilting point, a parameter associated with crop growth, is set to 0 cm H_2O/cm soil. Equations developed for calculating field capacity and saturation moisture content for open lots are:

$$SAT = PO + 0.4\ OM_{mp} \quad [11.24]$$

$$FC = 0.5\ (SAT) \quad [11.25]$$

SAT = water content at saturation, cm H_2O/cm soil

FC = water content at the drained upper limit, cm H_2O/cm soil

PO = porosity, fraction

OM_{mp} = fraction of the organic matter content of the manure pack

For open lots, stage 2 water evaporation (**Ritchie, 1972**) starts at a water-filled pore space of 30%, which is dry or near dry conditions for feedyard soils (**Razote et al., 2006**).

As manure lays on the open lot until manure harvesting, ammonia can be emitted from fresh and non-fresh manure areas. Hourly ammonia emissions rates from fresh manure are determined using equations 11.6 to 11.11 and 11.13 to 11.15, with the resistance to mass transfer (R_m in equation 11.13) equal to the inverse of the manure pack's hydraulic conductivity (equations 11.28 to 11.30). The same equations are used in estimating hourly ammonia emission rates from non-fresh manure areas. However, instead of using equation 11.6, ammonium adsorption is considered in calculating the ammonia fraction in *TAN* for non-fresh manure areas due to its higher degree of organic matter decomposition. As organic matter decomposes, the adsorption capacity of the manure pack increases (**Bernard et al., 2009; Waldrip et al., 2012**), which then gives more sites to adsorb cations that can include ammonium. The ammonia fraction in *TAN* (*F*) is computed by:

$$F = 1 / [1 + (10^{-ph_f} / K_a) + (K_f C_s 10^{-ph_n} / K_a)] \quad [11.26]$$

where

K_a = dissociation constant, computed using equation 11.7

pH_f; = surface pH of fresh manure, 8.0

pH_n = surface pH of non-fresh manure, 7.5

K_f = reference linear partitioning coefficient for ammonium adsorption

= 10.0 L/kg (**Waldrip et al., 2012**)

C_s = concentration of solids available for ammonium adsorption, kg solids/L

An equation for predicting C_s is derived using the manure pack characteristics reported in previous studies (**Mielke et al., 1974; Razote et al., 2006**):

$$C_s = [\,(OM + F_{clay}) / OM_{ref}\,]\,(\rho_{s,avg} / WFP) \quad [11.27]$$

where

OM = organic matter content of the manure pack, fraction, 0.38

F_{clay} = clay content of the manure pack, fraction, 0.06

OM_{ref} = organic matter content at which K_f was measured, 0.70

$\rho_{s,avg}$ = average density of the whole manure pack layer, 1.25 g/cm^3

WFP = water-filled pore space of the manure pack, fraction

Important parameters for predicting ammonia emission from open lots are air velocity, temperature of the manure pack, and mass transfer resistance through the manure pack. Hourly manure pack temperatures are estimated from daily maximum and minimum manure temperatures using relationships presented by **Parton (1984)**. Effects of solar radiation on the manure pack temperature is accounted for in the daily maximum manure temperature computation. Similar to hourly ambient air temperatures, hourly manure temperatures are calculated from daily maximum and minimum values using a hyperbolic tangent fitting algorithm (**USAF, 1991**) (equations 11.17 to 11.18).

The resistance to mass transfer in the soil is the inverse of its hydraulic conductivity (**SSDS, 1993**). For fresh manure, the mass transfer resistance is based on its saturated hydraulic conductivity assuming that fresh manure is at 100% saturation. For non-fresh manure areas, the mass transfer resistance is based on its unsaturated hydraulic conductivity to account for effects of lower moisture on the flow of ammonia solution through the manure pack. The saturated hydraulic conductivity is estimated from the clay and silt contents using the relationship (R^2 = 0.95) derived by **Delgado-Rodriguez et al. (2011)**:

$$K_{hc,sat} = 0.101176\ FINES^{-1.62} / (24 \times 3600) \qquad [11.28]$$

where

$K_{hc,sat}$ = saturated hydraulic conductivity, m/s

$FINES$ = average of clay and silt contents, fraction

FINES is calculated from clay and silt contents of the manure pack layer, 6 and 32%, respectively (**Razote et al., 2006**), and the underlying soil layer, which are available as input through the soil characteristics menu of IFSM. Assuming that the particle density remains constant throughout the manure pack, the calculated saturated hydraulic conductivity, $K_{hc,sat}$, is adjusted to account for the lower porosity at the surface using the Kozeny-Carman equation (**USDOE, 2009**):

$$K_{hc,adj} = K_{hc,sat}\ (f_{sur}^{3} / (1-f_{sur})^{2})\ ((1-f_{mp})^{2} / f_{mp}^{3}) \qquad [11.29]$$

where

$K_{hc,adj}$ = adjusted saturated hydraulic conductivity, m/s

f_{sur} = porosity of the surface, fraction

f_{mp} = porosity of the manure pack, fraction

Mass transfer resistance for fresh manure is the inverse of the adjusted saturated hydraulic conductivity, $K_{hc,adj}$. For computation of the mass transfer resistance for non-fresh manure, the unsaturated hydraulic conductivity is estimated from the adjusted saturated hydraulic conductivity based on manure pack moisture content and texture. The relationships used in calculating the unsaturated hydraulic conductivity are based on **Saxton and Rawls (2006)**. The equation for the unsaturated hydraulic conductivity is given by:

$$K_{hc,unsat} = K_{hc,adj}\ (WFP / 100)^{(3+2/\gamma)} \qquad [11.30]$$

where

$K_{hc,unsat}$ = unsaturated hydraulic conductivity, m/s

WFP = manure pack water-filled pores space, %

γ = slope of the logarithmic tension-moisture curve

The variable γ is a function of soil texture as computed using equations 1, 2, 15 and 18 of **Saxton and Rawls (2006)**.

Similar to the computations for other facilities, hourly emissions from open lots are summed to obtain the daily emission. At the end of each day, remaining *TAN* either infiltrates the manure pack or stays on or near the surface for potential volatilization the next day depending upon the infiltration characteristics of the surface for that day. Expressions for predicting ammonia emissions for open lot facilities used are discussed in more detail by **Bonifacio et al. (2015)**.

Bedded Pack Barns

For bedded pack barns, there are three general ways of managing the bedded manure pack (i.e., manure pack with bedding): 1) the bedded manure pack, or just bedded pack, is scraped and removed at regular short intervals from daily to every few weeks; 2) the bedded pack is allowed to accumulate; and 3) the bedded pack is allowed to accumulate and is aerated through regular stirring or tilling to enhance microbial decomposition. Barns that practice the last two bedded pack management styles are typically called deep-bedded pack barns and compost barns, respectively. In IFSM, bedded pack barns modeled are those that fall under the category of deep-bedded pack.

Animal spacing for bedded pack barns is set at 5.0 m^2 per cow and 3.0 m^2 per growing animal or finishing beef animal. With the presence of a bedded pack, which is similar to the manure pack in open lots, simulation of ammonia emissions for bedded pack barns follows the procedure implemented for open lot facilities (see **Ammonia Emission Open Lo**t section above; **Bonifacio et al., 2015**). The mass of *TAN* for bedded pack barns is calculated based on daily urine excretion, and decomposition of organic matter present in the bedded pack (see **Nitrous Oxide** section). Expressions used in simulating processes such as urea hydrolysis (equation 11.20) and ammonia volatilization from fresh (equations 11.6 to 11.11, 11.13 to 11.15) and non-fresh manure areas (equation 11.26) are those used for open lot facilities. Simulation of ammonia emissions is done on an hourly time step and the daily emission is obtained by summing hourly emissions within the day.

Unlike open lots, however, bedded pack barns are structures with sidewalls and a roof resulting in lower air velocity in the barn with negligible effects from solar radiation. As a result, bedded pack barns have wet manure pack conditions throughout the year, with moisture contents ranging from 60% to 75% (**Spiehs et al., 2011**; **NRCS South Dakota, 2011**). To provide drier conditions for cattle, bedding materials such as straw and manure solids are added to the surface of the manure pack to absorb some of the excess moisture. Effects of these manure pack conditions (i.e., wet) and management (i.e., bedding use) on ammonia emissions are modeled for bedded pack barns.

Presence of bedding materials on the pack can reduce ammonia emission by absorbing some urine and immobilizing some of the ammonium (**Misselbrook and Powell, 2005**; **Gilhespy et al., 2009**). In the model, the fraction of urine absorbed by the bedding material is computed as a function of total absorbance capacity of the bedding and the amount of urine excreted:

$$F_{abs} = \min(F_{abs,max}, ABS_{total} / URINE) \quad [11.31]$$

where

F_{abs} = fraction of urine absorbed
$F_{abs,max}$ = maximum fraction of urine that can be absorbed
ABS_{total} = total absorbance capacity of the bedding material on the surface, kg H_2O
$URINE$ = daily urine production calculated using equation 8.15, kg/day

The setting for $F_{abs,max}$ is 0.50, based on refinement using measurements by **Gilhespy et al. (2009)** and **Misselbrook et al. (2000)**, from which 30%, 73%, and 80% reductions in ammonia emissions were approximated for 3-lb, 10-lb , and 20-lb amounts of straw bedding, respectively. In a simulation performed, the model predicted that application of 3-lb, 10-lb, and 20-lb straw bedding would lead to ammonia emissions lower than those from no bedding by 37%, 76%, and 78%, respectively, with the maximum amount of urine absorbed limited to half of the total excretion.

The ABS_{total} is given by:

$$ABS_{total} = ABS_{unit} \, (BED_{animal}) \, (ANIMALS) \qquad [11.32]$$

where

ABS_{unit} = absorbance per unit mass of bedding, kg H_2O/kg bedding
BED_{animal} = mass of bedding per animal per day, kg bedding/animal-day
$ANIMALS$ = number of animals kept in the bedded pack barn.

Properties, which include ABS_{unit}, for several types of bedding materials (**Misselbrook and Powell, 2005**; **Bickert et al., 2000**) are summarized in **Table 11.1**. The BED_{animal} is a user-defined parameter.

Ammonium adsorption is considered in calculating the ammonia fraction in *TAN* for non-fresh manure areas (equation 11.26). The adsorption capacity of the bedded pack is based on its two components: decomposed/non-fresh manure and bedding. An ammonium adsorption linear partitioning coefficient (K_f) for manure is set to 10.0 L/kg (**Waldrip et al., 2012**) whereas for bedding, it is approximated from the cation exchange capacity of the material used (**Table 11.1**). For both manure and bedding, concentration of solids for ammonium adsorption (C_s in equation 11.26) is calculated from their corresponding dry matter masses and the total volume of bedded pack moisture.

The IFSM water routine for bedded pack barns has been evaluated and found to be applicable in predicting water movement for beef cattle bedded manure packs (**Ayadi et al., 2015a**). The moisture content of the bedded pack is predicted using the soil water component based on relationships by **Jones and Kiniry (1986)** (see **Soil** section). However, relationships by **Jones and Kiniry (1986)** for simulating water evaporation and calculating water diffusivity do not apply for bedded pack barns due to the absence of solar radiation and significantly wetter pack conditions. For bedded pack barns, the amount of water evaporated is a function of the difference in moisture concentrations between ambient air and the air layer right above the bedded pack surface **(Black et al., 2013)**:

$$EVAP = K_{g,w} \; (C_{sur} - C_{air}) \, (3{,}600) \, (24) \, (AREA) \qquad [11.33]$$

where

$EVAP$ = amount of water evaporated, kg H_2O/day

$K_{g,w}$ = overall surface mass transfer coefficient of water, m/s

C_{sur} = moisture concentration of the air layer right above the surface, kg H_2O/m^3 dry air

C_{air} = moisture concentration of ambient air, kg H_2O/m^3 dry air

$AREA$ = surface area of the bedded pack, m^2

The $K_{g,w}$ value is calculated using an empirical equation derived using data by **Mackay and Yeun (1983)** (equation 9.11). The C_{sur} and C_{air} values are estimated from corresponding relative humidities (i.e., 100% and ambient air relative humidity, respectively) and ambient air temperature **(Black et al., 2013)**. Ambient air relative humidity is calculated using equation 9.12 (see **Manure Composting** section). The surface area is just the product of animal spacing and total number of animals in the barn. In situations in which *EVAP* exceeds urine excretion (*URINE*), *EVAP* will be limited by the total amount of moisture in the first 3 cm of the bedded pack (i.e., similar to assumption used by **Jones and Kiniry (1986)**).

The water diffusivity used in simulating unsaturated flows (see **Soil** section) (**Jones and Kiniry, 1986**), and also in calculating the resistance to ammonia mass transfer in the manure (R_m in equations 11.12 and 11.13), is estimated using an empirical equation derived using hydraulic conductivity data by **Sutitarnnontr et al. (2014)** (equation 9.10). In simulating water movement, the bedded pack profile is modeled in four layers. Depths of 7 and 8 cm are assigned for the first and second layers, respectively. The remaining depth of the bedded pack (i.e., total depth minus 15 cm) is divided equally into third and fourth layers. Saturation moisture and field capacity contents of the bedded pack used in the simulation are calculated using equations 11.24 (i.e., without the OM_{mp} variable) and 11.25, respectively. Simulated total bedded pack depth and assumed particle density are discussed in the **Nitrous Oxide** section.

Manure Storage

When long term storage of manure is used on livestock farms, the storage facility is another important source of ammonia emission. Manure is stored in a liquid, slurry, or solid form depending upon the manure management strategy used. By the time manure is placed into storage, most of the urea has been converted to *TAN*. Any remaining hydrolysis has no effect on ammonia emission, so urea conversion to *TAN* is assumed to be complete once manure is removed from the barn. Bedding and manure solids can be separated from manure to form liquid manure (< 5% DM). This liquid portion, containing most of the *TAN*, is typically stored in an earthen basin or tank. Due to wind-induced mixing and the mixing created when manure is pumped into the storage, this liquid portion remains relatively well mixed. When manure is stored as slurry (7-12% DM), less mixing occurs within the storage structure, so diffusion is more important. If the slurry is pumped into the bottom of the storage tank or basin, a crust can form on the manure surface. This crust provides additional resistance, further reducing the rate of migration to the surface. Manure mixed with bedding material may also be stored as semi-solid or solid manure (>12% DM). In this form, diffusion through the manure becomes a major constraint to the emission rate. For each type of storage, equations 11.6 to

11.15 are used to describe diffusion, dissociation, aqueous to gas partitioning, and mass transport away from the manure surface to predict emission rate. As described below, the difference among storage types is in the diffusion properties of the manure and the constraint they place on the movement of *TAN* to the surface.

On a given day, the amount of *TAN* in storage is that accumulated up to that day minus that lost from the storage between the date loading began and the given date. The accumulated *TAN* is that removed from the barn plus the portion of the organic *N* that mineralizes to an ammoniacal form during long-term storage. Mineralization is calculated on a daily time step where the rate of mineralization is a function of the manure temperature:

$$TAN_o = N_o \min (0.007, 0.007 (1.2^{(Tm-20)})) \qquad [11.34]$$

where

TAN_o = rate of organic *N* transformation to *TAN*, kg/d

N_o = organic *N* in storage, kg

T_m = Temperature of stored manure, ^oC

Manure temperature in the storage is set as the average ambient temperature over the previous 10 days.

The daily emission rate is a function of the exposed surface area, *TAN* concentration, temperature, air velocity, and surface pH. Slurry and liquid manures are assumed to spread across the exposed surface of the storage where the surface area is determined by the storage dimensions set by the model user. Thus in the early stages of loading, manure is in a relatively thin layer with a large surface area per unit volume stored. As the storage fills, this surface area to volume ratio decreases. *TAN* concentration on a given day is the total *TAN* remaining in the storage divided by the liquid mass in the storage. This liquid mass on a given day is the total manure mass in the storage minus the manure *DM* loaded into the storage. Daily changes due to precipitation and evaporation are not specifically modeled, but the total mass includes the long-term moisture added from wash water and rain. Air friction velocity at the surface is determined using equation 11.10 where the ambient air velocity is the average daily wind velocity.

Manure pH is a function of the solids content of the manure. A relationship was developed to vary the bulk pH of stored cattle manure from 7 with no manure solids to 8.5 with a relatively high solids content:

$$PH = \min (8.5, 15.3 - 8.2 (1 - DMC)) \qquad [11.35]$$

where

DMC = dry matter content of the stored manure, fraction

PH = pH in the bulk of the manure

Surface pH also varies with solids content. With no solids in the manure, carbon dioxide will not be formed and emitted, so the surface pH will be the same as the bulk pH. With increasing solids, there is greater opportunity for microbial decomposition, formation and emission of carbon dioxide, and thus a greater increase in surface pH relative to bulk pH:

$$PHS = \min(8.5, PH + 8.0 - 8.0(1 - DMC)) \qquad [11.36]$$

where

PHS = manure surface pH.

This effect on surface pH is included for stacked manure and top-loaded slurry or liquid storages. For bottom loaded storages, this surface pH effect is not included since fresh manure is not exposed at the surface.

The resistance to ammonia loss is the sum of the resistances to transport through the bulk manure to the surface and from the surface to the free atmosphere (Equation 11.13). The effective resistance of the manure is a function of manure type with assigned values of 3×10^5, 2×10^5, 33×10^3 and 0 s/m for solid, semi solid, slurry, and liquid manure types, respectively. The additional resistance for covered and enclosed manure storages is 2×10^5 and 2×10^6 s/m, respectively.

Daily loss of ammonia *N* is determined such that the cumulative loss up to a given date cannot exceed the accumulated *TAN* loaded into the storage. This is particularly important in the early stages of loading when a thin layer of manure on the bottom of the storage creates maximum exposure for the loss of *TAN*. By summing daily emissions over the full year, an annual storage loss is determined. For storages with a six-month capacity, the storage is emptied in early April and again in early October. With a twelve-month capacity, the storage is emptied only in April. The mass of TAN available for field application is the mass remaining in the manure when the storage is emptied.

Field Application

Manure is applied to fields either through daily hauling or from long-term storage. With a daily strategy, smaller amounts of manure are applied each day. When storage is used, large amounts of manure are applied over a period of several days. The same model is used to simulate each of these approaches. With daily hauling, the manure produced each day is applied the same day. With six-month storage, half of the annual manure produced and stored on the farm is applied to cropland over ten-day periods in early-to mid-April and early-to mid-October. For twelve-month storage systems, all manure for the year is applied in a ten-day period in April.

Four manure application methods are modeled: broadcast spreading, irrigation, band spreading, and direct injection into the soil (**Rotz et al., 2010**). Some *TAN* is lost as the manure moves through the air in the actual application process. This loss is 1% and 10% of the applied *TAN* for broadcast spreading and irrigation with no loss in band spreading and injection. Thus the manure *TAN* reaching the field surface is that hauled from the barn or manure storage on a given day minus this loss.

When applied to a soil surface, the manure is applied in a thin layer where remaining *TAN* can readily volatilize as ammonia. Emission from the manure applied on a given day is determined by integrating equations 11.6 to 11.15 over the period until the manure is incorporated by a tillage operation. A maximum of 15 d is set for this period since all *TAN* is normally lost or infiltrated into the soil after this much time on a field surface. Because the emission rate is very rapid when manure is first applied, this integration is done on a 2-hour (0.08 d) time step. Loss during each time step is determined using the average ambient temperature of each day over this period. Manure pH is set to increase to 8.6 immediately following application due to the rapid release of CO_2 (**Sommer et al., 1991**). As the manure lays in the field, the pH decreases at a rate of 0.3 units per day until it reaches a neutral pH of 7.0 (**Sommer et al., 1991**).

The mass of water contained in the manure (M_w) on the field surface varies through time. The initial amount following application is set assuming a manure application rate of 0.3 kg DM/m^2. The contained water is calculated from the application rate and the manure *DM* content (*DM* application rate divided by the manure *DM* content minus the manure *DM*). The remaining manure moisture is adjusted during each time step by subtracting infiltration and evaporation and adding moisture from rain.

Evaporation is predicted as proportional to the incident solar radiation of the day. Daily evaporation (*EV*) varies from 0 to 60% of the available solution mass as solar radiation varies between 0 and a maximum level of 30 MJ/m^2. When rain occurs, the manure solution is increased assuming a uniform rate of rainfall over the daily period.

Infiltration is determined as a function of the manure *DM* content (**Hutchings et al., 1994**):

$$IR = e^{(6.95 - 31.9\, DMC)} \quad [11.37]$$

where IR = infiltration rate, kg/m^2-d or mm/d

DMC = manure *DM* content, fraction

Daily infiltration is limited to a maximum of 70% of the available manure water content. The remaining mass of water at each time step is M_w minus *EV*. During each time step, the mass of water is reduced by the infiltration and evaporation rates times the length of the time step (0.08 d) and increased by the rainfall rate times the time step length.

Manure *TAN* on the soil surface also varies through time. The initial *TAN* is that reaching the soil following the application process. During each time step, ammonia loss occurs to the atmosphere and *TAN* moves into the soil with the infiltration of moisture. The *TAN* moving into the soil is set in proportion to the manure solution that infiltrates into the soil, i.e. if *IR* is 10% of M_w, 10% of the available *TAN* is removed from the surface pool and is thus unavailable for volatilization. Ammonia emission is determined for each time step using equations 11.6 to 11.15. This loss is a function of the *TAN* and M_w on the field surface at a given point in time. At the completion of each time step, *TAN* and M_w are adjusted to provide initial values for the next time step.

Ammonia loss is determined by integrating these relationships over the period from application until incorporation into the soil or 15 days. This provides an exponential decline in the emission rate through time as influenced by changes in manure *TAN* content, infiltration rate, and DM content along with the effects of rainfall and ambient air temperature. When manure is incorporated the same day as applied, an average exposure time of 8 h is assumed. When manure is not incorporated, remaining TAN becomes negligible after a few days, and the emission rate approaches zero.

To predict loss from manure directly injected into the soil, a simpler approach is used. Because little manure remains on the surface, the process level simulation of surface emissions is bypassed. Ammonia *N* loss is set at 5% of the *TAN* in manure applied through deep injection into cropland and 8% of the *TAN* in manure applied through shallow injection to grassland. This provides relatively small losses, similar to those measured in field experiments.

Losses occurring from daily applications are summed to determine an annual loss. The total loss includes ammonia volatilized during the application process plus that volatilized from the field surface. Any remaining *TAN* not volatilized is available in the soil for plant uptake along with mineralized organic *N*.

Grazing Animals

When grazing is used, ammonia emission occurs from fecal and urine deposits in the pasture. The *N* in feces is primarily organic, so about 90% of the ammonia emission occurs from the *N* in urine (**Rotz, 2004**). A portion of the urine (about 30-50%) infiltrates into the soil where the urea hydrolyzes and the resulting *TAN* binds to the soil. The remaining portion settles on plant and soil surfaces where it comes in contact with urease. Urease enzyme activity quickly transforms the urea to *TAN* that can volatilize.

To model ammonia emission from pastures, a similar approach is used as that for field application of manure, but some simplifying assumptions are made. The *TAN* available for volatilization is the urea *N* and *TAN* excreted by grazing animals. Although hydrolysis must occur to transform the urea to *TAN*, this process is relatively fast compared to the time animals are on pasture. Thus hydrolysis is assumed to immediately transform all urea to *TAN*. The *N* excreted is determined by how they are fed (See the **Herd and Feeding** section), and the portion applied to pasture is set proportional to the time each animal group spends on pasture. The amount of *TAN* applied is 71% of the urine *N* plus 9% of the fecal *N* excreted on pasture.

The daily solution mass applied is the total urine from all animals on the pasture. Of this total, a portion is assumed to immediately infiltrate into the soil and the remainder infiltrates at a slower rate. The amount remaining on the soil surface immediately after excretion (M_w) varies from about 3 to 7 kg/m^2 (or mm/d) as a function of the moisture-absorbing ability of the soil (**Rotz and Oenema, 2006**):

$$M_w = 16.5 - 0.146\ CN \qquad [11.38]$$

where

CN is the runoff curve number for the user-specified soil.

Of this remaining solution, a portion infiltrates at a daily rate:

$$IR = 1 - 0.55\ M_w / (M_w + RN) \qquad [11.39]$$

where

IR = daily infiltration rate into soil, mm/d

RN = daily rainfall, mm/d

If rainfall occurs on a given day, the manure mass is diluted by the rain, i.e. M_w is increased by the daily rainfall amount. This dilution reduces the concentration of the remaining *TAN* in the solution and increases infiltration. The portion of the *TAN* deposited that infiltrates into the soil is determined by the amount of manure moisture that infiltrates and the concentration of *TAN* in that moisture.

Hourly emission rates are determined using equations 11.6 to 11.15 based upon temperature, air velocity, and manure solution pH. Hourly ambient temperature is set using equation 11.17, and ambient air velocity is the average daily wind speed. The pH is set at 8.5 to reflect an increase that normally occurs in urine patches over the first few days following deposition (**Haynes and Williams, 1992**).

Daily ammonia loss from grazing animals is determined for each day animals are on pasture. When animals are maintained on pastures throughout the winter, a daily loss is determined for each day of the year. Otherwise, losses are integrated over the grazing season set by the model user (typically mid April through October) considering the time each animal group spends on pasture. Calculated losses are summed over the time on pasture to obtain an annual loss. Remaining *N* is available for fertilization of the pasture.

Table 11.1 - Bedding Material Properties

Properties of different bedding materials for bedded pack barns.

Property	Unit	Manure solids	Sand	Sawdust	Straw	Chopped straw
Absorbance capacity[a]	kg H_2O/kg	4.22	0.27	2.63	2.85	2.85
Cation exchange capacity[a]	$cmol_c$/kg	16.0	0.3	3.8	9.7	9.7
C/N ratio[a]	-	12	*no nitrogen*[b]	500	105	105
N content[a]	kg N/kg	0.033	0	0.0011	0.004	0.004
Density[a]	g/cm^3	0.09	1.35	0.07	0.04	0.11[c]
Lignin content[d]	kg lignin/kg	0.14	0	0.40[e]	0.12	0.12

[a] Values from **Misselbrook and Powell (2005)**.

[b] For computation purposes, set to $1x10^6$ in the simulation.

[c] Density for chopped straw from **Bickert et al. (2000)**.

[d] Based on lignin contents used in simulating croplands and open lots.

[e] Setting maximized based on ranges reported by **Spiehs et al. (2014)** and **Changirath et al. (2011)**.

Hydrogen Sulfide

Hydrogen sulfide is a toxic compound that is regulated by the US EPA under the Clean Air Act. In response to the Comprehensive Environmental Response, Compensation and Liability Act (CERCLA; **EPA, 2010**), there is a reporting requirement for any point source that emits more than 100 lb (454 kg) of this compound on any given day. Therefore, it is important for dairy producers to know the amount of this compound emitted from their farms. Normally emissions of hydrogen sulfide from dairy farms are well below this limit.

On dairy farms, hydrogen sulfide is primarily created and emitted from decomposing manure under anaerobic conditions. Major sources include the barn floor and long-term manure storage with minor losses following field application. Hydrogen sulfide is a contributor to the nuisance of manure odor. It is also a toxic compound when the concentration builds up in a confined space such as an enclosed manure storage. Therefore, it can be a threat to human and animal health in poorly ventilated facilities. Hydrogen sulfide is also very corrosive, which can lead to deterioration, greater maintenance, and shortened life of farm facilities.

Formation and Emission Processes

Hydrogen sulfide is primarily created and emitted from decomposing manure under anaerobic conditions. Major sources include the barn floor and long-term manure storage with minor losses following field application.

Cattle feeds contain minor amounts of sulfur with most of this sulfur present in the amino acids cystine and methionine. Hard drinking water is another potential source. In the rumen, sulfur in amino acids and sulfate are reduced to sulfide by bacteria (**Van Soest, 1994**). Excess sulfur in the diet is processed by bacteria to hydrogen sulfide, which is transported through the digestive track, absorbed, and oxidized to sulfate in the liver. Sulfate is then excreted in urine or recycled through salivary excretion. Although much of the excreted sulfur is in the form of sulfate, microbial activity in the manure can transform the sulfur to a sulfide form.

Hydrogen sulfide forms a weak diprotic acid that dissociates into hydrogen (H^+), bisulfide (HS^-), and sulfide (S^{2-}) ions when dissolved in an aqueous solution. The following reactions govern the presence of the different forms (**Arogo et. al., 1999**):

$$H_2S_{(aq)} \leftrightarrow H_2S_{(g)} \quad [12.1]$$

$$H_2S_{(aq)} \leftrightarrow H^+ + HS^- \quad [12.2]$$

$$HS^- \leftrightarrow H^+ + S^{2-} \quad [12.3]$$

The fractions of H_2S, HS^-, and S^{2-} (α_0, α_1, α_2, respectively) present in an infinitely dilute solution can be calculated from the pH of the solution and the ionization constants using the following equations (**Snoeyink and Jenkins, 1980**):

$$\alpha_0 = [H^+]^2 / ([H^+]^2 + K_{a,1}[H^+] + K_{a,1} K_{a,2}) \quad [12.4]$$

$$\alpha_1 = K_{a,1} [H^+] / ([H^+]^2 + K_{a,1}[H^+] + K_{a,1} K_{a,2}) \quad [12.5]$$

$$\alpha_2 = K_{a,1}\, K_{a,2} / ([H^+]^2 + K_{a,1}[H^+] + K_{a,1}\, K_{a,2}) \qquad [12.6]$$

where

$K_{a,1}$ = first ionization constant, $10^{-7.1}$ at 25 °C

$K_{a,2}$ = second ionization constant, 10^{-14} at 25 °C

Figure 12.1 shows the change in concentrations of the different sulfide species in an aqueous solution with respect to pH at 25°C. Only $H_2S_{(aq)}$ can be released from the liquid phase. As the pH changes from basic to acidic, the concentration of molecular hydrogen sulfide in water increases, increasing the potential for $H_2S_{(g)}$ emission. The sulfide anion forms at pH levels above 12. This condition is significantly above the pH of cattle manure, and therefore is ignored in our model.

The ionization constants for H_2S and HS^- are a function of temperature. Based on Van't Hoff's equation (**Snoeyink and Jenkins, 1980**):

$$\ln (K_{T1} / K_{T2}) = \Delta H° (1/T_2 - 1/T_1) / R \qquad [12.7]$$

where

T = temperature, K

K_{T1} = equilibrium constant at temperature T_1, mol/L

K_{T2} = equilibrium constant at temperature T_2, mol/L

$\Delta H°$ = standard enthalpy change, 21673 J/mol

R = universal gas constant, 8.314 J/K-mol

The hydrogen sulfide dissociation constant ($K_{a,1}$) can be estimated at different solution temperatures (T_L)with:

$$\ln K_{a,1} = \ln (1.26 \text{ x } 10^{-7}) - (2606\ (1 / (273 + T_L) - 1 / 298)\ ) \qquad [12.8]$$

where

T_L = solution temperature, °C

To determine the hydrogen sulfide emission rate, the $H_2S_{(aq)}$ concentration in the aqueous solution or liquid manure must be known. This cannot be directly measured, but the total sulfide concentration (sum of the three sulfides) is easily measured. At a typical manure pH of 6 to 8, the fraction of S^{2-} is negligible ($\alpha_2 \approx 0$ and $K_{a,1}\, K_{a,2} \approx 0$), so a simplified version of equation 12.4 and $C_{T,S}$ can be used to estimate the concentration of $H_2S_{(aq)}$:

$$C_L = C_{TS}\, (10^{-PH}) / (10^{-PH} + K_{a,1} / 0.7) \qquad [12.9]$$

where

C_L = concentration of hydrogen sulfide in manure solution [$H_2S_{(aq)}$], kg/m^3

C_{TS} = total sulfide concentration in manure solution, kg/m^3

PH = pH of the manure solution, -log [H^+]

In Eq. [12.9], the thermodynamic ionization constant calculated from Eq. [12.8] is corrected for the activity coefficient of HS^-, which is taken as 0.7 (see **Ammonia Emissions** section). The activity coefficient of H_2S was assumed to be unity.

The mass transfer or emission process is often described using the two-layer film model of molecular exchange between water and air (**Figure 12.2**). As described below, this model is a major simplification of the processes thought to control H_2S emission. In our model, we assume that H_2S diffuses from the bulk liquid through the liquid film to the air-liquid interface, where it further diffuses through the air film to the surrounding turbulent air (**Blunden et. al., 2008**). Using this theory, the main body of each fluid is assumed to be well mixed and the main resistance to gas transport is from the gas and liquid interfacial layers, where the gas transfer is by molecular processes. The overall flux is represented as (**Datta, 2002; Cussler 1997**):

$$J = 3600\, K\, (C_L - H\,(C_a)) \qquad [12.10]$$

where

J = emission flux, kg/m^2-s

K = overall mass transfer coefficient, m/s

H = Henry's Law constant, g liquid/g gas

C_a = concentration of hydrogen sulfide in ambient air [$H_2S_{(g)}$], kg/m^3

Equation 12.10 gives the overall emission flux used to estimate hydrogen sulfide mass transfer across the gas-liquid interface, with K being a function of the transfer resistances of the aqueous and gas layers:

$$K = 1 / (H / k_a + 1 / k_L + R_m) \qquad [12.11]$$

where

k_L = mass transfer coefficient through the liquid layer, m/s

k_a = mass transfer coefficient through the gaseous layer, m/s

R_m = resistance to mass transfer created by a cover, s/m

The Henry's Law constant for H_2S is modeled using a function developed by **Blunden et al. (2008)**. For a dimensionless Henry's Law constant (aqueous:gas), this equation is:

$$H = 1 / (-4\text{x}10^{-7}\, T_L^3 + 4\text{x}10^{-5}\, T_L^2 + 0.0067\, T_L + 0.2147) \qquad [12.12]$$

The mass transfer coefficients (k_a and k_L) are related to the properties of the gas and liquid layers. For our model, these are the properties of the air and manure solution. Important properties include the density, viscosity, and diffusivity of both the gas and liquid components. The density of moist air is related to both temperature and relative humidity (**Arogo et al., 1999**):

$$\rho_a = (353 / T_a)\,(760 - 0.3783\, RH\, e^{(0.0596\, Ta - 14.6135)}) / 760 \qquad [12.13]$$

where

ρ_a= density of moist air, kg/m^3

T_a= air temperature, K

RH= relative humidity, fraction

The density of the manure solution is assumed to be that of water. **Holman (1981)** reported values for water density as a function of temperature from 0 to 315°C. These values were fitted to a linear trend line to obtain an equation for the density as a function of temperature:

$$\rho_w = 1033.3 - 0.934\, T_L \quad [12.14]$$

where

ρ_w= density of water, kg/m^3

The dynamic viscosity of air is estimated as a function of temperature using the following empirical expression (**Jacobson, 1999**):

$$\mu_a = 1.8325\text{x}10^{-5}\,(416.16 / (T_a + 120))\,(T_a / 296.6)^{1.5} \quad [12.15]$$

where

μ_a = dynamic viscosity of air, kg/m-s

T_a= air temperature, °K

The dynamic viscosity of water is predicted using a relationship from **Xiang et al. (1997)**:

$$\mu_w = 4.57\text{x}10^{-5}\,(\, TR /647.1)^{-(1.77\, THETA\text{^}-0.25 + 2.95\, THETA)} \quad [12.16]$$

where

μ_w = dynamic viscosity of water, kg/m-s

$$THETA = (1 - TR)^2 / TR \quad [12.17]$$

TR = temperature T_L expressed as a fraction of absolute temperature

Based on the **Wilke and Chang (1955)** correlation, the following equation was used to determine the diffusion coefficient for hydrogen sulfide in water.

$$D_w = 0.00074\,(273 + T_L)\,(\varphi\, MW)^{0.5} / (\mu_w\, V^{0.6}) \quad [12.18]$$

where

D_w = diffusion coefficient of H_2S in water, cm^2/s

φ = solute-solvent interaction factor, 2.6

MW = molecular weight of water, 18.01g/mol

V = molar volume of hydrogen sulfide at the boiling point, 32.9 cm^3/mol

As presented in (**Cussler, 1997**), the diffusion coefficient of hydrogen sulfide in air was determined from:

$$D_a = 10^{-7}\,(\,(273 + T_a)^{1.75}\,(1/\text{MW}_1 + 1/\text{MW}_2)^{1/2}\,) / (\,P\,(\text{V}_1)^{1/3} + (\text{V}_2)^{1/3}\,)\,) \quad [12.19]$$

where

D_a = diffusion coefficient of H_2S in air, m^2/s

MW_1 = molecular weight of H_2S, 34 g/mol

MW_2 = molecular weight of air, 29 g/mol

V_1 = diffusion volume of H_2S, 20.96 cm^3/mol at 1 atm

V_2 = diffusion volume of air, 20.1 cm^3/mol at 1 atm

P = atmospheric pressure, 1 atm

The mass transfer coefficients were obtained from existing mass transfer correlations that are recommended as generally applicable for compounds including hydrogen sulfide **(EPA, 1994)**. The gas and liquid mass transfer coefficients are functions of wind speed at a reference height of 10 meters, kinematic viscosity, and diffusivity. The air mass transfer coefficient equation was taken from **Mackay and Yeun (1983)**:

$$k_a = 0.001 + 0.0462\,(U_*)\,S_{ca}^{-0.67} \qquad [12.20]$$

where

k_a = air mass transfer coefficient, cm/s

U_* = friction velocity, m/s

$$= 0.02\,U^{1.5} \qquad [12.21]$$

U = wind speed at reference height of 10 m

S_{ca} = Schmidt Number in air, dimensionless

$$S_{ca} = \mu_a \,/\, (\,\rho_a \,/\, D_a\,) \qquad [12.22]$$

The liquid mass transfer coefficient equations were obtained from **Springer et al. (1984)** as applied by the **EPA (1994)** :

For $U < 3.25$

$$k_L = 2.78 \times 10^{-6}\,(\,D_w \,/\, D_{ether}\,)^{2/3} \qquad [12.23]$$

For $U > 3.25$

$$k_L = (2.6 \times 10^{-9}\,\mathrm{FD} + 1.277 \times 10^{-7})\,\mathrm{U}^2\,(\,D_w \,/\, D_{ether}\,)^{2/3} \qquad [12.24]$$

where

k_L = liquid mass transfer coefficient, m/s

D_{ether} = diffusion coefficient for ethyl ether in water, cm^2/s

FD = linear distance across surface over depth

S_{cw} = Schmidt Number in the liquid, dimensionless

$$= \mu_w \,/\, (\,\rho_w \,/\, D_w\,) \qquad [12.25]$$

The diffusion coefficient for ethel ether (D_{ether}) is determined using equation 12.18 with a molar volume for ether of 107 cm^3.

This model has some potential shortcomings in representing the full emission process for hydrogen sulfide. First, our model only includes diffusion of hydrogen sulfide in the liquid film. Diffusion of HS^- is expected to also transport sulfide through the liquid film, but is not included. The assumption of a well-mixed bulk solution below a liquid film may not be an accurate description of manure in storage, where a gradient in redox potential may cause a gradient in total sulfide. Moreover, liquid phase diffusion may not be the only mechanism responsible for transferring sulfide to the manure surface, since biogas bubbles emitted from manure may be a significant mechanism of hydrogen sulfide transport (**Ni et al., 2009**). Despite these shortcomings, our model is able to match measured emission rates of hydrogen sulfide from farms, suggesting that the model is a reasonable approximation, or contains compensating errors. Simulation results suggest that hydrogen sulfide emission is limited by sulfide production. Therefore, accurate predictions of hydrogen sulfide emission will ultimately require a better understanding of sulfide production in manure.

Enteric Emissions

A potential source of emission on dairy farms is direct emission from the cattle through belching or flatulence. Microorganisms in the digestive tract produce gases during the digestion of feed, particularly during fermentation in the rumen (**Dewhurst et al., 2001**). Therefore, enteric and other direct emissions of hydrogen sulfide from the animals must be considered.

Hydrogen sulfide, methyl sulfide, and dimethyl sulfide are the predominant sulfur containing gases present in the rumen headspace of dairy cows (**Dewhurst et. al., 2001**). As stated by **Dewhurst et al. (2001)**, neither **Elliot-Martin et al. (1997)** or **Mottram et al. (1999)** found hydrogen sulfide above 2 mg/kg in expired breath, confirming that most of the hydrogen sulfide is absorbed via the lungs and detoxified (**Bird, 1972**). Studies by **Dewhurst et al. (2001)** confirmed significant production of dimethyl sulfide in the rumen. Although the dimethyl sulfide levels were 10-fold lower than hydrogen sulfide in rumen gas, only dimethyl sulfide was detected in the cows' breath (**Mottram et al., 1999**). Therefore, enteric hydrogen sulfide emission was assumed to be insignificant and is ignored as an emission source.

Animal Housing

Manure on the floor of housing facilities is another potential source of hydrogen sulfide emission. This hydrogen sulfide may form from sulfide in the manure excreted by the animal or it may be formed through microbial decomposition of sulfate in the manure. Floor emission is predicted on an hourly time step using the two-layer thin film model described above. The hourly emission is a function of temperature, air velocity, sulfide content in the manure, and manure pH. Hourly air temperature is predicted as a function of the daily maximum and minimum temperatures using equations 11.17 and 11.18. When the cattle are in an enclosed barn, the indoor temperature is a function of outdoor temperature (Eq. 11.16). Manure temperature is set to the average daily temperature. Air velocity in outdoor facilities is set equal to the mean daily wind velocity measured at a 10 m height as obtained from the weather input file. When animals are in an open barn, this velocity is reduced by 50%. For an enclosed barn with mechanical ventilation, the velocity is set as a function of the outdoor temperature (Eq. 11.19) to reflect an increase in ventilation rate with temperature.

Little information is available on the sulfide content of freshly excreted dairy manure on a barn floor or open lot surface. Data reported by **Zhao et al. (2007)** and **Finke and Jorgensen (2008)** indicate that sulfate reduction to sulfide increases exponentially from 0^oC to around 35^oC and then declines. Based upon the work of **Zwietering et al. (1991)**, the following relationship was developed to predict the sulfide concentration that results from microbial activity in excreted manure laying on the barn floor:

$$C_{TS} = C_S \ (0.0033\ (T_L + 5)\ )^2\ (1 - e^{(0.75\ (TL\ -\ 45)\ )}\ ) \qquad [12.26]$$

where

C_S = total sulfur concentration in excreted manure, kg/m^3

C_{TS} = total sulfide concentration in manure solution, kg/m^3

This sulfur concentration is a function of the diet fed with a value of 0.625 kg m^{-3} when the sulfur requirement for the herd is met (**ASABE, 2010**). This value is increased or decreased in proportion to the amount of sulfur fed above or below the requirement. As temperature increases, increased microbial activity leads to greater decomposition of sulfate in the manure to sulfide.

When a flushing system is used for manure removal, manure solids are typically removed from the manure liquid, and the liquid portion is recycled as the flushing solution. With this process, high levels of sulfide accumulate in the liquid giving a relatively high concentration with less influence by temperature:

$$C_{TS} = C_S \ (0.125 + 0.0074\ (T_L)\ ) \qquad [12.27]$$

This relationship was also developed based upon data collected in the National Air Emissions Monitoring Study (**EPA, 2011**)

As illustrated in **Figure 12.1**, manure pH has a strong influence on the amount of hydrogen sulfide formed. The pH controlling volatilization is that at the manure surface or the interface between the liquid and gas phases. This surface pH is influenced by the rates of volatilization of carbon dioxide and ammonia (see **Ammonia Emission** section). For a freshly disturbed manure surface, the volatilization of carbon dioxide is greater than that of ammonia causing an increase in pH. For manure on a barn floor, this surface pH is set at an average value of 0.7 units greater than the bulk manure pH, which is set at 7.5.

Hourly emissions are summed to obtain a total emission for each day. This emission is proportional to the amount of time the animals spend in the housing facility assuming that the amount of manure excreted is proportional to the time spent in the barn or open lot. Daily emissions are summed to obtain the annual emission from the housing facility.

Manure Storage

When long term manure storage is used on the farm, this storage is typically the largest source of hydrogen sulfide emission. Stored manure emissions are modeled on an hourly time step as a function of manure and air temperatures, air velocity, sulfide concentration, manure pH, and the amount of manure in the storage. Manure temperature is predicted as the average ambient temperature over the previous 10 days. Hourly air temperature is predicted as a function of the daily maximum and minimum temperatures using equations 11.17 and 11.18. Air velocity is the reported mean daily wind velocity obtained from the weather input for the model.

The pH controlling the sulfide emission process is that at the manure surface, which can be greater than that within the storage. Bulk pH is determined as a function of the solids content of the manure using equation 11.35. For top loaded slurry storages or manure stacks, the surface pH can be greater than that of the bulk pH (See **Ammonia Storage Emissions** section). This increase is predicted as a function of the manure solids content using equation 11.36.

The amount of manure in the storage on a given day is the sum of that removed from the housing facility since the manure storage was last emptied. The sulfide accumulated in the manure is the balance between that added through sulfate decomposition and that emitted. That added on a given day is proportional to the sulfur content of the manure in the storage as influenced by temperature:

$$TS = C_S \,(M_m)\,(\max(0., 0.00032 + 0.000073\, T_L)\,) - E_{H2S} \qquad [12.28]$$

where

C_S = total sulfur concentration in manure, 0.625 kg/m^3

TS = total sulfide contained in manure on a given day, kg

M_m = mass of manure in storage, m^3

E_{H2S} = hydrogen sulfide emitted, kg

Sulfur concentration is that remaining in the manure removed from the barn. The temperature effect on sulfide production is modeled based upon data from various sources (ex. **Finke and Jorgensen, 2008; Zhoa et al., 2007**) indicating an increase in hydrogen sulfide production with increasing temperature within the normal range of temperature for stored manure. This reflects greater microbial activity and reduction of sulfate with increasing temperature.

When a natural crust forms on the manure surface or a cover is used over the stored manure, a resistance is added to the transfer of sulfide to the surface (Equation 12.11). Resistances for the natural crust, unsealed cover and fully enclosed storage were 4.6 x 10^5, 9.2 x 10^6, and 9.2 x 10^7 s/m.

When the storage is emptied, the model is reset and the storage begins to fill. As the storage fills, the potential emission of hydrogen sulfide increases in proportion the amount of manure in the storage and the sulfide contained in that manure. As described, the amount emitted in a given hour is a function of the manure and environmental conditions of that hour. Predicted hourly emissions are summed to obtain the daily emission, and daily emissions are summed to get an annual emission.

Field Application

When manure is spread on a field surface, the thin layer applied is exposed to aerobic conditions. Under these conditions, sulfide is not expected to form. Therefore, that emitted is that contained in the applied manure. The amount of sulfide applied is that remaining in the manure removed from the storage. Considering that the transformation of sulfide to hydrogen sulfide is very fast, we assume all sulfide will transform and be emitted. This hydrogen sulfide is assumed to quickly emit on the day that it is applied. Daily emissions are then summed to obtain an annual emission.

If manure is applied using a daily haul strategy, the assumption is made that no sulfide exists in the manure. Without long term storage of the manure under anaerobic conditions, no further sulfide forms. Therefore, any hydrogen sulfide from excreted manure would be emitted as it lies on the barn floor, and that emitted following application is negligible.

Grazing Animals

Little data exists on hydrogen sulfide emissions from the excretion of grazing animals. This is a minor source, but some emission is expected from fecal deposits on the pasture.

The emission from grazing animals is modeled similar to that from animal housing floors except that only feces deposits are considered as an emission source. Hydrogen sulfide is not expected to form under the more aerobic conditions of urine deposits, but sulfide excreted in feces can be emitted. As the feces decompose, further emission may occur. The feces is assumed to decompose within 60 days with no further sulfide formation after this period.

Emissions are predicted on an hourly time step as a function of temperature, air velocity, pH, and the sulfide concentration in the feces. Hourly temperature of the feces and air are assumed to be equal. This temperature is predicted as a function of daily maximum and minimum temperatures using equations 11.17 and 11.18. Air velocity is set as the mean daily wind velocity at a 10 m height as obtained from input weather data. The pH of the feces is set at a constant value of 7.0, and the sulfide concentration is set at a constant value of 1 g/m^3. Hourly emissions are summed to obtain the total daily emission and daily emissions are summed over the time animals are on the pasture to obtain total annual emissions. This emission source is typically very small relative to other farm sources of hydrogen sulfide, so the simplifying assumptions in this component of the model are justified.

Figure 12.1 - Hydrogen Sulfide Species

Fractions of sulfide species present in aqueous solution as a function of pH at 25°C (**Blunden and Aneja, 2008; Snoeyink and Jenkins, 1980**).

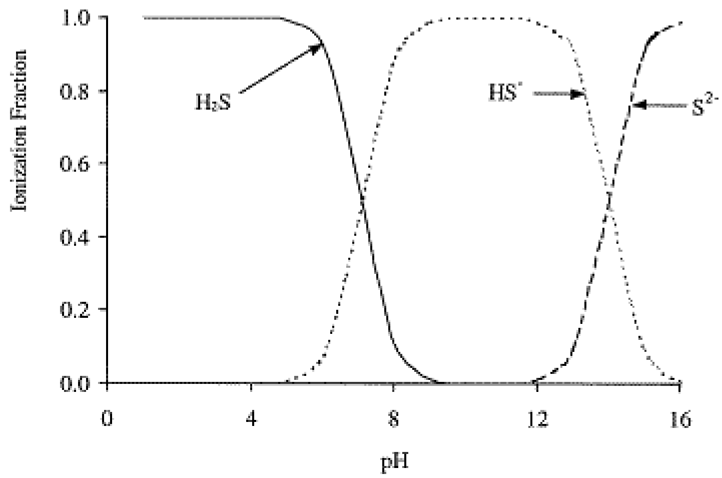
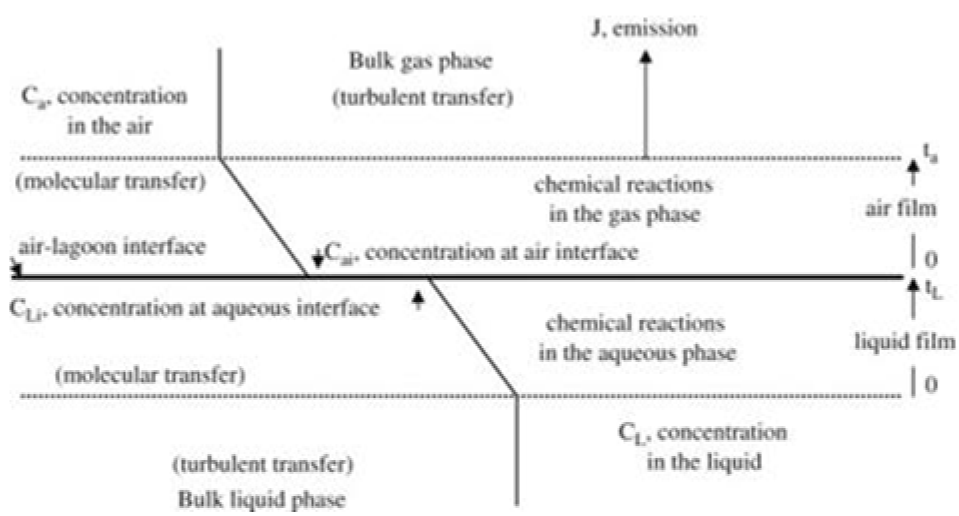


Figure 12.2 - Gas-Liquid Interface

Two-layer model of a gas-liquid interface (**Blunden et al., 2008**).



Greenhouse Gas Emissions

Important greenhouse gases (GHG) emitted from dairy and beef farms are carbon dioxide (CO2), methane (CH_4) and nitrous oxide (N_2O), with various sources and sinks of each throughout the farm. A major CO_2 sink occurs through the fixation of carbon in crop growth with emission sources including plant respiration, animal respiration, and microbial respiration in the soil and manure. Major sources of methane include enteric fermentation and the long term storage of manure with minor sources being the barn floor, field applied manure, and feces deposited by grazing animals. Nitrous oxide is a product of nitrification and denitrification processes in the soil and these processes can also occur in the crust on a slurry manure storage or during the storage of solid manure in a bedded pack or stack.

A comprehensive evaluation of production systems is obtained by considering the integrated effect of all sources and sinks of the three gases. Various processes affecting emissions interact with each other as well as with the climate, soil, and other components. Therefore, all individual processes and their interactions must be integrated in a comprehensive whole-farm analysis to determine the net result.

With the growing concern over GHG emissions, a need has developed for expressing the total emission associated with a product or service. A term that has come to represent this quantification is the C footprint or the net GHG exchange per unit of product or service. This net emission is best determined through a partial life cycle assessment that includes all important emission sources and sinks within the production system as well as those associated with the production of resources used in the system.

Carbon Dioxide

Multiple processes emit CO_2 from dairy farms. The major source is animal respiration, followed by less significant emissions from manure storages, and barn floors. Cropland assimilates CO_2 from the atmosphere through fixation during growth and emits CO_2 through plant and soil respiration. Typically, over the course of a full year, croplands assimilate C from CO_2. In other words, the plants capture more CO_2 through photosynthesis than is emitted through respiration.

Cropland Emissions

Relationships are used to predict the total C fixed through photosynthesis and the emission of CO_2 through plant (i.e., autotrophic) and soil (i.e., heterotrophic) respiration. These relationships are based upon those used in the CENTURY model. CENTURY is one of the most frequently used models to simulate the C cycle in agroecosystems. The daily time-step version, DAYCENT, was selected as the most appropriate approach for incorporating C dynamics in the crop and soil components of the farm. CENTURY has been well documented in previous publications (**CENTURY, 2007**). CENTURY was developed primarily to simulate the long-term effects of climate on SOM including decomposition, plant production, and nitrogen cycling. Further development of CENTURY has produced DAYCENT. In DAYCENT, a daily time step allows the simulation of other environmental processes (e.g., trace gas fluxes) in addition to SOM dynamics.

The majority of relationships incorporated into IFSM are taken directly from DAYCENT Version 4.5. A brief description of several important equations is provided here, along with a description of relationships included in IFSM that differ from those in DAYCENT. Further details can be found in the DAYCENT model (**DAYCENT, 2007**) and model documentation (**CENTURY, 2007**).

Photosynthetic fixation of C by plants is the main input of C for a farm system. DAYCENT simulates total potential production as:

$$C_{pot.photo} = R_{solar} \cdot F_{prod} \cdot F_{temperature} \cdot F_{H2Ostress} \cdot F_{bio} \cdot F_{seedling} \cdot F_{CO2} \cdot 4 \qquad [13.1]$$

where $C_{pot.photo}$ = total potential production from photosynthetic fixation, kg C/ha-day
R_{solar} = daily solar radiation at the desired location, ly/day
F_{prod} = coefficient to calculate daily aboveground production, g biomass/m^2-day
$F_{temperature}$= function for temperature effect on photosynthesis, dimensionless
$F_{H2Ostress}$= function for water stress effect on potential production, dimensionless
F_{bio}= coefficient for physical obstruction effect on potential growth, dimensionless
$F_{seedling}$ = coefficient to account for restriction of seedling growth, dimensionless
F_{CO2} = coefficient representing atmospheric CO_2 concentration effect on growth.

The original values of F_{prod} in DAYCENT were monthly values (i.e., g biomass/m^2-month); in order to simulate daily production, the values were divided by 30.4 to yield daily values (g biomass/m^2-day).

To determine plant respiration (i.e., autotrophic), the total potential production is divided between above and below ground potential production as:

$$C_{ag} = C_{pot.photo} \cdot (1- F_{bg}) \qquad [13.2]$$

$$C_{bg} = C_{pot.photo} \cdot (F_{bg}) \qquad [13.3]$$

where C_{ag} = total potential aboveground production, kg C/ha-day
C_{bg} = total potential belowground production,kg C/ha-day
F_{bg} = fraction of production allocated belowground, kg C/kg C

A fraction of the above and below ground potential production is assumed to be respired by the plants as:

$$C_{resp,ag} = C_{ag} \cdot (R_{ag}) \qquad [13.4]$$

$$C_{resp,bg} = C_{bg} \cdot (R_{bg}) \qquad [13.5]$$

where $C_{resp,ag}$ = aboveground respiration, kg C/ha-day
$C_{resp,bg}$ = belowground respiration, kg C/ha-day

R_{ag} = fraction of aboveground production respired, kg C/kg C
R_{bg} = fraction of belowground production respired, kg C/kg C

In Version 4.5 of **DAYCENT (2007),** above- and belowground respiration is not simulated, so the model does not provide values for R_{ag} and R_{bg}. To simulate this process in IFSM, these parameters were calibrated so that the model yielded appropriate results for above-and belowground respiration and C accumulation as compared to observed data. Based on the calibration, values were set so that 35% of aboveground and 20% of belowground production was respired as CO_2.

Microbial decomposition of organic matter is the driving force behind soil (heterotrophic) respiration. The C module simulates three surface C pools (surface structural, metabolic, and microbial C), three soil C pools (soil structural, metabolic, and microbial C) in each of four soil layers making up the soil profile, and two soil C pools for C with a long turnover rate (soil slow and passive C) (**Figure 13.1**). For each C pool, a total flow of C out of the pool is calculated. A portion of the C is respired as CO_2, while the remaining C is cycled into a different pool. The total flow of C out of a given pool is calculated as:

$$C_{flow} = \min(C_{pool,current}\ C_{max,flow}) \cdot F_{decomp} \cdot K_{decomp} \cdot F_{pH} \cdot F_{lignin} \cdot F_{cult} \cdot F_{texture} \cdot F_{anaerob} \qquad [13.6]$$

where C_{flow} = total flow of C from a given pool, g C/m^2-day
$C_{pool,current}$ = current mass of C in the pool, g C/m^2
$C_{max,flow}$ = maximum mass of C that can leave the pool, g C/m^2
F_{decomp} = decomposition factor based on soil moisture and ambient temperature, specific to above (e.g., surface) or belowground (e.g., soil) C pools, unitless
K_{decomp} = intrinsic decomposition rate specific to each pool, 1/day
F_{pH} = factor accounting for the effect of pH on decomposition, dimensionless
F_{lignin} = effect of the lignin content on decomposition, dimensionless
F_{cult} = effect of cultivation, dimensionless
$F_{texture}$ = effect of soil texture, dimensionless
$F_{anaerob}$ = accounts for the presence of anaerobic conditions, dimensionless

The first five terms are calculated for C flows leaving each pool. The lignin factor equals one for all pools other than the surface and soil structural pools. The surface and soil structural pools account for the effect of lignin content of the structural pools as:

$$F_{lignin} = \exp(- R_{lig/str} \cdot C_{strlig}) \qquad [13.7]$$

where $R_{lig/str}$= effect of the ratio of lignin to structural C on decomposition, dimensionless
C_{strlig} = ratio of lignin to structural C in the structural pool, g lignin C/g structural C

For the surface C pools (surface structural, metabolic, and microbial), the cultivation factor, F_{cult}, equals one. For the remaining pools, F_{cult} equals one on every day of the year that does not have a farm operation occurring. On days with a farm operation (e.g., tillage or harvest), cultivation factors are assigned based on the type of operation and type of machine (e.g., chisel plow, moldboard plow).

The texture factor, $F_{texture}$, affects the decomposition from the soil microbial pool only, and is a function of the silt, sand, and clay contents. Finally, the anaerobic factor, F_{anerob}, only affects the decomposition of soil pools, and is calculated based on the soil moisture content.

Respiration of CO_2 is predicted assuming a set fraction of total C flow out of the pool is respired as CO_2-C:

$$C_{respired} = C_{flow} \cdot k_{resp} \quad [13.8]$$

where $C_{respired}$ = daily respired C, g C/m^2-day
k_{resp} = fraction of the daily total C flow that is respired, g C respired/g C flow

This fraction varies as obtained from DAYCENT input files (**Table 13.1**).

Lime is often used to neutralize the acidity of soil and this provides an additional carbon source for emission as CO_2. Lime use is determined as a function of soil acidity and the crops grown following the agronomic guidelines for Pennsylvania (**Penn State, 2011**). For alfalfa and soybean crops, the calcium carbonate equivalent requirement is:

$$R_{CACO3} = 1121 \cdot EA \cdot A_{crop} \quad [13.9]$$

where R_{CACO3} = lime requirement in calcium carbonate equivalents, kg
EA = exchangeable acidity of the soil
A_{crop} = crop area, ha.

For all other crops and when the soil exchangeable acidity is greater than or equal to 4, the calcium carbonate requirement is:

$$R_{CACO3} = 942 \cdot EA \cdot A_{crop} \quad [13.10]$$

If the exchangeable acidity is less than 4 and the soil pH is less than 6.5:

$$R_{CACO3} = 2242 \cdot A_{crop} \quad [13.11]$$

For a soil pH of 6.5 or greater and an exchangeable acidity of 4 or greater, the calcium carbonate equivalent requirement is zero. By totaling the requirements for all crop areas, a total requirement is determined. Since this requirement is normally applied every three years, the total is divided by 3 to obtain an average annual requirement.

Over the three year period following lime application, most of the added carbon transforms to carbon dioxide that is volatilized to the atmosphere. We assume that 10% of the total applied will be lost through leaching, runoff or other non volatile means; therefore, 90% is lost through CO_2 volatilization. This primary emission of CO_2 is determined considering that there are 0.12 units of CO_2 carbon emitted per unit mass of calcium carbonate equivalent applied (**IPCC, 2006**).

$$E_{CO2,lime} = 0.12 \cdot 44/12 \cdot 0.9 \cdot A_{CACO3} \qquad [13.12]$$

where $E_{CO2,lime}$ = CO_2e emitted from applied lime, kg
A_{CACO3} = Average annual application of calcium carbonate equivalent, kg.

In addition to CO_2 losses, C is also lost due to leaching and erosion. Leaching losses are predicted using relationships in DAYCENT where a given fraction of the total C flow out of the microbial C pool is leached. This fraction is a function of the soil clay content, the water leached from the soil profile, and empirical parameters obtained from DAYCENT.

$$C_{leach} = 0 \quad \text{when } W_{leach} = 0 \qquad [13.13]$$

$$C_{leach} = C_{flow} \cdot K_{texture} \cdot F_{leach} \quad \text{when } W_{leach} > 0$$

$$K_{texture} = 0.03 + 0.12 \cdot F_{clay} \qquad [13.14]$$

$$F_{leach} = \min\left[1.0,\ 1.0 - \left((1.9 - W_{leach})/1.9\right)\right] \qquad [13.15]$$

where C_{leach} = amount of C leached from the soil microbial pool, g C/m^2-day
W_{leach} = water flow from the soil layer, cm
C_{flow} = total flow of C from the soil microbial pool, g C/m^2-day
$K_{texture}$ = effect of soil texture on leaching, dimensionless
F_{leach} = fraction of C leached, g C leached/g C flow
F_{clay} = soil clay content, decimal

Runoff of sediment-bound organic matter represents another pathway of C loss. Loss of C due to erosion is calculated as:

$$C_{erosion} = Y_{sed} \cdot C_{ER} \qquad [13.16]$$

where $C_{erosion}$ is the amount of eroded C, kg C/day
Y_{sed} = amount of daily erosion occurring from the given cropland, kg erosion/day
C_{ER} = C enrichment ratio, mg/kg erosion

The enrichment ratio is calculated using a relationship from **Sharpley (1985)**:

$$C_{ER} = \exp(1.63 - 0.25 \cdot Y_{sed}) \qquad [13.17]$$

Daily erosion was calculated in IFSM using the modified universal soil loss equation (MUSLE) as described above under phosphorus loss.

It is important to note that the current model does not allow for long term sequestration or depletion of soil C. By forcing a long term balance, it is assumed that there is no net change in soil C content over time. If major changes in tillage and cropping practices are made, soil C levels can change over a number of years until the soil again reaches an equilibrium level. For example, a summary of data from across North America indicates that conversion of tilled cropland to perennial grassland increases annual C sequestration by 0.3 to 1.0 t C/ha for up to 50 yr depending upon soil and climate conditions (Franzluebbers and Follett, 2005). From the same summary, conversion of conventional tillage systems to no-tillage practices can also increase annual sequestration by 0 to 0.5 t C/ha. Our model does not account for this potential change in soil C, but this change can be added or subtracted from the net CO_2 emission . To obtain values for long term changes in soil C, the COMET-VR model (available at http://www.comet2.colostate.edu/) provides a relatively easy to use tool for quantifying potential changes in soil C with changes in production practices.

Animal Respiration

Carbon dioxide emission through animal respiration is sometimes ignored as a greenhouse gas emission source (**IPCC, 2001 and 2007).** This respired CO_2 is part of the C cycle that initially begins with photosynthetic fixation by plants. When the animals consume the crop (fixed C in the plant material), they convert it back to CO_2 through respiration (**Kirchgessner et al., 1991**; **IPCC, 2001**). On a farm, animal respiration of CO_2 is a major source relative to other CO_2 emissions. In the overall farm balance, the CO_2 released largely offsets the CO_2 sequestered in the plant material. However, some of the feed intake of C is converted and released as CH_4 and some is in the milk and animals produced. To obtain a full accounting and balance of all C flows through the farm, all sources of C emissions, including animal respiration, are considered.

A relationship developed by **Kirchgessner et al. (1991**) relating CO_2 emissions to DMI is used to predict animal respiration. Respired CO_2 is determined as:

$$E_{CO2,cow} = -1.4 + 0.42 \cdot M_{DMI} + 0.045 \cdot M_{BW}{}^{0.75} \qquad [13.18]$$

where $E_{CO2,cow}$ = emission of CO_2 from animal respiration, kg CO_2/cow-day

M_{DMI} = daily intake of feed dry matter for each animal, kg DM/cow-day

M_{BW} = animal's body weight, kg

The DMI and body weight for each animal group is available from the herd component. DMI is determined based upon the nutrient requirements (fiber, energy and protein) and target milk production of a representative animal for each group within the herd and the amount and nutrient content of available feeds including pasture (See **Herd and Feeding** section). Body weight is determined based upon animal breed (as specified by the model user) and age and stage of lactation as simulated in the herd component.

Barn Floor Emissions

Floors of housing facilities can be a source of CO_2 emissions due to decomposition of organic matter in manure deposited by animals. Although not a major source, barn floor emissions are included to obtain a comprehensive simulation of farm-level CO_2 emissions from all sources.

Published models to predict CO_2 emissions from barn floors were not found. Using emissions data measured from manure covered floors in a free stall barn at the Penn State dairy facility (**Chianese et al., 2009b**), an equation was developed through regression analysis relating CO_2

emission to the ambient temperature in the barn and the manure covered floor area ($R^2 = 0.74$).

$$E_{CO2,floor} = \max(0.0, 0.0065 + 0.0192\ T)\ A_{barn} \qquad [13.19]$$

where $E_{CO2,floor}$ = daily rate of CO_2 emission from the barn floor, kg CO_2/day
T = ambient temperature in the barn, °C
A_{barn} = floor area covered by manure, m^2

Equation 13.19 represents the best available information describing CO_2 emissions from barn floors. As a function of temperature, this relationship provides a simple process-based model that predicts reasonable emission rates over a full range in potential ambient barn temperatures. Because barn floor emissions are so small compared to other sources, development of a more sophisticated model was not justified at this time.

Manure Storage

Compared to other farm sources, slurry storages emit relatively low amounts of CO_2. Because of this minimal contribution to whole-farm emissions, there were no models and few data available quantifying CO_2 emissions from storages. Lack of available data, as well as the relative importance of this loss to overall farm emissions did not support the development of a process-based model. Therefore, a constant emission factor represented the best available method for predicting this emission. To determine an emission factor, emission rates were obtained from two published studies and the average was used as our emission rate (**Table 13.3**).

The average emission rate of 0.04 kg CO_2/m^3-day is applicable to uncovered slurry storages. Covers are sometimes used to reduce gaseous emissions, but no data were available documenting the effect of covers on CO_2 emissions. To model this effect, we assumed that CO_2 emissions are reduced by a similar proportion when using a cover as found for more important gases such as ammonia. The ammonia emission model in IFSM predicts about an 80% reduction in loss with the use of a cover, depending upon the storage dimensions. Therefore, to simulate CO_2 emissions from a covered storage, the emission rate was reduced to 0.008 kg CO_2/m^3-day. To represent a sealed storage where biogas is burned, the loss of CO_2 was eliminated. The total emission of the storage though includes the CO_2 created through the combustion of CH_4. (see **Methane Emission** section).

Fuel Combustion

During the operation of tractors and other engine powered equipment, C in fuel is transformed to CO_2, which is released in engine exhaust. The amount of CO_2 produced is proportional to the amount of fuel consumed. The conversion factor used is 2.637 kg CO_2e/liter of diesel fuel consumed (**Wang, 2007**). Fuel consumption is determined during the simulation of each individual operation (See **Energy and Labor** section). By summing the fuel use over all operations, a total annual use on the farm is obtained. This total is then multiplied by the emission factor to obtain the combustion CO_2 emission.

Methane Emission

Methane is a strong GHG with a GWP around 25 times that of CO2 (**IPCC, 2007**). Multiple processes emit CH_4 from dairy farms. The majority of CH_4 is created through enteric fermentation, followed by emissions from manure storages (**Chianese et al., 2009a**). In addition to these major sources, smaller emissions result from field-applied manure and manure deposited by animals inside barns or on pasture. Most field studies report croplands as a negligible source, or very small sink, of CH_4 over full production years. However, field-applied manure can result in significant emissions for a few days after application. In this model, emissions from cropland are neglected except for this small emission that occurs immediately after manure application.

Enteric Fermentation

Enteric fermentation in ruminants is the largest source of CH_4 emission from dairy farms (**Chianese et al., 2009a).** Ruminant animals subsist primarily on forages. Like most animals, ruminants do not have the enzymes necessary to break down cellulose. Instead, enteric methanogens, which exist in a symbiotic relationship with other microorganisms in the rumen, break down and obtain energy from cellulose. During this process, hydrogen is produced and can build up in the rumen, leading to acidosis, a health problem in dairy cows. However, these methanogens decrease the amount of hydrogen in the rumen by using the excess to reduce CO_2 to CH_4, preventing this health effect. The CH_4 produced is released to the atmosphere by eructation or belching. Other roles of these microorganisms are not fully understood. The amount of CH_4 produced from enteric fermentation is impacted by various factors including animal type and size, digestibility of the feed, and the intake of dry matter, total carbohydrates, and digestible carbohydrates (**Chianese et al., 2009b**).

After considering the various mechanistic and empirical models available to predict enteric fermentation emissions (**Chianese et al., 2009b**), a relatively simple approach is used, which uses the Mitscherlich 3 (Mits3) equation developed by **Mills et al. (2003**). Mits3 is a simplified process model that satisfies the requirements for use in whole-farm simulation. The model is based on dietary composition and is capable of accounting for management practices that alter the animal's intake and diet as well as animal type and size. When compared to data from the U.S., Mits3 has yielded a regression slope of 0.89 with an intercept of 3.50 and a square root of the mean square prediction error (MSPE) of 34.1% (**Mills et al., 2003**). In addition, Mits3 predicts realistic emissions at the extremes of the parameter ranges. With zero feed intake, the model predicts zero CH_4 production; at the other extreme of very high feed intake, the nonlinear model predicts that CH_4 emission approaches a maximum. Thus, the model can be applied to conditions outside those for which it was originally developed and evaluated without predicting unreasonable emissions.

Three model inputs are required: starch content of the diet, acid detergent fiber (ADF) content of the diet, and metabolizable energy intake. These inputs are readily obtained from the feed and animal components (See **Herd and Feeding** section). Through these inputs, CH_4 production is directly related to diet and indirectly related to animal size and type. This allows prediction of changes in CH_4 production as affected by changes in animal nutrition and management. A detailed description of the selected model can be found in **Mills et al. (2003**). A brief description is provided here to document the model, parameters used, and the integration with IFSM.

Emission of CH_4 is predicted as:

$$E_{CH4,ent} = [E_{max} - E_{max} \exp(-c \cdot M_{EI})] \cdot F_{kgCH4} \quad [13.20]$$

where $E_{CH4,ent}$ = emission due to enteric fermentation, kg CH_4/cow-day

E_{max} = maximum possible emission, MJ CH_4/cow-day

c = shape parameter determining emission change with increasing M_{EI}, dimensionless

M_{EI} = metabolizable energy intake, MJ/cow-day

F_{kgCH4} = conversion of MJ to kg of CH_4, 0.018 kg CH_4/MJ

From **Mills et al., (2003)** the maximum possible emission is defined as 45.98 MJ CH_4/cow-day. This maximum possible emission is constant for all animals; the effect of animal size and type is indirectly provided through the value of M_{EI}. The shape parameter, c, is calculated as:

$$c = -0.0011 \cdot [Starch / ADF] + 0.0045 \quad [13.21]$$

where $Starch$ = starch content of diet

ADF = acid detergent fiber content of diet

Equation 13.21 models the observed trend of increased CH_4 emission with high fiber diets and decreased emission with high starch diets.

To use the above equations, values are needed for the starch and ADF contents of diets and the metabolizable energy intake of animal groups making up the herd. The herd component determines the ration that each animal group is fed based upon a representative animal's nutritional requirements and the available feeds (See **Herd and Feeding** Section). This information includes the required energy content of the diet [MJ/kg DM], the total dry matter intake [kg DM/cow-day], and the amount of each feed used. The first two parameters are used to calculate M_{EI}. The ADF contents of feeds are determined assuming a linear relationship with neutral detergent fiber (NDF) for each feed type **(Table 13.2**). These relationships were developed using feed composition data from the National Research Council (**NRC, 2001**). The starch contents of feeds are determined assuming a linear relationship with the amount of nonfiber carbohydrate (NFC) in the feed **(Table 13.2**). The fraction of NFC is determined as:

$$F_{NFC} = 1 - (F_{NFC} + F_{CP} + F_{fat} + F_{ash}) \quad [13.22]$$

where F_{NFC} = fraction of NFC in the diet

F_{CP} = fraction of crude protein (CP) in the diet

F_{fat} = fraction of fat in the diet

F_{ash} = fraction of ash in the diet

The fractions of NDF and CP are available in the herd component; typical fractions of fat and ash (**Table 13.2**) were obtained from the National Research Council (**NRC, 2001**). A given animal group is typically fed a mixture of feeds making up the whole diet. A weighted average of the individual feed characteristics in the ration is used to determine the starch and ADF contents of the full ration fed to each of the six possible animal groups making up the herd.

Barn Emissions

Manure on housing facility floors is also a small source of CH_4. No published model or data were found for this emission source. Therefore, unpublished CH_4 emission data measured from free stall barn floors (**Chianese et al., 2009b**) were used to develop an empirical equation relating CH_4 emission to the ambient temperature in the barn ($R^2 = 0.48$). The resulting model is:

$$E_{CH4,floor} = \max(0.0,\ 0.13\,T) \cdot A_{barn} \big/ 1000 \qquad [13.23]$$

where $E_{CH4,floor}$ = daily rate of CH_4 emission from the barn floor, kg CH_4/day
T = ambient barn temperature, °C
A_{barn} = area of the barn floor covered with manure, m^2

This relationship represents the best available information describing CH_4 emissions from free stall and tie stall barn floors. The temperature dependence of CH_4 production is well-documented (**Chianese et al., 2009b**). As a function of temperature, equation 13.23 is a simplified, process-based equation. This simple relationship predicts reasonable emission rates for ambient temperatures of 0°C and greater.

When manure is allowed to accumulate into a bedded pack, CH_4 emissions are increased. For this management option, an adaptation of the tier 2 approach of the **IPCC (2006)** is used. Emission on a given day is determined as a function of the ambient barn temperature and a methane conversion factor (MCF).

$$E_{CH4,floor} = VS\,(B_o)\,(0.67)\,(MCF) / 100 \qquad [13.24]$$

where $E_{CH4,floor}$ = daily CH_4 emission, kg CH_4/day
VS = volatile solids excreted in manure, kg VS
B_o = maximum CH_4 producing capacity for dairy manure, 0.24 m^3 CH_4/kg VS
0.67 = conversion factor of m^3 CH_4 to kg CH_4
MCF = CH_4 conversion factor for the manure management system, %.

MCF is modeled as an exponential function of ambient barn temperature through a regression of the data provided by the **IPCC (2006)**:

$$MCF = 7.11\ e^{\,0.0884(T_b)} \qquad [13.25]$$

where T_b = ambient barn temperature, ^oC
MCF is limited to a minimum value of 0 and maximum of 80.

In warm dry climates, animals are often housed in open, non vegetated areas referred to as open lots. Manure typically accumulates on the soil surface for weeks or months before being removed. To predict emissions from this surface, the tier 2 approach of **IPCC (2006)** is again used. Based upon the IPCC data, MCF was modeled as a linear relationship with ambient outdoor temperature.

$$MCF = 0.0625\ Ta - 0.25 \qquad [13.26]$$

whereT_a = ambient temperature, ^oC

MCF is limited to a minimum value of 0. In systems that combine free stall and open lot housing, the assumption is made that half of the manure is deposited in free stall allies with the remainder deposited on the open lot. The total emission is then the sum of the two sources modeled using the appropriate relationships

Manure Storage

During manure storage, CH_4 is generated through a reaction similar to that described for enteric fermentation. The cellulose in the manure is degraded by microbes, with products of this process serving as substrates for methanogenesis. Temperature and storage time are the most important factors influencing CH_4 emissions from stored manure because substrate and microbial growth are generally not limited. Although the processes are similar, there are important differences between the rumen and manure storage. The temperature in the storage varies, in contrast to the relatively constant temperature in the rumen, and the manure in storage is more heterogeneous (e.g., the substrate is less well mixed and some carbohydrates are already partially decomposed) as compared to the consistency of the rumen.

As with enteric fermentation, both mechanistic and empirical models have been developed to predict CH_4 emissions from manure storages. Unlike some of the empirical enteric fermentation models that simply use statistical correlations that are not necessarily based on biological processes, the majority of empirical manure storage models are biologically based. After considering two mechanistic and four empirical models (**Chianese et al., 2009b**), the model of **Sommer et al. (2004)** was selected as the most appropriate approach for our application. Their model employs commonly used empirical relationships (e.g., Arrhenius relationship) that are more general and thus more applicable to conditions outside of which they were developed. Additionally, this is a more recent model, incorporating more recent developments and data. Unlike most the other models, the model of **Sommer et al. (2004)** was developed for more general application to either digested or untreated slurry manure.

The model of **Sommer et al. (2004)** simulates the production and emission of CH_4 from manure storages based upon the degradation of volatile solids (VS). Additional factors affecting CH_4 production are temperature and storage time. A detailed description of the development of their model is found in **Sommer et al., (2004).** The model is presented here along with a brief discussion on the establishment of parameters and integration with other components of the farm model.

Emission of CH_4 from slurry or liquid manure storages is predicted as:

$$E_{CH4,man} = \left(\left(24 \cdot V_{s,d} \cdot b_1 \right) / 1000 \right) \cdot \exp\left[\ln(A) - \left(E / RT \right) \right] + \left(\left(24 \cdot V_{s,nd} \cdot b_2 \right) / 1000 \right) \cdot \exp\left[\ln(A) - \left(E / RT \right) \right] \quad [13.27]$$

where $E_{CH4,man}$ = emission of CH_4 from the storage, kg CH_4/day

$V_{s,d}$ and $V_{s,nd}$ = degradable and nondegradable VS in the manure, g

b_1 and b_2 = rate correcting factors, dimensionless

A = Arrhenius parameter, g CH_4 /kg VS-h

E = apparent activation energy, J/mol

R = gas constant, J/K-mol

T = temperature, ^oK (**Table 13.3**).

From **Sommer et al. (2004)**, the degradable volatile solids entering storage is:

$$V_{s,d} = V_{s,tot} \; B_o / [E_{CH4,pot}] \quad [13.28]$$

where $V_{s,tot}$ = total VS in the manure, g

B_o = achievable emission of CH_4 during anaerobic digestion, g/kg VS

$E_{CH4,pot}$ = potential CH_4 yield of the manure, g/kg VS

$E_{CH4,pot}$ can be estimated using Bushwell's equation and the carbohydrate, fat, and protein content of the manure. For cattle slurry, **Sommer et al. (2004)** defined B_o as 0.2 g CH_4/kg VS and $E_{CH4,pot}$ as 0.48 g CH_4/kg VS.

Total VS in the manure storage at any point in time is the difference between that entering the storage and that lost from the storage up to that point. The amount entering can be determined from the manure mass, the total solids content, and the VS content:

$$V_{s,tot} = M_{manure} \cdot P_{TS} \cdot P_{VS} - V_{s,loss} \quad [13.29]$$

where M_{manure} = accumulated mass of manure entering the storage, kg

P_{TS} = total solids content in the manure, g TS/kg manure

P_{VS} = fraction of VS in the total solids, g VS/g TS

$V_{s,loss}$ = accumulated VS loss

To obtain a similar rate of VS loss as that reported by **Sommer et al. (2004),** this loss was predicted as three times the methane loss from the stored manure. The mass of nondegradable volatile solids, $V_{s,nd}$, is then calculated using a mass balance:

$$V_{s,nd} = V_{s,tot} - V_{s,d} \quad [13.30]$$

The inputs required are the mass and temperature of the manure in storage. The amount of manure in storage is modeled as the accumulation of that produced by the herd with daily manure excretion determined in the animal component (See **Herd and feeding** section). The temperature of the manure in storage on a given simulated day is estimated as the average ambient air temperature over the previous ten days.

This predicted storage emission is for an uncovered, bottom-loaded storage of slurry (7 – 12% DM) manure where a crust forms on the surface. For a top-loaded tank or with manure containing less DM, this emission rate is increased 40% (**IPCC, 2006**). Storage covers are sometimes used to reduce emissions. With a non-sealed cover, the emission rate is reduced to 20% of that occurring from the open storage. A more tightly sealed cover or enclosed storage can be used where the biogas produced is burned to convert the emitted CH_4 to CO_2. This technique drastically decreases the emission of CH_4, although it does increase the emission of CO_2 through the combustion of CH_4. To simulate this storage treatment, the emission of CH_4 from an enclosed manure storage is calculated as:

$$E_{CH4,cov} = E_{CH4,man} \cdot (1 - \eta_{eff}) \qquad [13.31]$$

where $E_{CH4,cov}$ = CH_4 emitted from the enclosed manure storage, kg CH_4/day

$E_{CH4,man}$ = CH_4 emission from the storage with no cover using equation 13.27, kg CH_4/day

η_{eff} = efficiency of the collector, dimensionless

The efficiency of the collector and flare is assumed to be 99%. The subsequent flaring of the captured CH_4 releases CO_2, which adds to the overall farm emission of this gas. Assuming complete combustion, the additional emission of CO_2 due to the combustion of CH_4 is calculated as:

$$E_{CO2,flare} = E_{CH4,cov} \cdot 2.75 \qquad [13.32]$$

where $E_{CO2,flare}$ = emission of CO_2 from the combustion of captured CH_4, kg CO_2/day

2.75 = ratio of the molecular weights of CO_2 and CH_4.

Semi-solid (8-14% DM) and solid manure (>15% DM) can be stored in stacks. Methane emission from this type of storage is modeled through an adaptation of the tier 2 approach developed by the **IPCC (2006)**. Emission on a given day is determined as a function of the total volatile solids (VS) placed into the storage and the methane conversion factor:

$$ECH4 = VS\ (B_o)\ (0.67)\ (MCF) / 100 \qquad [13.33]$$

where ECH4 = daily CH_4 emission, kg CH_4/day

B_o = maximum CH_4 producing capacity for dairy manure, 0.24 m^3 CH_4/kg VS

0.67 = conversion factor of m^3 CH_4 to kg CH_4

MCF = CH4 conversion factor for the manure management system, %.

From the **IPCC (2006)** data, a function was developed to predict MCF as a function of the temperature of the stored manure:

$$MCF = 0.201\ Tm - 0.29 \qquad [13.34]$$

where T_m = manure temperature, ^oC.
MCF is set at a minimum of zero, and the manure temperature is the average ambient temperature over the previous 10 days.

Field-applied Manure

Research has shown that field-applied slurry is a source of CH_4 emissions for several days after application, emitting between 40 to 90 g CH_4/ha-day (**Chianese et al., 2009b**). Emissions drastically decrease within the first few days, and the soils return to being a neutral source of CH_4 by 11 days.

Sherlock et al. (2002) related CH_4 emissions from field-applied slurry to the volatile fatty acids (VFAs) concentration in the soil. Because the VFAs in the soil were due to the application of the slurry, their model was used to relate CH_4 emissions to the VFA concentration in the slurry as compared to the concentration in the soil. Therefore, emission of CH4 from field-applied slurry is predicted as:

$$E_{CH4,app} = (0.170 \cdot F_{VFA} + 0.026) \cdot A_{crop} \cdot 0.032 \qquad [13.35]$$

where $E_{CH4,app}$ = emission of CH_4 from field-applied slurry, kg CH_4/day
F_{VFA} = daily concentration of VFAs in the slurry, mmol/kg slurry
A_{crop} = land area [ha] where the manure is applied.

Equation 13.35 is valid for CH_4 emissions within the first 11 days of application; after this time, CH_4 emissions are assumed to be negligible.

Sherlock et al. (2002) found that the daily VFA concentration exponentially decreased in the days following the application of manure slurry and approached background levels within approximately four days. Using this information, we derived a relationship predicting the daily concentration of VFA in the field-applied slurry.

$$F_{VFA} = F_{VFA,init}\, e^{-0.6939\, t} \qquad [13.36]$$

where F_{VFA} = daily concentration of VFAs in the slurry, mmol/kg slurry
$F_{VFA,init}$ = initial concentration of VFAs in the slurry at application, mmol/kg slurry
t = time since application [days], with t = 0 representing the day of application.

Paul and Beauchamp (**1989**) developed an empirical model relating the pH of manure slurry to VFA and total ammoniacal nitrogen (TAN) concentrations:

$$pH = 9.43 - 2.02 \cdot [F_{VFA,init} / F_{TAN}] \qquad [13.37]$$

where pH = the pH of the manure slurry, dimensionless
F_{TAN} = concentration of TAN ($NH_4^+ + NH_3$) in the slurry, mmol/kg slurry

Rearranging Equation 13.33, we obtained an equation predicting the initial concentration of VFAs based on the pH and TAN of the manure slurry:

$$F_{VFA,init} = [F_{TAN} / 2.02]\,(9.43 - pH) \qquad [13.38]$$

To predict emissions from field applied manure, equation 13.38 is used to determine an initial VFA concentration and equation 13.36 is used to track the VFA concentration through time following field application. Using this concentration, an emission rate is determined until the remaining VFA concentration approaches zero.

Grazing Animals

On farms that incorporate grazing for at least a portion of the year, freshly excreted feces and urine are directly deposited by animals on pastures. Studies have shown that feces are a small source of CH_4 and that emissions from urine are not significantly different from background soil emissions (e.g., **Jarvis et al., 1995**; **Yamulki et al., 1999).** Because animal-deposited feces contribute only minimally to overall farm CH_4 emissions, there are few data quantifying these emissions.

Due to the lack of supporting data and the relatively low importance of this emission source to overall farm emissions, a constant emission factor was used to predict CH_4 emission from feces deposited by grazing animals. To determine this emission factor, emission rates were obtained from four published studies and the average (0.086 g CH_4/kg feces) was used for our emission rate (**Table 13.4**). Therefore, for grazing systems, the daily emission of CH_4 is predicted as the product of this emission rate and the daily amount of feces deposited by grazing animals.

Nitrous Oxide Emission

Nitrous oxide is the strongest of all greenhouse gas emissions occurring in agricultural production with a global warming potential 298 times that of CO_2 (**IPCC, 2007**). In 2005, agriculture had the greatest overall impact on N_2O emissions, contributing 78% of the U.S. total (**EIA, 2006**). In fact, this contribution has become increasingly important, with reported emissions increasing by 10% between 1990 and 2005 (**EIA, 2006**). Multiple sources emit N_2O on dairy farms. The majority is emitted from soil, followed by manure storages, with relatively small amounts emitted from manure in bedded pack barns or dry lots (**Chianese et al., 2009d**).

Cropland Emissions

Croplands are the largest source of N_2O. Although undisturbed soils emit N_2O naturally, the rate of emission from cultivated soils is much greater because of the greater N inputs on farmland. Two pathways can lead to emissions of N_2O: denitrification and nitrification. Denitrification is the microbial reduction of NO_3 to N_2 under anaerobic conditions, with the production of NO and N_2O as intermediates (**Figure 13.5**).

Historically, denitrification was believed to be the primary source of N_2O emissions; however, scientists have established that nitrification also contributes. Nitrification is an aerobic process that oxidizes NH_4^+ to NO_3, with the production of NO and N_2O as intermediates (**Figure 13.3**).

The emission of N_2O is thus dependent on both denitrification and nitrification. A conceptual model published by **Davidson et al. (2000)** describes how denitrification and nitrification are connected (**Figure 13.4**). This model, known as the "hole-in-the-pipe" (HIP) model, connects the two pathways and thus links the emission of NO and N_2O (**Davidson et al., 2000**).

Both mechanistic and empirical equations have been used to predict N_2O emissions from soils, and reviews of both categories of models have been published. We considered five models for use in IFSM: one mechanistic (DNDC) and four other process-based models with less mechanistic detail (**Chianese et al., 2009d**). Of the available models, relationships in DAYCENT were selected as most appropriate for integration with other existing components of IFSM.

DAYCENT is process-based, accounting for how management scenarios affect the moisture content, pH, nitrate concentration, and ammonium concentration in the soil. DAYCENT has been used to accurately simulate N_2O emissions for a variety of different applications. Comparisons with observed data show that the gas module more accurately predicts observed data ($R^2 = 0.74$) as compared to the IPCC methodology (**Chianese et al., 2009d**). Detailed documentation of the N_2O module of DAYCENT can be found in **Del Grosso et al. (2000)** and **Parton et al. (2001).** This section provides a brief description of the model, parameter selection, and integration with IFSM.

Emission of N_2O from soils is predicted as the sum of nitrification and denitrification losses:

$$E_{N2O,soil} = E_{N2O,soil,N} + E_{N2O,soil,D} \quad [13.39]$$

where

$E_{N2O,soil}$ = total emission of N_2O from soils, kg N_2O/ha-day

$E_{N2O,soil,N}$ = emission from soils due to nitrification, kg N_2O/ha-day

$E_{N2O,soil,D}$ = emission from soils due to denitrification, kg N_2O/ha-day

Emission from nitrification is predicted as:

$$E_{N2O,soil,N} = K_2 \cdot R_{NO3} \cdot F_{N,conv} \quad [13.40]$$

where

K_2 = fraction of nitrified N lost as N_2O flux, g N/g N

R_{NO3} = soil nitrification rate, g N/m^2-day

$F_{N,conv}$ = conversion factor, 15.7 (kg N_2O/ha-day)/(g N/m^2-day)

Parton et al. (2001) defined K_2 as 0.02 g N flux g^{-1} N nitrified. Based on the model provided by **Parton et al. (2001)**, the equation used for computing the soil nitrification rate, R_{NO3}, is:

$$R_{NO3} = K_{max} \cdot N_{NH4} \cdot F_{temp} \cdot F_{wfp} \cdot F_{ph} \quad [13.41]$$

where

K_{max} = maximum fraction of ammonium concentration in the soil nitrified, 0.15

N_{NH4} = ammonium concentration in the soil, g N/m^2-day
F_{temp} = factor for the effect of temperature, dimensionless
F_{wfp} = factor for the effect of soil moisture, dimensionless
F_{ph} = factor for the effect of soil pH, dimensionless

The value of K_2 was reduced to 0.01 g N flux g^{-1} N nitrified.

Ammonium in the soil comes from the application of fertilizers and the mineralization of crop residue, applied manure and soil organic matter. The effects of temperature, soil moisture and soil pH on the nitrification rate are computed using relationships described in **Parton et al. (1996)**. Nitrification is also predicted for the upper layer only. Because there is no NH_4^+ source for the lower layer and NH_4^+ in the upper layer does not leach, it is assumed that no nitrification occurs in the lower layer.

For both upper and lower soil layers, emission of N_2O due to denitrification is predicted as:

$$E_{N2O,soil,D} = \left[\left(min(F_{d,NO3} \cdot F_{d,CO2}) \cdot F_{d,WFPS} \right) / (1+R_{Nratio}) \right] \cdot \rho_{soil} \cdot d_{soil} \cdot F_{N,mass} \qquad [13.42]$$

where
$E_{N2O,soil,D}$ = emission of N_2O from soil, kg N_2O/ha-day
$F_{d,NO3}$ = factor for the effect of soil nitrate concentration, µg N/g soil-day
$F_{d,CO2}$ = factor for the effect of soil respiration, µg N/g soil-day
$F_{d,WFPS}$ = factor for the effect of soil moisture, dimensionless
R_{Nratio} = ratio of N_2 to N_2O emission, µg N/µg N
ρ_{soil} = bulk density of the soil, g/cm^3
d_{soil} = active soil depth of layer simulated (upper, lower), cm
$F_{N,mass}$ = unit conversion factor, 0.157 (kg N_2O/ha-day) /(µg N/cm^2-day)

Similar to the model of **Parton et al. (1996)**, the effect of soil nitrate concentration on the N_2O flux due to denitrification, $F_{d,NO3}$, is calculated using an arctangent function (**DAYCENT, 2007**). The nitrate concentration for the upper layer is estimated from the amount of nitrified N (equation 13.41) and for the lower layer, is estimated from the amount of nitrate that leached from the upper layers to the lower layer (equations 13.51 to 13.53). The effect of soil respiration on the N_2O flux due to denitrification, $F_{d,CO2}$, is predicted as (**Parton et al., 2001**):

$$F_{d,CO2} = 0.1 \cdot (C_{CO2})^{1.3} \qquad [13.43]$$

where C_{CO2} = soil CO_2 flux, µg C/g soil.

The amount of N for denitrification is also constratined by a model-specified minimum nitrate concentration for the soil (1 ppm) (**DAYCENT, 2007**).

The model of **Parton et al. (2001)** assumes that denitrification does not occur at a soil moisture below approximately 55%. Above 55%, denitrification increases exponentially and asymptotically approaches a maximum as soils approach saturation. This effect is predicted as:

$$F_{d,WFPS} = 0.45 + \arctan\,[0.6 \cdot \pi\,(0.1 w_{wfps} - a)]\ /\ \pi \qquad [13.44]$$

where

w_{wfps} = water-filled pore space, percent
a = factor controlling soil moisture content where denitrification is half the maximum rate
arctan = arctangent function, radians

Parameter a is calculated as:

$$a = 9.0 - \mathrm{M} \cdot C_{CO2} \qquad [13.45]$$

$$M = 0.145 - 1.25 \cdot \min\,(0.113, D_{fc}) \qquad [13.46]$$

where

M = the interaction between soil moisture and respiration, dimensionless
D_{fc} = gas diffusivity coefficient, dimensionless

As in DAYCENT (**Del Grosso et al., 2000**), the ratio of gas diffusivity in the soil or manure pack to gas diffusivity in the air, D_{fc}, is computed using the method described by **Potter et al. (1996)**.

The ratio of N_2 to N_2O, R_{Nratio}, is predicted as:

$$R_{Nratio} = F_{r,NC} \cdot F_{r,WFPS} \qquad [13.47]$$

where

$F_{r,NC}$ = ratio of electron donor (NO_3) to substrate (CO_2), dimensionless
$F_{r,WFPS}$ = effect of soil moisture on the relative emissions of N_2 and N_2O, dimensionless

DAYCENT uses empirical equations to model $F_{r,NC}$ and $F_{r,WFPS}$. The effect of the ratio of NO_3 to CO_2 is predicted as:

$$F_{r,NC} = \max\,[(0.16 \cdot K_1), (K_1\, e^{-0.8\, r})] \qquad [13.48]$$

$$K_1 = \max\,[1.7, (38.4 - 350 \cdot D_{fc})] \qquad [13.49]$$

where K_1 = intercept of $F_{r,NC}$, dimensionless
r = ratio N_{NO3} to C_{CO2}, g N/g C

The effect of soil moisture is predicted as:

$$F_{r,WFPS} = \max\,[0.1, (0.015 \cdot w_{wfps} - 0.32)] \qquad [13.50]$$

Leaching affects the amount of nitrate available for denitrification. Similar to the calculation of carbon leaching (equations 13.13 to 13.15), leaching of nitrate is predicted using relationships from DAYCENT (**2007**). The fraction of the total nitrate leached from a layer is a function of the nitrate concentration, the sand content in the layer, the amount of water leached, and empirical parameters from DAYCENT:

$$N_{leach} = 0 \qquad \text{when } W_{leach} = 0 \qquad [13.51]$$

$$N_{leach} = N_{NO3} \cdot K_{texture} \cdot F_{leach} \qquad \text{when } W_{leach} > 0$$

$$K_{texture} = 0.6 + 0.2 \cdot F_{sand} \qquad [13.52]$$

$$F_{leach} = \min\left[1.0,\ 1.0 - \left((CF_{leach} - W_{leach}) / CF_{leach}\right)\right] \qquad [13.53]$$

where

N_{leach} = amount of nitrate leached from a layer, g N/m^2-day
W_{leach} = water flow from the soil layer, mm
$K_{texture}$ = effect of soil texture on leaching, dimensionless
F_{sand} = soil sand content, decimal
F_{leach} = leaching intensity, dimensionless
CF_{leach} = critical water flow for nitrate leaching, mm

CF_{leach} is set to 1.0 mm for the upper layers. Using experimental farm data, CF_{leach} for the lower layer is set to 3.0 mm. In calculating nitrate leaching, the lowest layer (100-cm depth) is subdivided into five sublayers. The first 3 sublayers have depths of 10, 15 and 15 cm. The difference between the total rooting depth and the upper sublayers is divided between the two lowest sublayers. The total *N* leaching loss reported by the model is the amount of nitrate *N* that leached through the lowest sublayer.

To implement the above equations, inputs are needed for ammonium concentration in the upper layer, soil bulk density, CO_2 flux, water-filled pore space, air-filled pore space, and total porosity. Soil *N* mineralization is simulated in other components of IFSM, so the soil mineralization rate and ammonium concentration are available (see **Soil** section). Specific soil properties, including bulk density, are available as inputs through the soil characteristics menu of IFSM, with water-filled pore space and total porosity calculated using these user-defined soil properties (see **Soil** section). Air-filled pore space is calculated from water-filled pore space and total porosity. Soil CO_2 flux is available from the carbon module (see **Carbon Dioxide** section).

Barn Emissions

Free Stall and Tie Stall Barns

Manure on the floors of free stall and tie stall barns appears to be a negligible source of N_2O emission. Based upon limited available data, the emission of N_2O is modeled as zero from the floors of these facilities where manure is typically removed on a daily basis (**Chianese et al., 2009d**).

Open Lot Facilities

Similar to croplands, nitrogen in open lot soils is transformed through mineralization and nitrification and lost through volatilization, leaching and denitrification. In predicting N_2O emissions for open lots, the same equations for nitrification, denitrification and leaching described for croplands (equations 13.39 to 13.53) are used with a few changes. Ammonium in the manure pack comes from both hydrolyzed urine *N* and mineralized manure *N*. Based on experimental data (**Pratt and Castellanos, 1981**), the daily mineralization rate for cattle manure is equivalent to 0.052/day. In calculating the nitrification rate (equation 13.41), the effect of temperature is removed because no relationship has been established between manure pack temperature and nitrification for open lots (**Woodbury et al., 2001**). The maximum fraction of ammonium that can be nitrified, K_{max}, is set to 0.40, based on a feedyard soil experiment (**Stewart, 1970**). In calculating a gas diffusivity coefficient (**Potter et al., 1996**), effective saturation porosity (equation 11.24) is used instead of total porosity, *PO* to account for the changes implemented in the soil water model when used for open lots (see **Ammonia Emission Open Lot** section). The lowest layer is also divided into five sublayers when computing nitrate leaching, with depths of 10, 15, 15, 30 and 30 cm. In addition to the assumed animal densities for beef and dairy open lot facilities (see **Ammonia Emission Open lot** section), the following assumptions are made in calculating the soil CO_2 flux (see **Carbon Dioxide** section): 1) an average 3-month accumulation of manure on open lots (i.e., based on a typical 6-month feeding cycle at beef feedyards); and 2) a manure carbon-to-nitrogen (C/N) ratio of 15. For facilities that combine free stall and dry lot use, half of the manure is assumed to be deposited in each.

Bedded Pack Barns

Temperature of the bedded pack is modeled because of its influence on *N* transformations, and consequently N_2O emissions. Even without aeration, microbial decomposition (also referred to as organic matter mineralization) taking place in a deep-bedded pack is high enough to raise bedded pack temperatures above ambient levels. As an example, **Spiehs et al. (2011)** reported average bedded pack temperatures of 15^{o}C, 19^{o}C, and 29^{o}C for periods with barn air temperatures of < 0^{o}C, 0^{o}C to 20.6^{o}C, and > 20.6^{o}C, respectively, which corresponded to average temperature differences between the bedded pack and barn air of 18^oC, 7^oC, and 5^oC, respectively. Compared to open lots, bedded pack barns have a greater potential for organic C and N mineralization because of wetter conditions and additional carbon from bedding.

In predicting *N* transformations and N_2O emissions for bedded pack barns, nitrification, denitrification, and leaching are modeled using equations for croplands and open lots (equations 13.39 to 13.53) whereas N decomposition is based on C decomposition. As it is a process parameter for both mineralization (**Shaffer et al., 1991**) and nitrification (equation 13.41), temperature can affect the amount of nitrate *N* that can be lost as N_2O through denitrification.

For compost barns, temperature at the surface of the bedded pack is similar to ambient air temperature while temperature within does not vary significantly with depth (**Barberg et al., 2007**). Bedded pack barns would likely have similar temperature profiles. Using simulated 33-cm deep non-aerated bedded packs, **Ayadi et al. (2015c)** reported median temperatures that varied with depth by 1.2^{o}C or less only. Therefore, in modeling temperature, the bedded pack is simulated as two layers: the surface layer (i.e., 1 cm depth) and the rest of the bedded pack. The depth of the bedded pack is approximated from amounts and properties of manure excreted and bedding applied. Similar to open lots, it is assumed that there is a 3-month accumulation of manure and bedding on bedded pack barns throughout the year, and the manure C/N ratio is set at 15.

The temperature model for bedded pack barns is adapted from **Cekmecelioglu et al. (2005)**. On a daily time step, bedded pack temperature is computed by considering heat gain from microbial decomposition and heat losses due to evaporation and convection. As bedded pack barns are covered structures, net heat gain or loss due to radiation is neglected. Following equation 9.14, calculation of heat gain involves simulation of C decomposition (equation 13.6) and CO_2-C respiration (equation 13.8). Evaporation heat loss is the product of the amount of water evaporated (equation 11.33) and the latent heat of evaporation (**Cekmecelioglu et al., 2005**) (equation 9.15). Following **Cekmecelioglu et al. (2005)**, convection heat loss is a function of the temperature difference between the bedded pack and ambient air.

For bedded packs, C decomposition is simulated for both manure and bedding. Unlike for croplands and open lots, K_{decomp} (in equation 13.6) for bedded packs is a function of temperature:

$$K_{decomp} = x_1 \left[1.066^{(T_{bp}+20)} - 1.21^{(T_{bp}-20)} \right] \qquad [13.54]$$

where

x_1 = effectiveness of decomposition rate, dimensionless

T_{bp} = bedded pack temperature, ^oC

Equation 13.54 is based on **Haug (1993)** modified to have the maximum decomposition rate at 30^oC. This modification is made to have simulated bedded pack temperatures agree with measurements by **Spiehs et al. (2011)**. Assuming that the decomposition rate for manure is four times that for bedding (e.g., difference in decomposition rates between metabolic and structural C in **DAYCENT (2007)**), x_1 is set to 1.35 x 10^{-3} for manure and 3.58 x 10^{-4} for bedding through refinement using measurements from simulated bedded packs **(Ayadi et al., 2015b)**.

However, the temperature model described above is limited to above freezing conditions only (**Cekmecelioglu et al., 2005**). Assuming that CO_2-C respiration (equations 13.6, 13.8, and 13.54) and water evaporation (equation 11.33) models perform appropriately in predicting heat gain and heat evaporation loss, respectively, a different approach in simulating convection heat loss is applied for periods with freezing ambient air temperatures. Convection heat loss is estimated through iteration, which involves the following steps: 1) a step heat transfer of 1 MJ from the bedded pack to the surface layer is applied; 2) based on **Barberg et al. (2007)**, heat loss from the surface layer to the atmosphere is simulated until the surface layer temperature is equal to ambient air temperature + 1^oC; and 3) the iteration cycle is repeated until the temperature difference between the surface layer and the rest of the bedded pack is less than 20^oC. Convection heat loss from this procedure, which is just the sum of all simulated heat losses in step 2, is lower than the corresponding value if based on **Cekmecelioglu et al. (2005)**. The 20^oC temperature difference criterion in step 3 is based on temperature observations by **Spiehs et al. (2011)**. In a one year-long simulation, this criterion led to temperature differences between the surface layer and the rest of the bedded pack ranging from 9^oC to 20^oC, with an average of 18^oC, and bedded pack temperatures ranging from 7^oC to 21^oC, with an average of 15^{o}C during conditions with freezing ambient air temperatures.

As particle density is an important parameter in modeling moisture contents (**Jones and Kiniry, 1986**), it can affect simulation of C decomposition (i.e., F_{decomp} in equation 13.6) and, therefore, bedded pack temperature. In the absence of published values appropriate for each manure-bedding material combination simulated in IFSM, particle density used in simulating the bedded pack is calculated on the first day of each simulation year:

$$\rho_p = \rho_{w,i} / (1 - PO_{air}) \qquad [13.55]$$

where

ρ_p = particle density, g/cm^3

$\rho_{w,i}$ = initial wet bulk density, g/cm^3

PO_{air} = air-filled porosity, fraction

The $\rho_{w,i}$ value is approximated from amounts of manure, bedding, and moisture in the bedded pack. At the start of simulation, a 65% wet-based moisture content is assumed based on yearly averages by **Spiehs et al. (2011)** and **NRCS South Dakota (2011)**. The PO_{air} is initially set to 0.45, which is approximated from gas pore space measurements by **Ayadi et al. (2015b)** for simulated bedded packs. The computed ρ_p is held constant throughout the simulation year.

With a slower decomposition rate for bedding, most of organic N that decomposes comes from manure and is approximated from decomposed manure C using a C/N ratio of 15. In simulating decomposition, a microbial C/N ratio requirement of 23.8 is assumed **(Shaffer et al., 1991)**. Given that microbial C/N ratio is higher than manure C/N ratio (i.e., N microbial requirement < N decomposed), some of decomposed N stays as NH_4^+ and becomes available for nitrification.

Nitrification for bedded packs is modeled using the equation for croplands (equation 13.41). Adapted from **DAYCENT (2007)**, the equation for F_{temp} in equation 13.41 was refined using ammonium concentration data by **Ayadi et al. (2015b)** and is given by:

$$F_{temp} = (-25^{o}C - T_{bp})/(-60^{o}C)^{1.5} \text{ x } exp[(1.5/18)(1-((-25^{o}C - T_{bp})/(-60^{o}C))^{18})] \qquad [13.56]$$

Using the above equation allows higher nitrification rates even at lower temperatures. With equations 13.54 and 13.56 incorporated in simulating decomposition (13.6) and nitrification (13.41), respectively, the model was able to predict the profile of ammonium concentration with time for simulated bedded packs at both low (10^{o}C) and high (40^{o}C) ambient temperature conditions **(Ayadi et al., 2015b)**. Assuming that trends of NH_4^+-N/NO_3^--N ratio for bedded packs are comparable to those for compost barns **(Shane et al., 2010)** (i.e., average NH_4^+-N/NO_3^--N ratios of 267 and 608 for summer and winter conditions, respectively), K_{max} in equation 13.41 is set to 2.67 x 10^{-4} for bedded packs.

Denitrification, and leaching are simulated using the same expressions used for open lots

(**Bonifacio et al., 2015**). However, the leaching routine is slightly revised for bedded pack barns such that nitrate within the bedded pack can move in both downward and upward directions depending on simulated water movement, and no nitrate leaches out of the bedded pack based on the assumption that the bedded pack barn is built with an impermeable floor (e.g., concrete slab, lining).

Enteric Emissions

Limited data indicate that a small amount of enteric N_2O is emitted by the animals (**Hamilton et al., 2010**). Based upon these data and similar experiments conducted at UC Davis, an emission rate of 0.8 g N_2O/kg N intake was established and used to predict this enteric emission from dairy cattle. For beef cattle, an emission rate of 2.2 g N_2O/kg N intake is used. The daily *N* intake of each animal group in the herd is determined in the animal component of the model (See **Herd and Feeding** section)

Manure Storage

Nitrous oxide emissions from stored slurry or liquid manure are predicted as a function of the exposed surface area of the manure storage. A proven process-based model was not available to represent this emission source, so a simpler approach is used. For an uncovered slurry storage tank, an average emission rate of 0.8 g N_2O/m^2-day determined by **Olesen et al. (2006)** is used to predict N_2O emissions as a function of the exposed surface area:

$$E_{N2O,manure} = E_{F,N2O,man} \cdot A_{storage} / 1000 \qquad [13.57]$$

where $E_{N2O,manure}$ = emission of N_2O from slurry storage, kg N_2O/day

$E_{F,N2O,man}$ = emission rate of N_2O, 0.8 g N_2O/m^2-day

$A_{storage}$ = exposed surface area of the manure storage, m^2

This relatively simple model is justified given the lack of available information to support a more complex model and because the N_2O emission from this type of manure storage is typically a relatively small portion of the whole farm emission of GHGs (**Olesen et al., 2006**).

The average emission rate of 0.8 g N_2O/m^2-day is applicable to bottom-loaded, uncovered slurry storage tanks where a natural crust forms on the manure surface. When a natural crust does not form, no N_2O is formed and emitted (**Chianese et al., 2009d**). A crust is assumed to not form if the manure DM content is less than 8%, manure is loaded onto the top of the stored slurry, or a covered or enclosed tank is used. Therefore, when any of these three options in manure handling are used, the emission rate is set to zero.

For stacked manure with a greater DM content, an emission factor of 0.005 kg N_2O-N/kg N excreted is used (**IPCC, 2006**). The excreted *N* stored in this manner is multiplied by this factor to predict a daily emission.

Grazing

Urine deposits in pasture are also a source of nitrous oxide emissions (**IPCC, 2006; Snell et al., 2014; van Groenigen et al., 2005**). While grazing, urine excreted by animals on pastures either infiltrates into the soil or stays on the surface depending on soil conditions (see **Ammonia Emission** section). Through hydrolysis, urine *N* on the surface becomes available for volatilization (see **Ammonia Emission** section) and urine *N* that infiltrates into the soil undergoes further transformation processes. Through soil nitrification and denitrification, *N* in urine spots can be lost to the environment in forms of dinitrogen, nitrogen oxide, and nitrous oxide emissions.

The same set of equations for nitrification and denitrification (equations 13.39 to 13.50) are used to predict N_2O emissions from urine deposits on pastures. Compared to N_2O prediction for croplands and open lots, however, there are few assumptions applied to make the simulation simpler for pastures. Each day the animals spend time on the pasture, urine is excreted in new spots, and thus the total area of urine spots increases. Ammonium considered in predicting N_2O emissions due to grazing is urinary urea *N* and urinary and fecal ammoniacal *N* that infiltrates into the soil (equations 11.38 to 11.39). In calculating the nitrification rate (equation 13.41), surface pH of urine spots is set to 8.5 (**Haynes and Williams, 1992**). Denitrification is simulated only for the upper 15 cm of soil under urine spots, and nitrate leaching is not considered. Concentrations of ammonium and nitrate used in calculating nitrification and denitrification rates, respectively, are based on the total amount of each *N* present in urine spots. Also, the amount of carbon needed in calculating soil CO_2 flux (see **Carbon Dioxide** section) is equal to the sum of carbon contents of feces and urine, estimated from the fecal and urine *N* contents using C/N ratios of 15 and 0.8, respectively.

The N_2O, NO and N_2 emitted from urine spots is added to that predicted from other sources in the pasture as determined through simulation of the pasture using the cropland component. These sources include the fecal *N* deposited, any fertilizer or additional manure applied, deposition through precipitation, decomposition of crop residue, and any urinary *N* that has leached to the lower layers. Summation of the *N* lost from each pasture source provides the total emission for grazing cattle.

Table 13.1- Daily Respiration Rates

Daily respiration rates used in IFSM as obtained from DAYCENT Version 4.5.

Source of C[a]	Daily respiration rate[b] [g C respired g^{-1} C flow]
Structural	
Surface pool (to microbial pool)	0.45
Surface pool (to slow SOM pool)	0.30
Soil pool (to microbial pool)	0.55
Soil pool (to slow SOM pool)	0.30
Metabolic	
Surface and soil pools	0.55
Microbial	
Surface pool	0.6
Soil pool	$0.17 + 0.68(F_{clay})$[c]
Passive pool	0.55
Slow pool	0.55

[a] Source of C represents the pool where the C originates, i.e the respiration rate for "Surface pool (to microbial pool)" represents the fraction of C respired as CO_2 of the total C leaving the surface structural pool.

[b] Respiration rates were obtained from DAYCENT version 4.5 input files.

[c] The respiration rate for the soil microbial pool is a function of F_{clay}, the soil clay content.

Table 13.2-Feed Relationships to Starch and ADF

Relationships used to model starch and ADF contents of feeds in IFSM.

Feed type	Starch[a],[b] [fraction]	ADF [fraction]
Alfalfa hay	$0.64*(1-F_{NDF}-F_{CP}-0.11)$	$0.78*F_{NDF}$
Alfalfa silage	$0.89*(1-F_{NDF}-F_{CP}-0.12)$	$0.82*F_{NDF}$
Grass hay	$0.45*(1-F_{NDF}-F_{CP}-0.11)$	$0.61*F_{NDF}$
Grass silage	$0.65*(1-F_{NDF}-F_{CP}-0.12)$	$0.64*F_{NDF}$
Corn grain	0.68	0.036
High moisture corn	0.52	0.004
Corn silage	$0.80*(1-F_{NDF}-F_{CP}-0.07)$	$0.62*F_{NDF}$
Perennial grass/legume	$0.48*(1-F_{NDF}-F_{CP}-0.14)$	$0.72*F_{NDF}$
Alfalfa pasture	$0.48*(1- F_{NDF}-F_{CP}-0.14)$	$0.55*F_{NDF}$
Protein supplement 1	0.0	0.0
Protein supplement 2	0.0	0.0
Fat additive	0.0	0.0

[a] The last value in the equations developed to predict starch content represents an average total of fat plus ash contents for the given feed. Typical values for fat and ash were obtained from NRC (2001).

[b] F_{NDF} (fraction of neutral detergent fiber in feed) and F_{CP} (fraction of crude protein in feed) are available in IFSM.

Table 13.3 - Parameters for Manure Storage Emissions Model

Parameters and values for the manure storage emissions model of **Sommer et al. (2004)**.

Parameter	Variable	Value	Units
Volatile solids content[a]	P_{VS}	0.726, 0.698, 0.68[b]	g VS g^{-1} TS
Achievable CH_4[c]	B_o	0.2	g CH_4 g^{-1} VS
Potential CH_4[c]	$E_{CH4,pot}$	0.48	g CH_4 g^{-1} VS
Correcting factors[c]	b_1, b_2	1.0, 0.01	dimensionless
Arrhenius parameter[c]	ln(A)	43.33	dimensionless
Activation energy[c]	E	112,700	J mol^{-1}
Gas constant[c]	R	8.314	J K^{-1} mol^{-1}

[a] From USDA-SCS (1999).

[b] Values for heifers, dry cows, and lactating cows.

[c] From Sommer et al. (2004).

Table 13.4-Average Methane Emission Rates from Feces

Published and average emission rates of CH_4 emitted from feces directly deposited by animals on pasture lands.

Reference	Emission rate [g CH4 kg^{-1} feces]
Jarvis et al. (1995)	0.110
Flessa et al. (1996)	0.130
Holter (1997)	0.068
Yamulki et al. (1999)	0.036
Average	0.086

Figure 13.1 - Carbon Flow Diagram for Carbon Module

Carbon flow diagram for the C module incorporated into IFSM (modified from **Parton et al., 1994**).

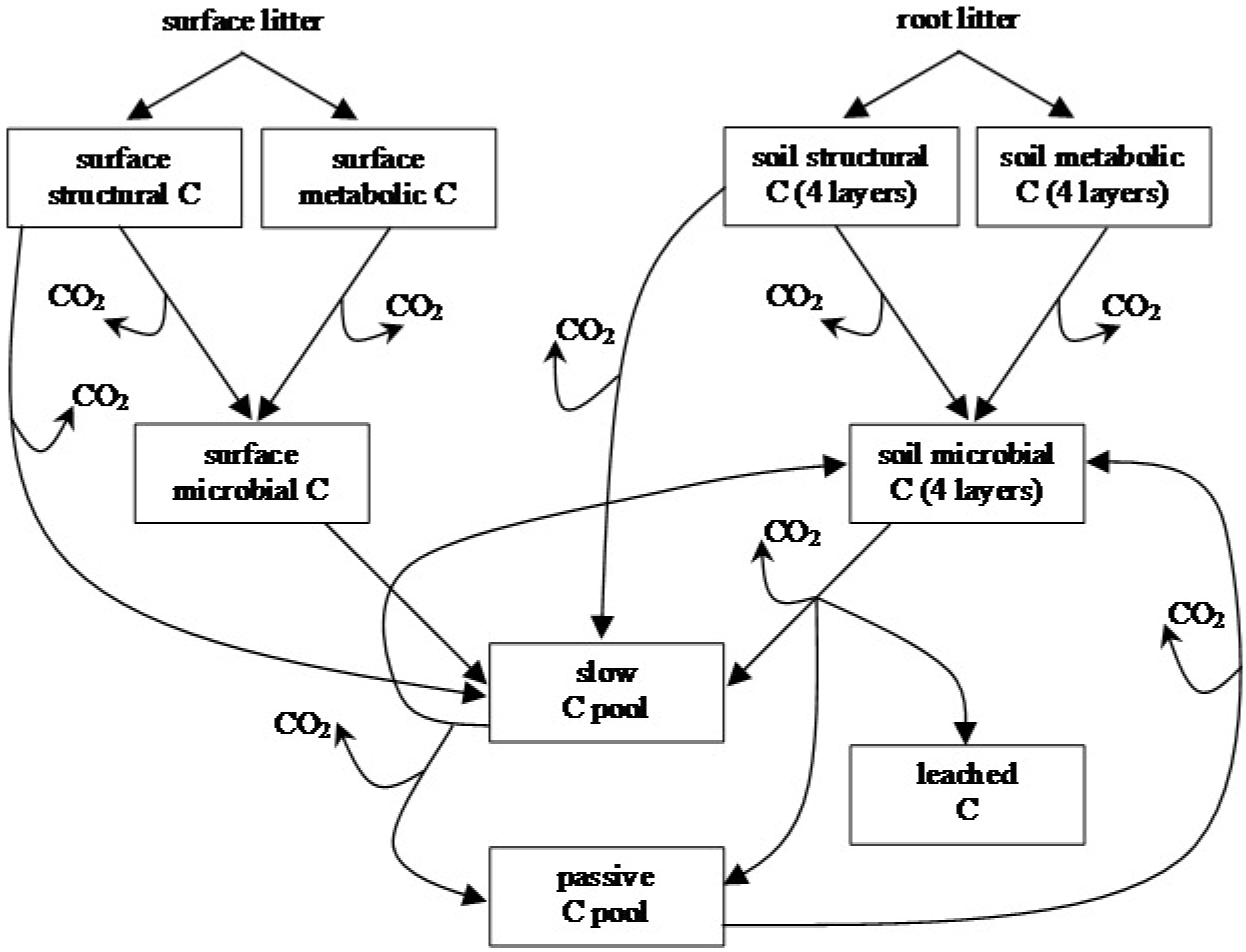


Figure 13.2 - Pathway of Denitrification in Soils

Pathway of denitrification in soils **(Parton et al., 1996).**

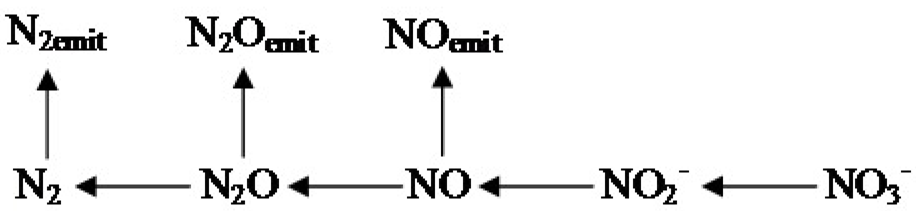


Figure 13.3- Pathway of Nitrification in Soils

Pathway of nitrification in soils. Dashed lines and square brackets indicate incompletely understood processes and intermediates (**Parton et al., 1996**).

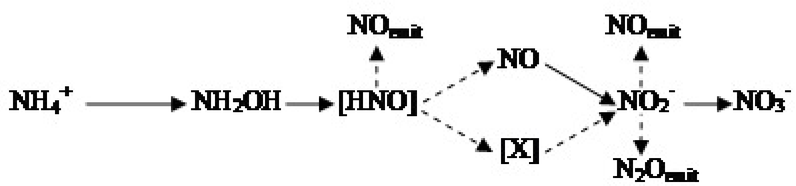
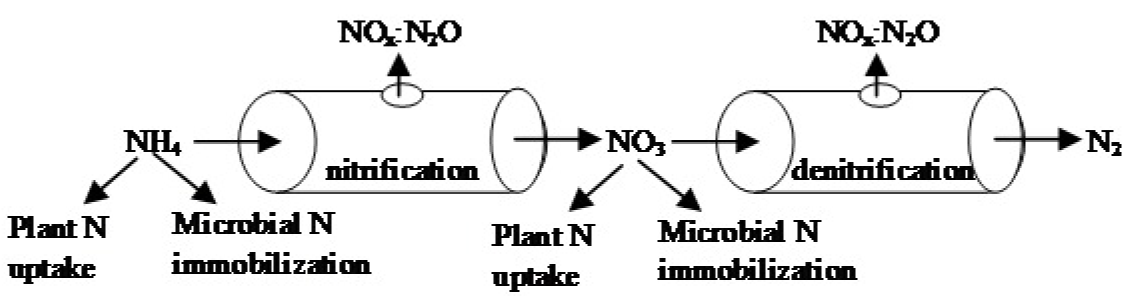


Figure 13.4 - Model of Nitrogen Gas Emissions from Soil

Conceptual model of controls on N gas emissions from soil using the leaky pipe metaphor (**Parton et al., 2001**).



Volatile Organic Compounds

Emissions of volatile organic compounds (VOCs) from farms can contribute to the formation of ground-level ozone and other components of photochemical smog. Silage has been identified as a significant source of VOC emissions from farms, but manure also contributes. Development of emission inventories requires estimates of VOC emissions, but on-farm measurement is difficult and expensive. Simulation of emission processes provides an alternative method for estimating VOC emissions. Integration of VOC emission processes in IFSM provides a tool for estimating whole farm emissions and evaluating the effects of alternative management strategies for mitigating those emissions along with other environmental and economic impacts.

The contribution of a particular VOC to ozone formation is determined by the emission rate of the compound and its reactivity in the atmosphere. Following physical and chemical principles, emission rates are controlled by the concentration of VOCs in silage or manure and their volatility (Henry's law constant). A compound's volatility will control emission rate when the concentration is not limiting. When the concentration is limiting, i.e., when cumulative emission approaches the total quantity of a compound present, volatility is less important. These relationships are described in more detail in **Hafner et al. (2012)** and **Hafner et al. (2013).**

Silage Sources

Although many different organic compounds are emitted from silage, alcohols (which can be formed by both bacteria and yeasts) appear to be the most important (Howard et al., 2010; Hafner et al., 2013). To represent total VOC emission, we consider four groups of VOCs which have the most potential to contribute to poor air quality: acids, alcohols, esters, and aldehydes (Hafner et al., 2013). On farms, VOC emission from silage is determined by the production of VOCs in silage and the amount of each compound that is volatilized. VOC production can vary greatly among silages, and the sources of this variability are not yet known (Hafner et al., 2013). Therefore, in our model, VOC production is set based on typical values for different types of silage. From these fixed initial concentrations, we simulate VOC emissions.

For each VOC group, a given concentration in silage after fermentation is assigned. Emission losses are predicted and the remaining VOC mass is tracked as silage moves through three stages: storage removal (when silage is exposed following daily or more frequent feed removal), feed mixing, and feeding. VOC emission during storage removal and mixing reduces the concentration of VOCs present in the remaining stages. From the storage face and during feeding, cumulative VOC emission is determined over a defined exposure period using a numerical solution to the convection-diffusion model described by Hafner et al. (2012). Description of the numerical solution is provided in Bonifacio et al. (in review). VOC emission from the mixing stage is simply based on the assumption that all VOC in the gaseous phase of silage is lost during mixing (Bonifacio et al., in review).

Emission processes

Simulation of VOC emissions from silage storages and feed lanes is based on the convection-diffusion model by **Hafner et al. (2012).** In this model, silage emissions take place from exposed surfaces through convection, but VOC molecules from deeper layers are lost as well once transported to the surface through dispersion or diffusion **(Hafner et al., 2010; Hafner et al., 2012)**. To simplify simulation of VOC emissions, assumptions include no VOC production/destruction after fermentation (i.e., once storage is opened), no VOC sorption to particles, and equilibrium partitioning between gas and aqueous phases **(Hafner et al., 2012).**

The governing equations defining the convection-diffusion model can be solved analytically **(Hafner et al., 2012)** and numerically **(Bonifacio et al., in review).** However, analytical and numerical solutions are both computationally intensive in nature. Thus, the simulation model described below is basically a numerical solution implemented using a very coarse computational domain (2 to 3 simulation layers only) and time step (1 hour) instead of using a fine resolution (e.g., 1-mm grid size, 1-sec time step) typical of numerical solutions.

For storages and feed lanes, the overall modeling approach for VOC emissions is illustrated in **Fig. 14.1**. Simulation inputs include silage source type (storage or feed lanes) and meteorological parameters (temperature and wind speed). Silage source type is used in setting bulk density, moisture content, and exposed surface area. Initial VOC concentrations for storages are fixed regardless of storage type while those for feed lanes depend on the remaining silage VOC mass after simulating losses during silage removal and feed mixing. The mass of VOC is transferred from a simulation layer to the adjacent outward layer by diffusion. Through convection, the mass of VOC is emitted from the surface (i.e., first simulation layer) of the silage source. VOC emission from the surface and transport within silage is performed on an hourly time step.

Following **Hafner et al. (2012),** the hourly flux of VOC emitted from the surface of the silage source is given by:

$$j_{sur} = 3600\ \alpha C_{b,sur} \qquad [14.1]$$

where j_{sur} = hourly VOC emission flux, g/m^2-hr

α = effective surface mass transfer coefficient, m/s

$C_{b,sur}$ = bulk concentration at the silage surface (first simulation layer), g/m^3.

It is assumed that VOC concentration in the ambient air is negligible. Hourly flux of VOC transferred from one layer to the adjacent upper layer is calculated as:

$$j = -3600\ D(C_{b,l+1} - C_{b,l})/\Delta x \qquad [14.2]$$

where j = hourly VOC transport flux, g/m^2-hr

D = effective diffusion coefficient, m^2/s

$C_{b,l+1}$, $C_{b,l}$ = bulk concentrations for layers l+1 and l, respectively, g/m^3

Dx = depth from the midpoint to the top edge of layer l, m.

Effective transport parameters are related to gas-phase values (**Hafner et al., 2012**):

$$D = E_{sg} / (H\rho_w w + \Phi) \qquad [14.3]$$

$$\alpha = K_g / (H\rho_w w + \Phi) \qquad [14.4]$$

where E_{sq} = diffusion-dispersion coefficient for VOCs through silage gas pores, m^2/s

K_g = surface mass transfer coefficient, m/s

c_b = bulk volumetric concentration of a VOC group, g/m^3

ρ_w = wet silage density, kg/m^3

w = gravimetric water content of silage, kg/kg

Φ = gas-phase porosity, m^3/m^3.

VOCs in aqueous and gas phases are assumed to be in equilibrium at all times and locations (**Hafner et al., 2012**) and VOC partitioning between these two phases is based on Henry's Law:

$$K_H = m/P \qquad [14.5]$$

where K_H = Henry's constant, mol/kg-atm

m = molal concentration of VOC, mol/kg

P = partial pressure of VOC in equilibrium with m, atm.

Following **Warneck (2006),** K_H can also be written as:

$$K_H = 1 / (P_{sat} MW_{H2O}) \qquad [14.6]$$

where P_{sat} = saturated vapor pressure of VOC, atm

MW_{H2O} = molecular weight of water, 18 g/mol

Since mass transfer calculations are based on concentrations, it is useful to transform the Henry's law constant into one based on concentrations (i.e., aqueous mol/kg per gaseous mol/m = m^3/kg):

$$H = m/c_g \qquad [14.7]$$

$$H = K_H R T \qquad [14.8]$$

where H = concentration-based Henry's law constant, m^3/kg

c_g = gas-phase concentration

R = universal gas constant, 8.2057 × 10^{-5} m^3 atm/K-mol.

The computational domains for silage storages and feed lanes are set-up through refinement using experimental data from **Montes et al. (2010)** and **Hafner et al. (2010)** (**Bonifacio et al., in review**). For silage storages, only the first 1 m from the surface (silo face) is considered – this 1 m is simulated in 3 layers. Depths for these 3 layers are functions of friction velocity and dry bulk density:

$$d_1 = (9.21 \text{ x } 10^{-3} - r_{dry}(1.47 \text{ x } 10^{-5})) + 1053.6 U r_{dry}^{-1.668} \qquad [14.9]$$

$$d_2 = 40.5 U r_{dry}^{-1.336} \qquad [14.10]$$

$$d_3 = 1.0 - (d_1 + d_2) \qquad [14.11]$$

where d_1, d_2, and d_3 = depths for first (surface), second, and third layers, respectively, m

U = friction velocity, m/s

r_{dry} = silage dry bulk density, kg/m^3.

For feed lanes, the depth of the feed is set constant at 0.15 m, which is simulated as two layers. Depths for these layers are given by:

$$d_1 = max(4.7 \text{ x } 10^{-3}, 1.23 \text{ x } 10^{-2} - r_{dry}(5.87 \text{ x } 10^{-5})) + U(1.469 - 0.263\ln r_{dry}) \quad [14.12]$$

$$d_2 = 0.15 - d_1 \quad [14.13]$$

Derivation of these depth equations for storages and feed lanes is described in **Bonifacio et al. (in review).** As these equations were derived using ethanol emission measurement data (**Hafner et al., 2010; Montes et al., 2010**), calculated depths are adjusted when simulating other VOCs to account for the difference in volatility relative to ethanol.

For feed mixing, it is assumed that all gas-phase VOCs in the silage are lost during mixing. Effects of mixer operating parameters and presence of other feed ingredients on silage VOC emissions during mixing are neglected. The initial mass of VOC in silage to be mixed with other total mixed ration (TMR) feed ingredients is the average concentration for the total depth removed from the face of the silage storage (i.e., after accounting for VOC losses from the silo face). With very short mixing time (i.e., several minutes only), simulation of VOC emissions from feed mixing is done on a per load basis, with the number of loads approximated from the total weight of TMR feed ingredients to be mixed and feed mixer capacity.

Equal to the total mass of gas-phase VOCs in the silage prior to mixing, total VOC loss due to feed mixing is given by (**Bonifacio et al., in review**):

$$j_{mix} = C_g V_g \quad [14.14]$$

where j_{mix} = mass of VOC loss, g

C_g = gas-phase VOC concentration, g/m^3

Vg = silage gas-filled pores volume, m^3.

C_g is approximated from bulk concentration following **Hafner et al. (2012)** and V_g is the product of feed mixer capacity and gas-phase porosity (Φ) of silage during storage (prior to being mixed with other feed ingredients). Calculation of Φ follows the procedure of **Hafner et al. (2012).**

Calculated emissions from the four groups of compounds are aggregated after normalizing emissions based on the ozone formation potential of each group. Normalized emission for a VOC group is calculated as:

$$M_{O3} = r\, M_{VOC} \quad [14.15]$$

where M_{O3} = potential ozone forming emission, kg O_3

r = Equal Benefit Incremental Reactivity, kg O_3 per kg VOC

M_{VOC} = mass of VOC emitted, kg VOC.

The Equal Benefit Incremental Reactivity (EBIR) is a measure of the ozone formation potential of VOCs that is more suitable for rural environments than that of the maximum incremental reactivity (MIR).

Emission parameters

Characteristics of each VOC group were assigned based upon available data. With the exception of acids, data on VOC concentrations within silage are limited. Mean VOC concentrations from a compilation of silage data (**Hafner et al. 2013**) are presented in **Table 14.1**. Data for alcohols include ethanol, 1-propanol, methanol, and other alcohols for corn and grass silage, but only ethanol for other feeds. Aldehyde data include acetaldehydes and several others for corn, grass, and alfalfa. Several esters have been measured in corn and grass silage, but not in other types of silage. We estimated concentrations for groups for which data were not available based on measurements for other silages.Aldehyde data include acetaldehydes and several others for corn, grass, and alfalfa. Several esters have been measured in corn and grass silage, but not in other types of silage. We estimated concentrations for groups for which data were not available based on measurements for other silages.

The Henry's law constant is based on a single representative compound for each group: acetic acid (CAS number 64-19-7) for acids, ethanol (CAS 64-17-5) for alcohols, ethyl acetate (CAS 14178-6) for esters, and acetaldehyde (ethanal; CAS 75-07-0) for aldehydes. In calculating the Henry's law constant (Eq. 14.6), P_{sat} for the representative compounds is computed using the Antoine equation:

$$P_{sat} = 10^{(A - B/(C+T))} / 760 \qquad [14.16]$$

where A, B, and C = compound-specific parameters

T = temperature, °C.

Values used for A, B, and C for the representative compounds are obtained from **DDBST (2015)** and **NIST (2015)** (summarized in Table S-2 of **Bonifacio et al., in review**).

To determine K_g and E_{sg}, we use relationships derived using ethanol measurement data of **Montes et al. (2010)** and validated using data of **Hafner et al. (2010).** Both parameters are functions of and are given by:

$$K_g = 0.0002 + 0.1625U - 0.1257U^2 \qquad [14.17]$$

$$E_{sg} = (0.0256 + 7.82U) \times 10^{-4} \qquad [14.18]$$

Derivation of these equations is described in **Bonifacio et al. (in review).** Similar to the computational domain, calculated K_g and E_{sg} are adjusted when simulating other VOCs to account for the difference in volatility relative to ethanol.

Equal Benefit Incremental Reactivity values used to aggregate emissions were assigned based upon the work of **Carter (2009)** (**Table 14.2**). The potential ozone formation from each VOC group (M_{O3}) is summed over all groups to give an estimate of the total potential ozone formation from the emitted VOCs.

Farm processes

VOC emissions are determined for each silage source on the farm each year at the completion of the storage period. As shown in **Fig. 14.1**, input parameters include silage source properties (bulk density, moisture content, exposed surface area, and initial concentrations), daily ambient temperature, and wind speed. These parameters are based on user-inputs or computed in other components of IFSM. Silage bulk density and moisture content are modeled from the type of silage storage facility used and the characteristics of the crop harvested. Exposed surface area for the silo face is computed from the size of the storage facility whereas for feed lanes, this is based on the number of feedings per day and the amount of TMR delivered per feeding. Initial concentrations at the start of simulation are set based on the type of feed stored (**Table 14.1**). Effective wind speed is a function of the type of structure where silage is stored or the type of barn where animals are fed for feed lanes.

Daily emissions are determined for each silage source through 365 days of weather for each simulated year. For each storage, emissions of each VOC group are predicted for each day in which silage is being removed, using the emission process relationships described above (Eqs. 14.1 to 14.13). Emissions are first determined for the silage face exposed to the ambient atmosphere. The portion of each VOC group emitted is removed from the silage and the mass is moved to the feed mixer. Emissions from the mixer are than predicted (Eq. 14.14), losses of each VOC group are removed, and the remaining mass moves to the feed bunk. Emissions continue from the feed bunk until the feed is consumed. The temperature of the silage and surrounding air at each stage is the average daily ambient temperature.

Five different types of storage structures are considered: stave tower silo, sealed tower silo, bunker, silage bag, and bale silage. Sealed tower silos are assumed to be open during feed removal for only two hours per day, and the air speed across the face is assumed to be very low (0.01 m/s). The air speed is also set to this low value for bale silage where removal from storage is essentially immediate. Because of complexities in estimating reduction in the wind speed profile due to the presence of structures, air speed for all other storages during silage removal is set to 70% of the ambient wind speed. Required in calculating transport coefficients and the computational domain, U is calculated from the effective air speed using Eq. 11.10. Other information needed to calculate emissions from the silo face are silage bulk density, dry matter content (i.e., moisture content), and the exposed surface area. For tower silos, density is calculated as a function of silo height and for bunker silos, density is a function of the moisture content of the silage entering the silo (**Savoie and Jofriet, 2003**). For bagged silage and bale silage, wet densities are 550 and 450 kg/m^3, respectively. Silage dry matter content is determined in the silage component of IFSM based upon the harvest moisture content and storage conditions (see Silo Storage section). The exposed surface area is calculated from the radius of tower silos and bagged silage or the width and settled depth of bunker silos.

For feed lanes, density of the TMR is set to 160 kg/m^3 and dry matter content to 55% (i.e., 45% moisture content). Air speed setting and U calculation are based on the type of animal housing. For open lots, air speed is set at ambient wind speed and U is calculated using Eq. 11.10. For mechanically ventilated barns, air speed is calculated from ambient temperature (Eq. 11.19), with U also calculated using Eq. 11.10. For naturally ventilated barns, effective air speed inside the barn is set to 20% of the ambient wind speed (**Stowell et al., 2001**) to represent the decrease in air speed due to the presence of the structure and animals. Calculation of U is based on the log wind profile:

$$U = kV/\ln(z/z_f) \qquad [14.19]$$

where V = air speed at animal height, m/s

k = von Karman's constant, 0.4

z = animal height, m

z_f = surface roughness of feed, m.

In the simulation, animal height is set at 1.2 m and surface roughness of feed is assumed to be 25% of the total feed depth (15 cm).

The exposed surface area for feed lanes is calculated from the amount of feed delivered per feeding, TMR density, and feed depth. But as the amount of feed in feed lanes is consumed by animals over time, the decrease in the exposed surface area is simulated. For beef farms, feed is delivered 3x/day with the feed consumed within 2 hours after delivery. It is assumed that the exposed surface area decreases by half on the 2nd hour after delivery. Animals in dairy farms is simulated to have access to the feed 24 hours a day and feed is delivered once. Based on the observations of **DeVries et al. (2005)** on animal feeding behavior, the exposed surface area for feed lanes over time is computed as:

$$A_{feed} = A_i \,' \; [1.0\ (0.10 + (2.1/p)\ \tan^{-1}(0.04p(Ft - 2.0)))] \qquad [14.20]$$

where A_{feed} = exposed area, m^2

A_i = initial exposed area of the feed (at the start of feeding), m^2

F = number of feedings per day,

t = n^{th} hour after feed delivery.

In the simulation, the minimum value of A_{feed} is set to 10% of A_i.

For feed mixing, the number of loadings per day is calculated from the total amount of TMR to be fed within the day and feed mixer capacity. In IFSM, the total amount of TMR to be fed is based on animal groups and numbers, nutrient requirements, and feed availability. Default capacities for small, medium, and large feed mixers are 7.0, 8.5, and 12.0 tonnes.

Output from the silage VOC model includes daily emissions of each of the four VOC groups (kg of VOC) and corresponding daily values of the potential ozone formed (kg ozone, based on EBIR). Daily values of the four VOC groups are summed to obtain a total daily value.

Manure Sources

Several VOCs have been measured in cattle manure, and these measured compounds fall within three groups: acids, alcohols, and aromatics (**Table 14.3**). It is not clear if other compounds are present at much lower concentrations or if other compounds simply have not been measured within manure. Emissions of other VOCs have been measured indicating their presence in some form.

In general, volatile fatty acids are the most concentrated VOCs in manure (**Fig. 14.2**). However, their importance for ozone formation is reduced by ionization in solution (which effectively lowers volatility) and low reactivity. Ethanol has been measured at high concentrations in some cases, and is the only alcohol that has been measured in multiple studies. Measurements suggest that concentrations of most aromatic compounds are lower than concentrations of acids and alcohols, although some compounds may be present at high concentrations.

Measurement of VOC concentrations in manure during incubations has shown that production and consumption of organic compounds significantly impact VOC concentrations. In incubations of beef manure at room temperature, **Varel et al. (2010)** found that alcohol concentrations doubled within a few days, and acetic acid concentrations more than doubled over two weeks. Alcohol concentrations began to decline after a week of incubation, and the total alcohol concentration (mostly ethanol) was less than half of the initial concentration after four weeks. Aromatic compounds showed less change over time.

These production processes complicate modeling efforts. The magnitude of changes in VOC concentrations during manure storage are probably dependent on numerous variables, including cattle feed, manure handling and storage, and weather. With only limited data on changes in VOC concentrations over time, it is not currently possible to develop a robust model for predicting these changes, so fixed initial concentrations are used. Since the goal of our model is to predict the impact of manure handling strategies on emissions, initial concentrations are not particularly important as long as reasonable levels are assumed.

Volatility, reactivity, and implications for emission and ozone formation

The principles of volatility and reactivity were incorporated into two indices for estimating the relative importance of VOCs with regard to emission rate and ozone formation. Concentration alone provides an indication of the total mass available for emission, and therefore can serve as an index of relative emission (mass units) when concentrations are limiting. The second index is the product of concentration and Henry's law constant, which indicates the emission rate potential (mass units) when concentration is not limiting.

For manure in the barn, where exposure time is short, the second index (which includes volatility) seems most relevant. For stored manure, where exposure time is long but the depth of manure is high, volatility is also likely controlling, since it is unlikely that emission loss will be high enough for concentrations to be limiting. For field-applied manure, where losses of moderately- to highly-volatile compounds may approach 100%, an index without volatility seems most relevant.

Volatility of the compounds found in manure varies widely (**Table 14.4**). Alcohols have the highest volatility of the compounds considered. Reactivity also varies widely. In general, aromatic compounds have higher MIR values than alcohols and acids. However, this pattern is not true for EBIR, for which some aromatic compounds have negative values.

Alcohols have the highest emission potential (product of concentration and Henry's law constant), although variability is high, reflecting the variability in concentrations (**Fig. 14.3**). The acid (acetic acid) and aromatic (cresol) with the highest values have mean values about 10% of that of ethanol.

We considered MIR and EBIR to evaluate reactivity and ozone forming potential (**Table 14.4**). The relationship among the compounds differs substantially among the indices; no one compound dominated in all cases. Considering reactivity and concentration, acids are the most important compounds for index 1, but for index 2 (with volatility included) alcohols are most important. Ethanol is the most important alcohol for both indices. Aromatic compounds generally have low values, with some exceptions. For index 1, the aromatic acids approach the values of some acids. For index 2, values of cresol and skatole are within a factor of 10 of the value for ethanol, while the indices of all acids are low.

Assuming that concentration and volatility control emission rates, these results suggest that alcohols, and ethanol in particular, are the most important VOCs emitted from manure, in terms of both mass emitted and ozone formation potential. This conclusion is consistent with emission measurements. Results suggest that some compounds can be ignored, but, unfortunately, numerous compounds in each group have the potential to make a significant contribution to ozone formation.

Based upon concentration, volatility and reactivity, five groups of compounds are defined as important: two groups of acids, one group of alcohols, and two groups of aromatics. Including each individual compound may provide a more accurate model, but given the large uncertainty in concentrations of VOCs in manure, this accuracy would not be realized. Furthermore, a lumped parameter approach provides a more usable model. Bulk concentrations of compounds are fixed as constant, or set at an initial value and allowed to decline due to emission with a fixed time step. Initial VOC concentrations for fresh manure within the barn are set at different levels (typically lower) than for manure in storage, to reflect an accumulation of VOCs over time (**Table 14.3**).

Ethanol is used as the representative compound for alcohols. Two groups are used for acids to capture differences in volatility and reactivity: C2 and C3 acids (group 1), and C4 acids (group 2). Two groups are also used for aromatic compounds: aromatic acids and others, since the acids are generally less volatile than the other aromatic compounds present in manure. Parameter values for these five groups are given in **Table 14.5**.

Emission processes

Emission is modeled using a two-film model with an additional resistance term that incorporates any gradient below the liquid film as well as resistance due to a surface cover or crust:

$$j = K\,c \qquad [14.21]$$

where j = VOC flux, g/m^2- s

K = overall mass transfer coefficient in aqueous phase units, m/s

c = VOC concentration in manure, g/m^3.

This relationship assumes that the VOC concentrations in the ambient air are negligible. The overall mass transfer coefficient is given by:

$$K = 1 \,/\, (\, (H / k_g) + 1/\,k_l + R_m\,) \qquad [14.22]$$

where k = individual mass transfer coefficients for the gas (g) and liquid (l) films, m/s

R_m = additional resistance term, s/m

For the alcohol and aromatic groups, c in Eq. 14.21 is the total aqueous volumetric concentration of each group. For the acid groups, ionization must be considered:

$$RCOOH \leftrightarrow RCOO^- + H^+ \qquad [14.23]$$

For a given group of acids, the fraction of the total concentration in the free form (α) is determined as:

$$\alpha = 1 - \gamma_{RCOO}\, K_a \,/\, (10^{-pH} + K_a) \qquad [14.24]$$

where K_a = dissociation constant, dimensionless

γ_{RCOO} = activity coefficient of the ionized species, dimensionless

pH = solution pH, taken as the activity of H$^+$

We assume that γ_{RCOO} is 0.7.

Calculation of the mass transfer coefficients for both gas and liquid phases follows the procedure used for modeling ammonia emission (see **Ammonia Emission** section). The gas phase mass transfer coefficient is related to air velocity near the surface based on the correlation of **MacKay and Yuen (1983):**

$$k_g = 0.001 + 0.0462\; U \cdot SC^{-0.67} \qquad [14.25]$$

where U = friction velocity, m/s

SC = Schmidt number, dimensionless

Friction velocity is given by:

$$U = 0.02\ V_g^{\ 1.5} \qquad [14.26]$$

where V_g = ambient air velocity measured at a 10 m height.

Determination of the liquid-phase mass transfer coefficient is more difficult. Correlations have been developed for solutions, but the higher viscosity of manure is expected to increase the thickness of the liquid film. The liquid mass transfer coefficient (k_l, m/s) is determined as a function of temperature:

$$k_l = 1.417 \times 10^{-12}\ (T^4) \qquad [14.27]$$

where T = temperature (K).

Farm processes

VOC emissions can occur from manure in the housing facility, during long term storage, following land application and from feces deposited on pasture. Each of these processes is simulated on an hourly or daily time step, and daily emissions from each VOC group are converted to potential ozone forming units using the EBIR. Daily emissions are summed to give an annual emission from each manure source.

Daily VOC emissions from the housing facility are predicted using a procedure similar to that used to predict ammonia emissions (see **Ammonia Emission section**). Emissions are determined for each hour of the day using Eq. 14.21 to 14.26. Hourly ambient temperature throughout the day is set as a function of maximum and minimum daily temperatures using Eq. 11.17 and 11.18. Air and manure temperature within barns is determined as a function of the ambient temperature using Eq. 11.16. For outdoor facilities, the temperature is the ambient temperature. The air velocity is equal to the average daily wind speed for outdoor facilities and half the ambient wind speed for open structures. For enclosed barns, air velocity is a function of ventilation rate which is directly related to ambient temperature (Eq. 11.19). Surface pH of the manure is set as determined in the ammonia emission routine. For most barn types, the surface pH is 0.7 units greater than the bulk manure pH.

VOC concentration in the manure decreases each hour following excretion, i.e. the initial concentration is reduced each hour by the amount volatilized. At the end of 24 h, the amount and concentration of each VOC group remaining moves into long term storage or they provide the amount applied through daily spreading of manure.

When long term manure storage is used, emissions of each VOC group are again predicted each hour using Eq. 14.21 to 14.26. Air velocity over the storage is set to the average wind speed of the day. Temperature throughout the day is predicted using Eq. 11.17 and 11.18. Bulk manure pH and surface pH are determined as a function of manure dry matter content using Eq. 11.35 and 11.36. The amount of each VOC group in the storage is tracked by adding that coming into the storage and subtracting that emitted. When the storage is emptied, these amounts are reset. Hourly emissions are totaled to give daily and annual emissions of each VOC group.

Covers are sometimes used on manure storages. To represent cover effects, an additional transfer resistance is included in Eq. 14.16. For lack of better information, resistance values are those used to represent the effect on ammonia emission from covered storages (see **Ammonia Emission section**).

Emissions following field application are determined on a 2 h time step beginning the day of application and continuing until the manure is incorporated into the soil. With incorporation, all emissions are assumed to cease. Emissions are predicted using Eq. 14.15 to 14.20 and mean daily air temperature and wind velocity. Manure pH increases to 8.6 immediately following application due to the rapid release of CO_2 (see **Ammonia Emission section**). As the manure dries in the field, the pH decreases at a rate of 0.3 units per time step until it reaches a neutral pH of 7.0. Emissions for each time step are totaled for each VOC group.

Field emissions are also affected by infiltration of the manure into the soil. Following the procedure used to predict ammonia emission, the infiltration rate is a function of the dry matter content of the manure (Eq. 11.37). When rain occurs, the dry matter content is reduced in proportion to the amount of rain, and this increases the infiltration rate (see **Ammonia Emission section**). The VOCs contained in the portion of the manure that infiltrates into the soil are no longer available for volatilization.

Feces deposits are the only VOC source considered from pasture. This source is tracked on a daily time step for up to 15 days following excretion. Emissions are predicted for each VOC group using equations 14.21 to 14.26. Temperature and air velocity are set to the mean daily ambient temperature and wind speed. Surface pH of the manure pat is set at 0.5 units greater than the bulk pH or about 8.0. As the manure dries, an additional transfer resistance is assumed to increase by 2×10^5 s/m each day, which decreases the potential emission. As with the other sources, daily emissions from each VOC group are converted to potential ozone forming emissions and totaled for the year.

Table 14.1 - VOC Concentrations

Initial VOC concentrations (mg/kg, dry matter basis) used in the model, based on a compilation of literature data. Values in bold are estimates based on measurements in other feeds, and are approximate at best.

Group	Corn silage	Small grain silage	Alfalfa silage	Grass silage	High-moisture corn
Acids	22	27	28	38	**5**
Alcohols	9.7	2.9	3.0	5.6	**2**
Esters	1.9	0.5	**0.5**	0.04	**0.5**
Aldehydes	0.58	0.5	0.020	0.43	**0.1**

Table 14.2 - EBIR Values

Equal Benefit Incremental Reactivity (EBIR) values used to aggregate emissions (**Carter, 2009**).

Group	Reference compound	EBIR (g/g)
Acids	Acetic acid	0.20
Alcohols	Ethanol	0.57
Esters	Ethyl acetate	0.24
Aldehydes	Acetaldehyde	1.61

Table 14.3 - Manure VOCs

Geometric mean concentrations of VOCs present in fresh and incubated manure. See **Fig. 14.1** for information on variability and the number of studies identifying each compound.

			Concentration	(mg/kg DM)
Group	Compound	CAS no.	Initial	Incubation
Acids	Acetic acid	64-19-7	12300	27700
	Propionic acid	79-09-4	6820	11800
	Butyric acid	107-92-6	2730	4300
	Isobutryic acid	79-31-2	1140	1440
	Lactic acid	50-21-5	756	9480
	Valeric acid	109-52-4	519	867
	Hexanoic acid	142-62-1	445	463
	Isovaleric acid	503-74-2	334	423
	Isohexanoic acid	646-07-1	29.9	28.9
	Heptonoic acid	111-14-8	10.2	10.7
	Octanoic acid	124-07-2	1.81	1.81
Alcohols	Ethanol	64-17-5	117	1440
	Propanol	71-23-8	20.9	71.3
	Butanol	71-36-3	10.6	36.2
	Methanol	67-56-1	1	514
	Isobutanol	78-83-1	12.3	13.3
Aromatics	Phenyl acetic acid	103-82-2	1230	
	Benzoic acid	65-85-0	1860	1320
	Phenyl propionic acid	501-52-0	213	
	Cresol	1319-77-3	117	119
	Skatole	83-34-1	8.46	2.98
	Indole	120-72-9	10.2	4.87
	4-ethylphenol	123-07-9	9.5	4.5
	Phenol	108-95-2	15.6	23.8

Data are from: **Miller and Varel (2001), Miller and Varel (2002), Spiehs and Varel (2009), Varel et al. (2010), El-Mashad et al. (2010), and Archibeque et al. (2011).**

Table 14.4 - Volatility and Reactivity

Volatile organic compounds measured in cattle manure and their volatility and reactivity.

			Log 10 Henrys	Incremental	reactivity‡
Group	Compound	Cas no.	law constant (g:aq)*	Maximum (MIR)	Equal benefit (EBIR)
Acids	Acetic acid	64-19-7	-7.33	0.66	0.203
	Propionic acid	79-09-4	-7.13	1.17	0.342
	Butyric acid	107-92-6	-6.86	1.75	0.548
	Isobutryic acid	79-31-2	-7.07	1.15	0.376
	Lactic acid	50-21-5	-9.26		
	Valeric acid	109-52-4	-6.62	2.3§	0.702§
	Hexanoic acid	142-62-1	-6.66	2.86§	0.87§
	Isovaleric acid	503-74-2	-6.58	2.3§	0.702§
	Isohexanoic acid	646-07-1	-6.36	2.86§	0.87§
	Heptonoic acid	111-14-8	-6.35	3.42§	1.04§
	Octanoic acid	124-07-2	-6.18	3.98§	1.21§
Alcohols	Ethanol	64-17-5	-3.67	1.45	0.571
	Propanol	71-23-8	-3.54	2.38	0.792
	Butanol	71-36-3	-3.47	2.76	0.882
	Methanol	67-56-1	-3.74	0.65	0.197
	Isobutanol	78-83-1	-3.36	2.41	0.723
Aromatics	Phenyl acetic acid	103-82-2	-8.45	3.35§	-0.676§
	Benzoic acid	65-85-0	-8.46	2.75§	-0.845§
	Phenyl propionic acid	501-52-0	-8.49	3.86§	-0.537§
	Cresol	1319-77-3	-4.4	2.34	-0.765
	Skatole	83-34-1	-4.2	3.66§	0.999§
	Indole	120-72-9	-4.33	3.66§	0.999§
	4-ethylphenol	123-07-9	-4.44	2.95§	-0.746§
	Phenol	108-95-2	-4.67	2.69	-0.879

*From NIST (measured) or ChemSpider (predicted from structure). For all acids, value was adjusted downward to reflect the fraction of the compound in the free form at pH 6.5.

‡From **Carter (2009)**

§Estimated value, based on extrapolation from smaller analogous compounds, addition of values for smaller compounds, or substitution of the value for a similar compound.

Table 14.5 - Emission Parameters

Parameter values for the manure VOC emission model.

			Henry's law constant (g:aq)		Reactivity (g/g)		Concentrations (g/kg dry matter)	
Group	Representative compound	*pKa*	*a*	*b*	MIR	EBIR	Initial conc.	Storage conc.
C2 & C3 acids	Acetic acid	4.83	3.652	2596	0.90†	0.27†	20	30
C4 and larger acids	Butyric acid	4.84	-4.673	0	1.5†	0.46†	5.0	20
Alcohols	Ethanol	---	5.576	2757	1.45	0.57	0.2	2.0
Aromatic acids	Phenylacetic	4.31	-5.76	0	3.35‡	0	3.0	3.0
Aromatics	Indole	---	-4.33	0	3.0†	0†	0.2	0.2

*Dimensionless constant (g:aq) is calculated by: log $H = a - b / T$, where T = temperature, K

†Composite value

‡An estimate based on addition of values for individual compounds

Figure 14.1 - VOC Simulation Diagram

Diagram for the hourly simulation of VOC emissions from silage storage and feed lanes.

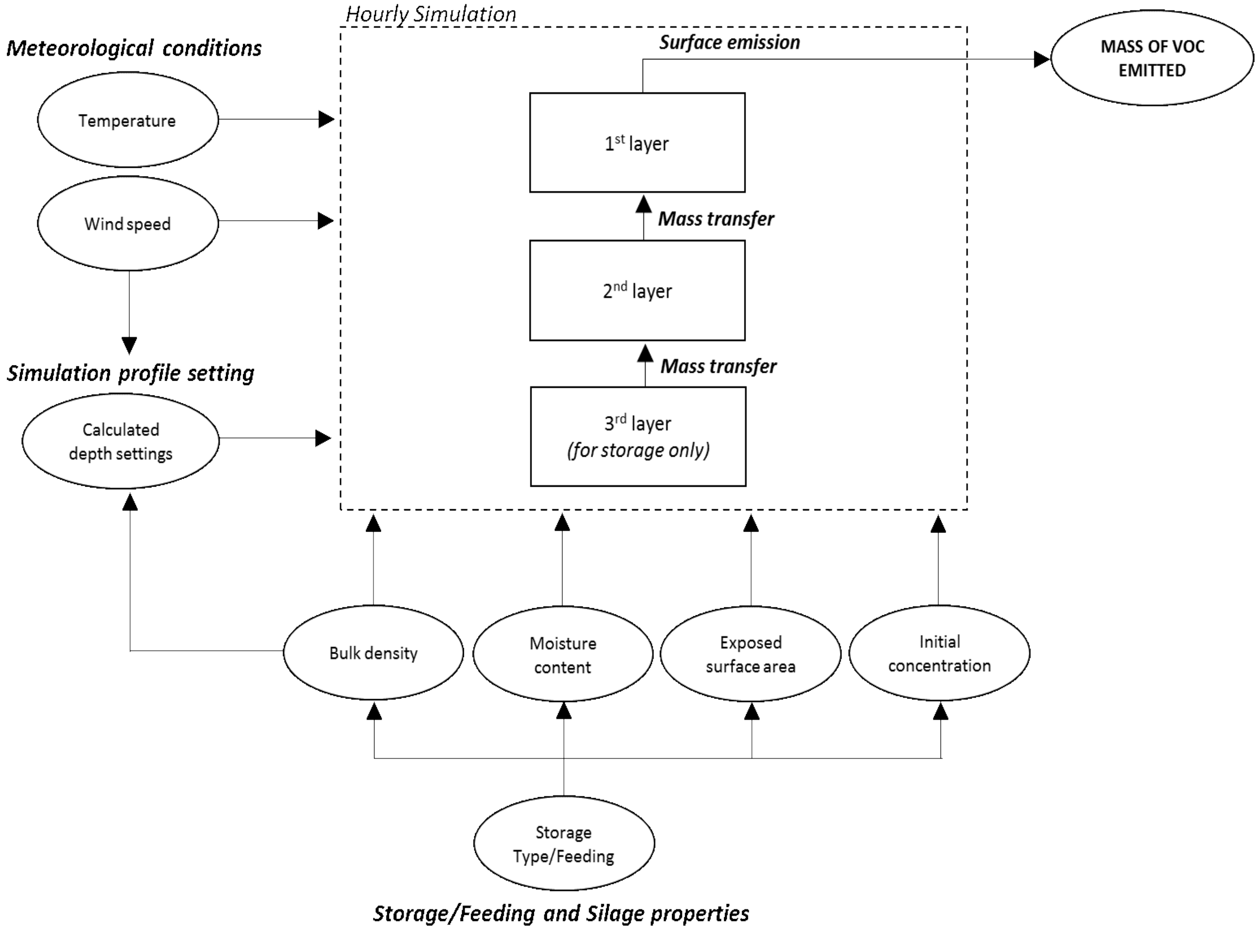


Figure 14.2 - VOC Concentration

Concentrations of VOCs in cattle manure for both fresh manure (initial) and incubated manure (incubations). Points show values from individual studies (including medians, minima, and maxima), while vertical lines show overall geometric means. Numbers in parentheses show the number of studies that data came from.

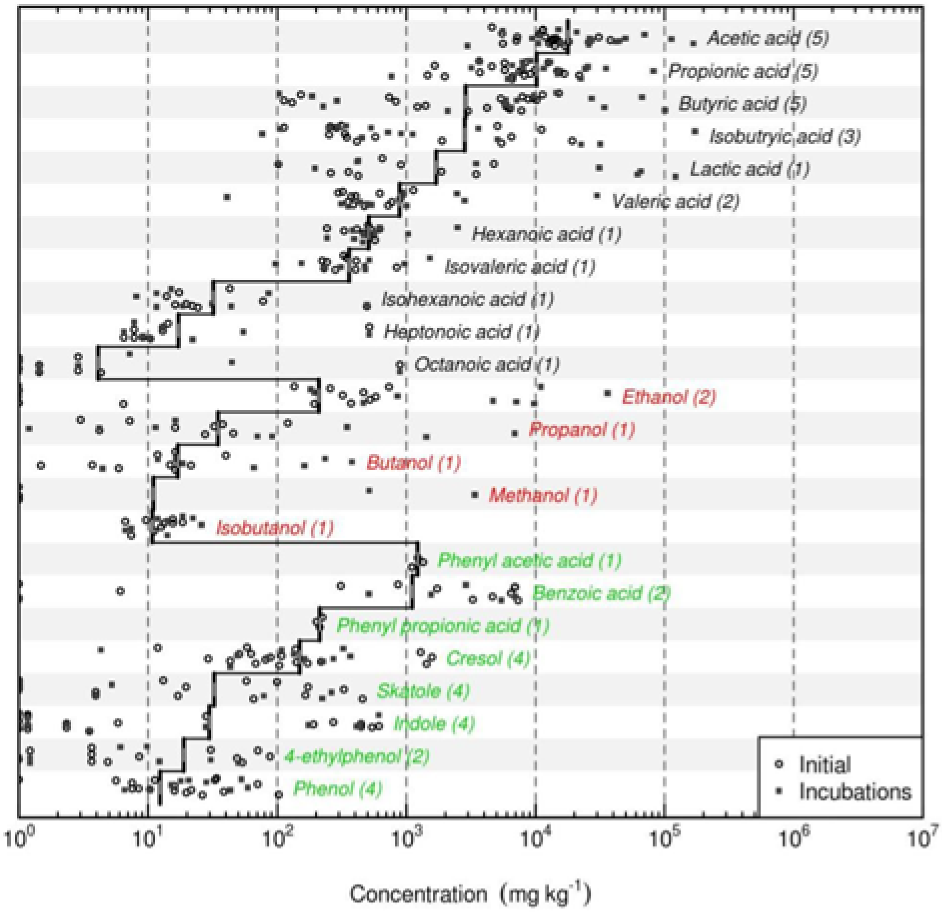
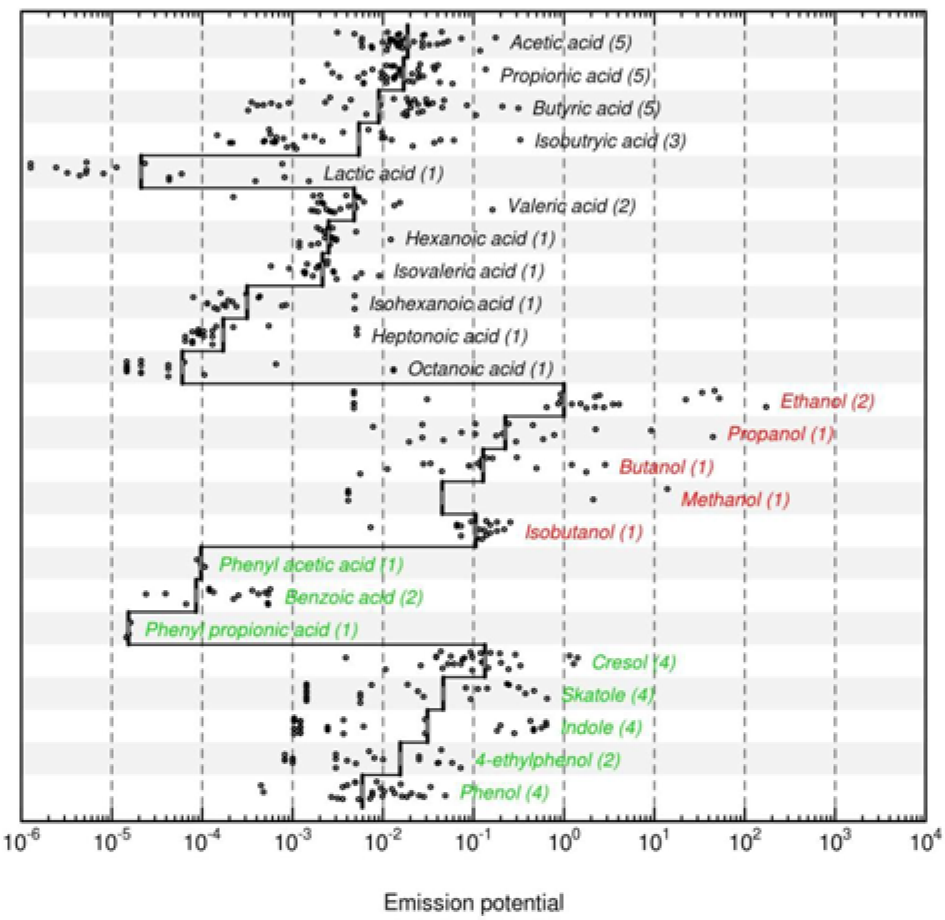


Figure 14.3 - Emission Potential

Emission potential (product of concentration and Henry's law constant) for all observations. Values are normalized to ethanol. Vertical lines show overall medians.



Environmental Footprints

Environmental footprints are defined as the effect on the environment expressed per unit of product produced. In IFSM, four environmental footprints are assessed: water use, reactive N loss, energy use, and carbon emission. Functions or factors are used to estimate values for important uses or sources of each in the production system. This includes the major uses of water and fossil energy and the reactive N and GHG emissions that occur during the manufacture of resources used in the production system. These secondary uses or sources can include the manufacture or production of fuel, electricity, machinery, fertilizer, pesticides, seed, and plastic used on the farm. Other secondary inputs include any feed or replacement animals purchased and imported to the production system.

The unit of product on crop farms is the unit of crop or feed produced expressed in kilograms or pounds of dry matter. On dairy farms, the unit is fat and protein corrected milk. Following the recommendation of the International Dairy Federation (**IDF, 2010**), milk is corrected to a fat content of 4% and protein content of 3.3%. A correction factor is determined using equations 8.13 and 8.14 (see the **Feed Intake and Milk Production** section). Milk production is multiplied by this factor to make the correction. For beef operations, footprints are determined per unit of shrunk body weight sold, which is determined as 96% of live body weight.

A concern in determining an environmental footprint is the proper allocation of the environmental issue between the primary product and co-products produced on the farm. Farm co-products can include extra feed or crops produced and sold from the farm and animals sold from dairy farms for beef production or other uses. **Cederberg and Stadig (2003)** discuss four options for allocating between milk and co-products in a life cycle assessment: no allocation, economic allocation, physical or biological allocation, and system expansion. With no allocation, all emissions are attributed to the primary product (milk on a dairy farm) with no allocation toward the feed or animals sold. For an economic allocation, whole farm emissions are allocated between the products based upon the annual income received from each. A number of criteria can be used as a basis for a physical or biological allocation. Suggested approaches are to allocate based upon the mass of each produced or the energy required to produce each. The final option of system expansion avoids allocation by expanding the system to include the alternative method of producing the co-product.

In IFSM, a mass-based allocation is used to allocate between crops sold and that used in dairy or beef production. The total resource use or emission associated with all crop production is determined, but only that actually used in dairy or beef production is included in their footprints. The portion included is determined by subtracting that used to produce any crops sold. The water or energy used to produce the crop sold is the total used in crop production times the ratio of crop dry matter sold or exported from the production system over the total produced. Similarly, the GHG emission associated with the crop sold is subtracted from the total of the production system.

The animal co-product from dairy farms includes extra calves, heifers and cull cows sold from the farm. As discussed above, resource use and emissions associated with heifers produced on the farm are included in the total for the production system. The portion of these heifers used as dairy or beef replacements is determined from the replacement rate of the lactating cows and the heifer mortality rate. Any additional heifers raised but not used are exported from the production system. Extra calves and cull cows are also exported from dairy production systems for use in meat production or other products.

Following the recommendation of the International Dairy Federation (**IDF, 2010**), a physical allocation procedure is used to allocate resource use or emissions between milk and animal products in dairy production systems. For heifers produced on the farm, the resource use and emissions associated with the exported heifers is removed from that associated with milk production. That associated with exported heifers is the footprint of heifer production (per unit weight) times the heifer live weight leaving the farm. For calves and cull cows sold, an allocation factor is calculated based upon the mass of each sold from the production system (**IDF, 2010**). The allocation factor (*AF*) is determined as:

$$AF = 1. - 5.7717\ M_{meat} / M_{milk} \qquad [15.1]$$

where M_{meat} is the annual amount of animal live weight in calves and cull cows sold (kg) and M_{milk} is the annual amount of milk sold (kg) from the production system. This factor varies among production systems, but generally attributes 85 to 90% of the resource input or net farm emission to milk production with the remainder attributed to the production of the calves and cull cows used for meat production. This allocation factor provides the portion of the total water use, reactive N loss, fossil energy use, or GHG emission included in milk production.

Water Use

Water use in agricultural production is becoming an important environmental concern, particularly in drier regions. With a growing demand for water, the amount available for agriculture can be restricted. Knowing the amount required to produce farm products and where it is used can be useful in assessing the long term sustainability of production systems.The water use footprint calculated by IFSM should be used only as a general estimate of water use. There is variability among production systems as affected by climate and production practices, and these differences may not be fully accounted in this model. The predicted water footprint is most useful for evaluating the relative differences obtained through management changes.

The major water requirement is for the production of feed crops. Other uses include drinking water for the animals, cleaning of the parlor and holding areas on dairy farms, and animal cooling. A footprint is determined by summing the estimates for each of these uses, removing that allocated to other co-products, and dividing by the amount of feed, milk or beef produced.

Large amounts of water are required to produce crops. For each feed crop, the amount required is defined as the amount taken up by the crop or that emitted through evapotranspiration. That drained through the soil profile is available for other uses, such as well water. Likewise, that running off the field surface contributes to surface waters for recreational and other uses. Therefore, the amount attributable to feed production is that available through precipitation or irrigation minus that removed by drainage and runoff. This amount remains relatively constant over typical growing conditions, but water may be used more efficiently under drought conditions.

As discussed in the **Crop and Soil** section above, the daily amounts of evapotranspiration, runoff, and drainage from each crop are predicted based upon the crop, weather, and soil conditions of the day. Daily amounts of evapotranspiration are summed over each crop to get annual use for the farm. Output is also included that gives the footprint with precipitation excluded. To obtain this value, only water used through irrigation and other fresh water sources is divided by the amount of feed, milk or beef produced.

For each crop where irrigation is used, the amount of water needed to avoid plant stress is determined throughout the growing period (See **Crop and Soil Information**). This total is increased to account for an irrigation efficiency of 90%. That additional 10% is considered lost through evaporation during the irrigation process and is included in the water footprint.

Drinking water use by a dairy herd is determined using relationships from the **NRC (2001)** for estimating water requirement. For each group of lactating cows:

$$FWI = 15.99 + 1.58\ DMI + 0.9\ MILK + 0.05\ SI + 1.2\ TMIN \qquad [15.2]$$

where FWI = fresh water intake, kg/cow/d
DMI = feed dry matter intake, kg/cow/d
$MILK$ = milk production, kg/cow/d
SI = sodium intake, g/cow/day
$TMIN$ = average minimum daily temperature, ^{o}C

For nonlactating cows and heifers, the drinking water requirement is determined as:

$$FWI = 0.2296\ \mathrm{DM} + 2.212\ DMI + 0.0394\ CP - 10.34 \qquad [15.3]$$

where DM = dry matter content of diet, %
CP = crude protein content of diet, %

Feed intake, milk production, and feed characteristics are obtained from the animal component of the model (See **Herd and Feeding** section). Sodium intake is determined using an assigned typical sodium content of 0.18% of *DMI*.

For beef cattle, relationships for water consumption were obtained from **Beckett and Oltjen (1993).** For lactating cows, daily water intake is determined as:

$$WI = 37.0 + 1.2\ \mathrm{TAVG} + 0.00088\ \mathrm{TAVG}^2 \qquad [15.4]$$

where WI = water intake, kg/cow/d
$TAVG$ = monthly average ambient temperature, ^{o}C

For nonlactating cows:

$$WI = 39.0 - 0.034\ BW - 0.013\ TAVG + 0.026\ TAVG^2 \qquad [15.5]$$

and for growing animals:,

$$WI = 0.9 + 0.067\ BW + 0.0034\ TAVG + 0.017\ TAVG^2 \qquad [15.6]$$

The amount of water contained in the feed consumed is subtracted from *WI* to obtain *FWI*. Fresh water intake is determined each month for each animal group making up the herd, and these are summed to obtain the annual requirement.

Daily use of water for parlor and equipment cleaning on dairy farms is estimated at 25 kg/cow. This value will vary with parlor type and size and the number of animals milked. Because this water use is very small compared to other uses, a more farm specific value or function was not warranted.

Another relatively small water use is that for animal cooling. The amount of water used is primarily a function of the daily temperature. This is modeled by assuming that cooling is used on any day when the maximum daily temperature exceeds 25 ^{o}C. On days when cooling is used, water use is set at 30 kg/head.

Secondary water use in the production of farm inputs is considered only for purchased feed, animals, and seed. Water used in the production of machinery, fertilizer, pesticides, and plastic is considered to be very small and unimportant. That used for producing feed not produced on the farm is determined using water use factors for each feed imported to the farm. Water use factors are 1.5 Mg/kg DM for grain, 0.7 Mg/kg DM for corn silage, 1.0 Mg/kg DM for alfalfa and grass forage, 0.5 Mg/kg DM for crop based feed supplements and 0.2 Mg/kg DM for byproduct feeds. For heifers imported to the farm, a water footprint of 8 Mg/kg live body weight is assigned. These factors were determined by simulating various crop and heifer producing farms with IFSM using various management strategies. An average value for the water used to produce the feed or animals was divided by the mass produced to obtain this typical footprint. The remaining secondary water use is in producing seed. A water footprint of 2.0 Mg/kg of seed production is assigned based upon typical amounts of water required to produce grain crops.

Reactive Nitrogen Loss

Nitrogen is found in many forms in agricultural production systems. These forms include urea ($CO(NH_2)_2$), ammonium (NH_4), ammonia (NH_3), nitrous oxide (N_2O), nitrogen oxides (NO_x), nitrate (NO_3) and dinitrogen (N2). All forms other than atmospheric N_2 are in a reactive form. Reactive nitrogen is essential in the growing of crops and feeding of animals. Only N in this form can be taken up by crops to form the proteins needed by the animal. Leguminous crops such as alfalfa and soybeans can fix N_2 from the atmosphere to form reactive N usable by the plant, but most reactive N used in farming comes from organic and inorganic fertilizers.

The development of the Harber-Bosch process greatly increased the availability of reactive N in inorganic fertilizer, which has greatly increased crop productivity. As this added reactive N cycles through the production system, there are many leaks to the environment affecting both air and water quality. The increase in reactive N in our environment from agricultural and other sources is a growing concern due to its affect on natural ecosystems and contributions to other forms of air and water pollution.

As another basis for quantifying the sustainability of farm production systems, a reactive N footprint is determined for the farm production system. This footprint represents the total amount of reactive N released to the environment per unit of product produced. This includes both the primary emissions directly from the farm as well as the secondary emissions occurring during the manufacture or production of resources used on the farm.

Primary losses of reactive N include ammonia and nitrous oxide emissions to the atmosphere, nitrate leaching to ground water, and the combustion of fuels. Ammonia emissions occur anywhere on the farm where manure is exposed to air. Important sources include the barn floor or feedlot surface, a manure storage if one is used, field applied manure, and manure deposited by grazing animals (see **Ammonia Emission** section). The total N lost in this form is determined as the total ammonia emission from the farm divided by the ratio of the molecular weight of NH_3 over that of N (1.216). Nitrous oxide emission occurs through nitrification and denitrification processes in the soil or manure where the amount emitted is influenced by available N, temperature, and moisture conditions (see **Nitrous Oxide Emission** section). Nitrification and denitrification processes also create N_2, but this inert form of N that is returned to the atmosphere is not part of the reactive N footprint. Total N lost in this form is determined as the total loss of N_2O from the farm divided by the ratio of the molecular weight of N_2O over that of N (1.57).

Reactive N is also created and released during the combustion of fossil fuels. The primary form of this N is NO_x. An emission factor was obtained from the GREET model (**Wang, 2012**) to provide a value for this emission source. For every liter of fuel consumed, 7.64 g of reactive N are released.

Nitrate N is leached from the soil profile as moisture not taken up by the plant drains below the root zone. All N that moves below the root zone is assumed to eventually end up in ground water. The daily amount leached is predicted for each crop based upon precipitation, moisture in each soil layer, and crop uptake (see **Soil** section). The daily amounts of NO_3-N leached are summed for the full year across all crops grown to give the total loss from the farm. The sum of annual losses of NH_3-N, N_2O-N, NO_x-N, and NO_3-N gives the primary loss of reactive N from the farm production system.

Secondary sources include the reactive N released during the production of fuel, electricity, machinery, fertilizer, seed, pesticide, purchased feeds, and purchased animals. Each of these sources are quantified using an emission factor for the amount of reactive N released per unit of each produced. In fuel production, 0.513 g N are released per liter, and for electricity the factor is 0.188 g N/kWh (**Wang, 2012**). For machinery, 1.1 g of reactive N are released per megagram of machinery mass produced (**Wang, 2012**). This portion of the footprint is determined by multiplying this factor times the total mass of each machine divided by the life of the machine to get an annual contribution. For fertilizers, the factors are 2.0, 2.0, 0.5, 0.2 g N/kg for N, phosphate, potash, and calcium carbonate amendments, respectively (**Wang, 2012**). For pesticide use, the factor is 9 g N/kg of active ingredient applied (**Wang, 2012**). The amount applied is estimated using the factors listed in **Table 15.1**.

Emission factors are also used for feed, seed, and animals purchased and imported to the farm. Emissions from feed and animals produced on the farm are included in the primary emission, but any additional feed or animals brought on the farm must include their production footprint. To obtain factors for purchased feeds, IFSM was used to simulate crop farms of various sizes on different soils and in different climatic regions. An average or typical footprint was used, although simulated values varied by up to 50% across conditions. Values used are 1.0, 2.0, 2.0 and 0.5 g N/kg of imported alfalfa hay or silage, corn silage, corn grain, and bedding material, respectively. For seed, the footprint was set similar to that of corn grain at 2.0 g N/kg of seed. To determine a footprint for purchased animals, IFSM simulations were done for heifer raising operations of various sizes, feeding strategies, and regions. From the average of these simulations, a typical value for producing heifers was set at 0.12 kg N per kg of body weight. By multiplying each of these factors by the total amount of each resource, a total secondary loss of reactive N to the environment is determined. The sum of the primary and secondary emissions divided by the quantity of feed, milk or beef produced provides the cradle to farm gate reactive N footprint.

Energy Use

Another important consideration in the evaluation of the sustainability of production systems is the energy footprint. This is defined as the total energy required to produce the feed, milk or beef except for the solar energy captured by the growing feed crops. This includes all fuel and electricity directly used in the production system as well as the secondary energy used in the production of resources used on the farm.

A major use of energy on farms is the fuel used to operate tractors and other equipment for feed production, feeding, and manure handling. As a production system is simulated in IFSM, the model tracks the amount of fuel and electricity used in each machinery operation (See **Energy and Labor** section). Therefore, at the completion of each simulated year, the total amounts of fuel and electricity used is known. Fuel use is converted to energy units assuming 35.8 MJ/liter of fuel. Electrical use is converted to energy units based upon 3.6 MJ/kWh of electricity.

Electricity is primarily used for milking, ventilation, and lighting. To estimate electricity consumption, electric use factors were obtained from a survey by **Ludington and Johnson (2003).** Electricity required for milking activities using a pipeline, parlor or automatic milking system is estimated as 0.015, 0.04 and 0.06 kWh/kg of milk produced, respectively. This factor times the total annual milk production provides annual use. Electricity use in lighting is 60 kWh per cow or head for a drylot and 80 kWh per cow or head for all other facilities. That used in ventilation is 0, 50, and 120 kWh per cow or head for drylots, naturally ventilated barns, and mechanically ventilated barns, respectively. When drylot and free stalls are combined, the electrical use is the average of the two facility types. When grazing is used, electrical use for lighting and ventilation are set proportional to the time animals spend in the barn.

Energy is also required for heating water used in cleaning dairy facilities. This requirement is estimated based upon the amount of milk received. The energy required for water heating is 0.08 MJ/kg of milk production, and this energy can be provided by either electricity or fuel oil.

Other energy inputs are the secondary energy uses during the production of farm inputs. These resource inputs include fuel, electricity, machinery, fertilizer, pesticides, seed, and plastic. Energy use factors for the production of each of these resources, except seed and plastic, were obtained from the GREET model (**Wang, 2012**). For fuel and electricity, the energy consumed in their production is 7.86 MJ/liter and 9.22 MJ/kWh, respectively. For fertilizers, energy use in production is 49.4, 14.13, 8.84 and 8.08 MJ/kg of nitrogen, phosphate, potash and calcium carbonate used, respectively. The amount of fertilizer used is determined based upon the user define application rates. The secondary energy use for pesticide is 275 MJ/kg of active ingredient where pesticide use is determined by feed crop using the factors of **Table 15.1**.

To determine the energy used in manufacturing equipment, the total mass of equipment used in the production system is required. For each machine used on the farm, the mass is user defined in the machinery data input file. The manufactured mass includes both the initial machine and the replacement parts used over the life of the machine. The repair part mass is calculated as a fraction of the initial machine mass using the repair and maintenance factors specified for each machine in the machinery data file (see **Production Costs** section). The sum of the initial and repair masses are divided by the life of the machine to get a total mass associated with each year of the life of the machine. This total, multiplied by an energy input factor of 42.6 MJ/kg of machinery mass, gives an annual value for this secondary energy use, i.e. the embodied energy in the manufacture of agricultural machinery (**Wang, 2012**).

Two relatively minor sources of secondary energy use are seed and plastic production. Seed us is a function of the feed crop produced (**Table 15.1**) and an energy use factor of 85 MJ/kg of seed is assumed. Plastic is used to produce silage in bags, bales or to cover silos. The amount of plastic used is a function of silo type with 0.3, 1.8 and 3.6 kg of plastic per tonne DM of silage produced for bunker, bag and bale silage systems, respectively; **Savoie and Jofreit, 2003**. The energy to produce this plastic is set at 50 MJ/kg of plastic.

When growing heifers or cows are purchased or imported to the farm as replacements for lactating cows, the energy used to produce those animals must be included in the footprint of the production system. This energy use is determined by multiplying the body weight of the imported animals by an energy use factor of 30 MJ/kg. This factor was determined by simulating a variety of heifer raising systems with IFSM and dividing the total energy use by the weight produced. Although this footprint of heifer production varies some among production strategies and size of operation, this average or typical energy use factor is used.

Carbon Emission

With the growing concern over global climate change and the potential impact of GHG emissions, a need has developed for expressing the total emission associated with a product or service. A term that has come to represent this quantification is the carbon footprint. A carbon footprint is defined in many ways dependent upon the product or service represented. In general though, the carbon footprint is the total GHG emission, expressed in CO2 equivalent units (CO_2e), associated with that product or service. The conversion to CO_2e is done using the global warming potential (GWP) of each gas where GWP values used for CH_4 and N_2O are 25 and 298 CO_2e/kg, respectively (**IPCC, 2001**; **EPA, 2007**).

We define the carbon footprint of farm produce to be the net of all greenhouse gases assimilated and emitted in the production system divided by the total product produced. For crop farms, the product is the feed produced, for dairy farms it is the fat and protein corrected milk produced, and for beef operations it is the shrunk body weight produced. This net emission is determined through a partial life cycle assessment of the production system. Emissions of CH_4 and N_2O are converted to CO_2e units by multiplying by their GWP index. All emission sources of the three gases are summed and the net CO_2 assimilated in feed production is subtracted to give the net emission of the production system. Emissions include both primary and secondary sources. Primary emissions are those emitted from the farm or production system during the production process. Secondary emissions are those that occur during the manufacture or production of resources used in the production system (machinery, fuel, fertilizer, etc.). Secondary emissions such as those in the manufacture of equipment must be apportioned to average annual values. By totaling the net of all annual emissions from both primary and secondary sources and dividing by the annual production, a carbon footprint is determined in units of CO_2e per unit of feed, milk or beef produced.

The carbon footprint is primarily determined as the net emission of the three GHGs including all sources and sinks of CO_2. A carbon balance is enforced, so a portion of the CO_2 assimilated in the feed is in the carbon exported from the system in the feed, milk, and animals produced. Although this provides a more complete assessment of the carbon footprint of the production system, this procedure deviates from the more standard protocol followed by the IPCC and most other studies publishing carbon footprints of agricultural produce. The more standard protocol does not consider assimilated CO_2 and includes only the CO_2 emitted by the combustion of fossil fuels. For comparison, a carbon footprint is also determined following this procedure. A minor deviation is included though to provide a more equitable assessment. The carbon in the CH_4 emitted from the system comes from CO_2 assimilated in feed. Therefore, the net GHG emission is reduced by the amount of CO_2 assimilated to meet the CH_4 emission. Including this refinement reduces the carbon footprint of the production system a small amount depending upon the production strategy used. Use of this protocol increases the footprint about 30% compared to the first approach, which includes the CO_2 assimilated in the carbon exported from the production system.

Primary Sources

Primary sources of GHG emissions include the net emission of CO_2 plus all emissions of CH_4 and N_2O occurring from the farm production system. Daily emission values of each gas are summed to obtain annual values. Carbon dioxide emissions include the net annual exchange in feed production, daily emissions from animal respiration, and daily emissions from microbial respiration in manure on the barn floor and during storage (see **Carbon Dioxide Emission** section). The annual net exchange in feed production is determined as that assimilated in the feed minus that in manure applied to cropland. Emission of CO_2 through animal respiration is a function of animal mass and daily feed DM intake (equation 13.18) and that from the barn floor is a function of ambient barn temperature and the floor surface area covered by manure (equation 13.19). Emission from a slurry manure storage is predicted as a function of the volume of manure in the storage using an emission factor. The CO_2 emission from fuel combustion in farm engines is proportional (2.637 kg CO_2e/L) to the amount of fuel used in the production and feeding of feeds and handling of manure. A final primary source is the use of lime as a soil amendment. The carbon emitted as CO_2 is the carbon added through lime reduced by an efficiency of 90%. Lime is assumed to be added every three years with a third of the emission assigened to each year. The amount of lime used is a function of the soil pH and exchagable acidity (see **Carbon Dioxide Emission** section).

Methane emissions in milk production include those from enteric fermentation, the barn floor, manure storage, and feces deposited in pasture (see **Methane Emission** section). Daily emission from enteric fermentation is a function of the metabolizable energy intake and the diet starch and fiber contents for the animal groups making up the herd (equation 13.20). Daily emissions from the manure storage are a function of the amount of manure in the storage and the volatile solids content and temperature of the manure (equation 13.27). Emissions following field application of manure are related to the volatile fatty acid content of the manure and the land area covered (equation 13.35). Emissions during grazing are proportional to the amount of feces deposited on the pasture and that emitted in the barn is a function of barn temperature and the floor area covered by manure (equations 13.23 and 13.24).

Nitrous oxide emissions considered in the carbon footprint are that emitted from crop and pasture land during the production of feeds with minor emissions from the manure storage and barn floor (see **Nitrous Oxide Emission** section). Emissions in feed production are a function of the nitrification and denitrification processes occurring in the fields (equation 13.39). Emissions from the crust on a slurry storage and from a bedded pack barn floor are predicted as functions of the exposed surface area of each (equation 13.57).

Secondary Sources

Secondary sources include the emissions during the manufacture or production of fuel, electricity, machinery, fertilizer, pesticide, and plastic used in the production of feeds and maintenance of animals. Secondary emissions are all expressed in annual values of CO_2e units. Most of these emissions are in the form of CO_2, but where appropriate CH_4 and N_2O emissions are converted to CO_2e units and included in these emission factors.

Emissions during the production of fuel and electricity are set using emission factors derived from the GREET model (**Wang, 2012**). These factors are 0.734 kg CO_2e/litre of fuel and 0.73 kg CO_2e/kWh of electricity used in the production system. Fuel use is determined for each machine operation, and these are summed to obtain the total annual use for each simulated year (See **Energy and Labor** and **Energy Use** sections). Electricity use is the total of that used for milking, milk cooling, and related milking activities and that used for barn lighting and ventilation (see **Energy Use** section).

Emissions in the manufacture of machines include both the initial manufacture as well as the repairs required to maintain the equipment. The total mass of machinery used on the farm is obtained by summing the mass of all equipment used where the mass of each machine is obtained from the user-defined machinery parameters. The mass of each machine is also increased in proportion to the repair cost for maintaining that machine. This total mass is divided by the life of the machine to obtain a mass to be attributed to each simulated year. This annualized mass is multiplied by an emission factor of 3.54 kg CO_2e/kg of machinery to get an annual value for this secondary emission source. This emission factor was established based upon available sources of information on embodied energy or emissions in the manufacture of agricultural machinery (**Wang, 2012**; **Rotz et al., 2010**).

Emissions in the manufacture of fertilizer were obtained from the GREET model (**Wang, 2012**). Emission factors used for nitrogen, phosphate, and potash fertilizers are 3.307, 1.026, and 0.867 kg CO_2e/kg of each used in the production of feeds. The annual amount of inorganic fertilizer used is the product of the user-specified rate for each crop times the crop area. Emission during the production of lime is determined using an emission factor of 0.63 kg CO_2e/kg of calcium carbonate equivalent used (**Wang, 2012**) where lime use is determined as described in the **Carbon Dioxide** section above.

Emissions in the manufacture of pesticides are generally small, but they are included. Pesticide use is estimated using a pesticide use factor set for each crop produced (**Table 15.1**). The total pesticide use is this factor times the crop area summed over all crops. An average emission factor of 22 CO_2e kg^{-1} of pesticide is used to determine emissions during manufacture. This emission factor was set based upon the GREET model (**Wang, 2012**) and other sources (**Rotz et al, 2010**).

Emissions in the production of seed are modeled similar to that of pesticides. Again this emission is very small so a more sophisticated model is not justified. Seed use factors were derived using typical seeding rates (**Table 15.1**). Seed use is summed over all crops based upon these typical seeding rates. An emission is determined using an emission factor of 0.3 CO_2e/kg of seed. This factor was estimated considering all the emissions in producing the seed crop minus the C contained in the seed (**Rotz et al., 2010**). This value is likely to vary among crops, but due to the lack of available information and the relative unimportance of this emission source, this average rate is used.

Plastic is often used in silage production for bags, to cover silos, or to wrap bales. Plastic use factors for tower silos, bunker silos, silage bags, and bale silage are 0.0, 0.3, 1.8, and 3.6 kg/t DM of stored feed for each storage type, respectively (**Savoie and Jofriet, 2003**). The emission factor for plastic production is set at 2.0 kg CO_2e/kg of plastic use (**IPCC, 2006; Rotz et al., 2010**). This emission source is normally very small and relatively unimportant compared to other secondary emission sources.

When heifers are purchased and brought onto the farm to replace lactating cows, the emissions associated with their production must be considered as part of the production system. These emissions will vary with the production practices used. To determine an average emission factor for heifer production, the IFSM simulations were used to determine the emissions for producing heifers over a range in farm size and feeding strategies including grazing. The range found for this secondary source was 8 to 14 kg CO_2e/kg of body weight produced with the lower values associated with larger farms or grazing production systems. An average emission factor of 11 kg CO_2e/kg of body weight was selected to best represent this source. This secondary emission is determined by multiplying this factor by the net body weight of the livestock purchased to meet the replacement rate of the dairy herd. If all replacements are raised on the farm, this source is eliminated. If extra animals are raised and sold from the farm, secondary emissions are reduced by the animal weight sold.

Table 15.1-Resource input factors

Use factors for pesticide and seed resource inputs in feed production.

Feed type	Pesticide use kg ai/t DM feed[a]	Seed use kg/t DM feed[b]
Grazed forage	0.05	0.9
Alfalfa or grass silage	0.10	0.9
Alfalfa or grass hay	0.10	0.9
Corn silage	0.30	1.7
High moisture corn	0.67	4.0
Corn grain	0.67	4.0
Protein supplement	0.00	0.0
Fat additive	0.00	0.0

[a] Mass of active ingredient applied per unit of each feed produced.

[b] Mass of seed used per unit of each feed produced.

ECONOMIC INFORMATION

The economic consequences of management decisions are evaluated for various farm systems over many years of weather. The economic analysis is a whole farm budget where the total cost of production is compared to revenues, to predict the net return or profit potential for the farm. A partial budget analysis is also used to determine the cost of producing each of the major feed crops on the farm, the total cost of feed production and use, and the cost of manure handling. Resources used, material flows, and production costs are all monitored as production events are simulated in the model. These economic measures are determined for each weather year, and they are averaged to determine the mean over all simulated years. Economic measures for individual weather years can be ranked and plotted in cumulative probability distributions to measure and compare the risk or variability caused by weather.

Production Costs

Costs associated with all resources used on the farm for crop and animal production are accounted on an annual basis. Since resources include operating and durable resources, both operating and fixed costs are included. Annual fixed costs convert the initial dollar investment for machinery and facilities into an annual flow. A capital recovery factor with a user-specified asset life and discount rate is used to determine annual fixed costs.

Resources used in crop and animal production include land, labor, fuel, repairs, fertilizers, seeds, and chemicals, as well as the service flows from durable assets. Durable assets include the machinery complement and all facilities on a given farm. Additional purchased resources in the form of feed supplements are also accounted. The user specifies the farm resource base for a simulation run. This resource base designates all system-controllable inputs, i.e. inputs assumed to be under the control and discretion of the farm operator. The controllable inputs describe the specific system alternative being simulated and include such input categories as land area committed to each crop, the specific set of machines in the machinery complement, size and number of feed storage structures, animal type and number, and the manure handling facilities. Once the controllable inputs have been designated, engineering relationships in the model establish the level of resource use of all operating and fixed resources. An unaccounted farm overhead cost can also be included to represent any and all other annual costs that are not specifically tracked in the model.

Facilities

Facilities refer to all structures on the farm. These typically include a machinery shed and shop, silos, hay shed, manure storage, milking center, animal housing, and feed facilities. The annual cost of facilities or structures is the sum of the annual costs of ownership, insurance, and repairs along with the cost of materials used such as plastic covers.

Since these structures normally have a useful life of many years, it is necessary to convert their initial cost into an annual cost. The annual cost of durable assets that depreciate with time is estimated using a capital recovery formula:

$$CRF = \left[i\,(1+i)^{n} \right] / \left[(1+i)^{n} - 1 \right] \qquad [16.1]$$

where CRF = capital recovery factor

i = interest rate, fraction
n = accounting life, years

Because inflation of monetary value is not considered, interest rates assigned in the model should be considered real rather than nominal rates. Subtracting a general inflation rate from the nominal interest rate where the nominal rate is that typically paid for a bank loan approximates a real interest rate. Separate rates can be assigned for medium and long-term investments. All permanent facilities are assumed to be long-term investments.

An annual ownership cost is determined for each facility where the annual cost is calculated as:

$$AOC = PP \left[(1 - \mathrm{SV})\, CRF + \mathrm{SV}\,(\,\mathrm{i}\,) \right] \qquad [16.2]$$

where AOC = annual ownership cost of a durable, depreciable asset
PP = initial purchase price, \$
SV = salvage value of the asset, % of initial cost

The initial cost, interest rate, life, and salvage value are user-specified variables. The accounting life is generally set at 20 years for structures with no salvage value. For milking equipment, the life, and salvage value are set to that of other equipment on the farm (usually 10 year life and 30% salvage value).

An insurance cost is also considered for most durable assets. All equipment and most facilities have an annual insurance rate of 0.5% of the initial cost. This rate is set inside the model and cannot be modified by the user. The annual insurance cost is this rate times the initial cost of the facility. The only facility that is assumed to be uninsured is the manure storage. For silos and the hay shed, the feed stored is also insured. This cost is 0.5% of the value of the crop stored (quantity stored times market price).

A cost for repair and maintenance is included on all animal facilities. This annual cost is determined as 0.5% of the initial cost of the structures used in animal housing and in the case of a dairy, the milking center structure. Repair and maintenance of the milking equipment is 3% of the initial cost for pipeline and parlor systems. For automatic or robotic milking equipment, the annual cost, including a maintenance contract, is \$700 plus about 4% of the initial cost. Repair and maintenance costs are ignored for storage facilities except for unloading equipment. Costs of unloading equipment are determined as described below for other machinery used on the farm.

Feed storage costs may also include an annual operating cost for materials such as plastic. This annual cost is assigned by the user in dollars per unit of feed *DM* stored. The annual storage cost than includes this value times the number of units of feed entering storage (before storage losses are subtracted). For hay stored in a shed, the annual cost includes only the amortized cost of the structure. When the amount of hay produced exceeds the shed capacity or when the hay is designated for outside storage, that portion of the hay can be assigned an annual cost for covers. Silo storage cost always includes both the annual ownership cost and the cost of materials specified by the user. Common material costs would include a cover for bunker silos (should a cover be used), silage bags, and plastic wrap or bags for bale silage.

Grain storage does not consider the use of a permanent structure on the farm (except for high-moisture grain stored in a silo). Grain storage cost is determined as price per unit *DM* per year (designated by the model user) multiplied by the grain *DM* placed into storage. This annual cost should reflect the cost of storing the grain off the farm in a grain elevator. If grain is stored on the farm, then this cost should be set to include the annual costs of ownership, insurance and maintenance of that permanent structure. For high-moisture grain, annual costs are determined as described above for other silos.

An estimated cost for property tax is included on all permanent structures (silos, sheds, animal housing, and milking center). This cost is determined as the user-specified property tax rate times the assessed value of the structure. This assessed value is internally set at 42% of the initial cost of each structure.

For the partial budgets determined in the model, the cost associated with the storage of any given feed is allocated to the feed being stored (hay, grain, or silage). For example, if alfalfa hay is stored, the costs of this storage are allotted to the alfalfa hay enterprise.

Machinery

Machinery use is tracked to determine total use as well as the use for each enterprise within the farm. When a piece of equipment is used in more than one enterprise, the total cost is divided between the enterprises based upon the number of hours worked in each enterprise. The model also calculates the total use and associated costs for the whole farm budget.

Machinery costs include both annual ownership and operating costs. Annual ownership costs are calculated as described above for facilities where the annual cost is a function of the initial cost, salvage value, interest rate, and accounting life. The accounting life is generally set at 10 years for machinery with a typical salvage value of 30% of the initial cost. For minor equipment used to apply preservative type treatments to forage, a shorter life of 5 years is internally set. The user-specified, medium-term interest rate is used to determine annual costs of equipment.

Costs of machinery operations include labor and energy used in the operations and machinery repair and maintenance costs. Labor use is determined in the tillage, harvest, feeding, and manure handling components. Machinery labor includes one operator for each tractor or self-propelled machine plus any additional labor required for tasks such as loading and unloading wagons. Labor for machine operation is set to be 10% more than the actual number of hours the tractor or other machine is used. This reflects the labor required for tasks such as machine set up, routine maintenance (greasing and cleaning), and delivery to the field. Additional labor used on a given operation is determined as the product of the number of additional labors assigned and the time required for the associated operation. For example, wagon unloading time is always the time required to complete a cycle of all parallel operations (harvest and transport) therefore, some idle time is included. If two additional people are required to unload hay wagons, then the labor requirement is three people (tractor operator plus two additional) times the cycle time. The same wage rate, specified by the user, is used for all labor. The annual labor cost is the wage rate times the total of all labor hours used.

Energy costs include fuel and electricity. Prices defined by the user are multiplied by the quantity of fuel and electricity consumed to obtain the total energy cost. The amount of fuel and electricity used are determined in the tillage, harvest, feeding and manure handling components. The amount consumed is the product of the hours each machine is used times the use rate for the operation (determined by the **Machinery** component) summed over all machines.

Repair and maintenance costs are determined for each machine to include both the parts and labor for installation. This cost is determined as the initial machine cost times an exponential function of the number of hours that each machine is used over its life (**ASAE, 2000):**

$$CRM = RF1(P)(h)^{RF2} \qquad [16.3]$$

where *CRM* = Accumulated repair and maintenance for a given machine, \$
RF1 and *RF2* = machine specific parameters, dimensionless
P = machine initial price
h = accumulated use of the machine, 1000 hours

Coefficients are used to describe the magnitude and exponential shape of the repair and maintenance functions for each individual machine. Values used are those published in the **ASAE Standards (2000)** for major farm machinery. The model user can modify the repair and maintenance coefficients and the wear-out life set for each machine. If the user chooses to describe machines where these coefficients are not available, values should be selected from a known machine that could be considered similar in terms of wear-out life, number of moving parts, and general wear.

When preservative treatments are applied to forage during harvest, a small additional cost for labor and repair and maintenance is charged. The labor requirement for applying this type of treatment is assigned as two minutes per tonne of forage treated. The annual repair and maintenance cost is 2.5% of the initial cost or initial cost of the application equipment.

Land and Crop

Land can be owned or rented with a portion of the farm in each category. Since land value typically does not depreciate, the only cost assigned to owned land is that of property tax. A property tax rate assigned by the user is multiplied times half the assessed value of the property. For simplicity, the assessed value of land is set at \$2,471/ha (\$1000/acre), the user cannot modify this value. If the assigned assessed value is not appropriate, the user can adjust the tax rate to obtain the appropriate annual cost for property tax. The annual cost of rented land is a user-specified rental rate times the rented land area; no tax cost is charged on rented land.

Cropping costs consist of charges for fertilizer, seeds, and chemicals. These costs are summed over all crops produced on the farm to obtain a total annual cost. The model user sets fertilizer use. The user specifies how much nitrogen, phosphate, and potash fertilizer is applied per unit of land area for each crop. The user also sets the price of each of these fertilizer types. The fertilizer cost for each crop is the total cost of the three fertilizers, where the cost of each is the fertilizer price multiplied by the number of units applied and the crop area.

The user assigns seed and other chemical costs for establishing and maintaining each crop. These values should reflect a total annual cost per unit of crop area. Separate values are assigned for newly seeded and established forage crops (grass and alfalfa). The portion of these crops that is seeded each year is one divided by the number of years specified for stand life, and the remainder is considered established. A separate value is also entered for corn following corn in a rotation to reflect the increased cost of pesticide required. The land area in corn following corn is determined assuming a preference for planting corn on land rotated from any other crop on a given year. If the total corn land exceeds that from other rotated crops, the remaining land is designated for corn following corn.

Machinery operations for chemical application are not simulated in the model. For chemicals not applied at planting, the cost assigned should include the application cost. Therefore, the assigned cost should be that of a custom applicator.

Chemicals can also be used during the harvest and storage of forages. These include chemical drying agents and preservative treatments. When chemical conditioning of alfalfa (drying agent) is used to speed field curing, the additional chemical cost reflects the cost of potassium carbonate or a similar chemical mix applied at a user-specified rate. For preservative treatments, the user also specifies the application rate. In either case, the annual cost is the user-specified treatment price times the application rate times the number of units of forage treated.

Costs of crop production may also include charges for drying and roasting of grain. When grain is harvested with a moisture content above that required for safe storage and marketing, drying is required. To determine a drying cost, the moisture that must be removed to dry corn to 15.5% moisture and other grains to 13.5% is calculated. The drying cost is then this amount of moisture times the amount of crop harvested times the user-specified drying charge. In the case of soybean harvest, the grain may also be roasted to reduce the rumen degradability of the protein in the feed. This annual cost is the quantity of soybeans produced and fed on the farm times the user-specified cost of the treatment.

Pasture

Pasture costs include annual costs for additional durable assets (fence and watering equipment), chemicals, and labor used for pasture management. Fence includes permanent (perimeter) fence and temporary electric fence. Fixed costs associated with pasture are calculated similar to that of other durable goods. The primary difference is that the accounting life is a set value that cannot be modified by the user. Both the watering system and the temporary fence have an assigned accounting life of 5 years, while the permanent fence has a life of 10 years. In either case, zero salvage value is assumed and the medium term interest rate is used.

Repair and energy costs for maintaining fence are also included. Annual repair and maintenance costs for both types of fence and the watering system are set at 3% of the initial investment. A small amount of electricity is used to power the fence. For simplicity, the annual amount used is set at 3 kW/ha of grazed area. The model user cannot modify these assumptions.

An added cost of seed and chemical can be assigned. This cost should reflect any cost associated with overseeding the pasture or spraying for weed or insect control. This cost is assigned by the user in dollars per unit of pasture area. When the grazed area varies throughout the season, the area used in this calculation is that assigned for the summer months.

Labor cost associated with pasture management includes that required to move animals, monitor pasture condition, and move temporary fences. The user sets this labor requirement in hours needed per week. The annual labor cost for pasture management is this labor requirement times the number of weeks animals are grazed times the labor wage rate. The number of weeks in the grazing season is internally set at 28.

Livestock

Animal production costs include purchased feed and bedding, livestock expenses, and purchased animals. The cost of purchased feeds is the total of cash expenditures required to balance the animal rations. Purchased feeds include hay, grain, protein feed supplements, animal or vegetable oil, and minerals. Annual feed cost is the total of the quantities of each feed purchased times the feed prices specified by the user. The amount of feed purchased is determined in the **Herd and Feeding** component. The feed allocation algorithm forces the use of farm grown feeds, and purchased feeds are used only as needed to supplement those produced on the farm. Bedding cost is the product of the user-specified bedding price and the bedding requirement. The bedding requirement is the requirement per mature animal unit times the number of equivalent mature animal units on the farm. When bedding is produced on the farm, this cost is reduced in proportion to the reduction in purchased bedding.

Livestock expenses are all costs associated with maintaining a healthy herd of animals. These costs include: Bovine somatatropin injections (for dairy animals only), veterinary and medicine costs, semen and breeding, animal and milking supplies, insurance of animals, utilities for milking and handling, animal hauling, and miscellaneous registration charges. The total livestock expense is calculated by multiplying the user-specified cost per mature animal for each of the above times the number of mature animals on the farm. This number of mature animals is the number of cows (lactating plus dry) for a dairy operation, the number of cows in a cow-calf operation, or the number of animals sold each year on a stocker or finished beef operation.

The cost of replacing animals in the herd is the animal price times the number of animals purchased. For a dairy or cow-calf beef operation, all cows leaving the herd are replaced with bred heifers. The number of bred heifers required each year is the user-specified replacement rate times the number of cows (including lactating and dry) in the herd. The number that must be purchased is the difference between the number required and the number of older heifers available on the farm. The number of bred heifers available is set at 98% of the user-specified number of heifers over one year old to reflect a 2% per year mortality rate.

For most animal groups, the buying and/or selling price is a fixed price set by the model user. This price should reflect a long-term average price in current value. For a beef operation, a difference can be set between the buying and selling prices using the marketing fee. This fee is used to increase the buying price by a user-specified ratio of buying price over the specified selling price. For prices provided on a per unit weight basis, the price is multiplied by the shrunk body weight of the animal to obtain the value of the animal.

For feeder cattle, factors of body weight, condition score, frame size, gender, and time of the year can have a large effect on their value. The model user has the option of using an adjusted price that considers these effects. When an adjusted price is selected, the price is established as the product of the specified base price and adjustments for each factor:

$$P_{feeder} = P_{base}\,(A_{bw})\,(A_g)\,(A_{fs})\,(A_{cs})\,(A_m) \qquad [16.4]$$

where P_{feeder} = price of feeder cattle purchased or sold, \$/kg

P_{base} = base price of feeder cattle, \$/kg

A_{bw} = adjustment for body weight

A_g = adjustment for gender

A_{fs} = adjustment for frame size

A_{cs} = adjustment for body condition score

A_m = adjustment for month of year

Data from **Smith et al., 1998** was used to develop price adjustment multipliers for factors of body weight, gender, frame size, and body condition. The empirical relationships found to predict these factors are:

$$A_{bw} = 1.28 - 0.00102(SBW), \quad \text{limited to a value <1.0)} \qquad [16.5]$$

A_g = 1.0 for steers and 0.863 for heifers

$$A_{fs} = 0.00324\ (FSBW) - 0.00000263\ (FSBW)^2 \qquad [16.6]$$

$$A_{cs} = -0.0412 + 0.411(CS) - 0.0405\ (BCS)^2 \qquad [16.7]$$

where SBW = animal shrunk body weight, kg
$FSBW$ = final shrunk body weight, kg
BCS = condition score using a 9 point grading system

The base price corresponds to the price of a feeder steer sold in June with a body condition score of 5, *FSBW* of 470 kg, and weight of 160 kg. The data of **Meyer (1997)** illustrates two yearly price cycles for large (>270 kg) feeders and one price cycle per year for smaller (<270 kg) feeders. Price adjustments were determined by averaging monthly price data within these two size groups. Table 16.1 includes the monthly price multipliers (A_m) for feeder cattle.

The labor required for milking and animal handling in a dairy operation is related to the type of milking and animal handling facilities used. For a beef operation this price relates to the handling of animals only. A user-specified labor requirement in minutes per cow (or per head for stocker and finished beef operations) per day is multiplied by 365 days per year and the number of mature cows (or head sold in stocker and finished beef operations) on the farm to obtain the total labor requirement. This labor requirement times the user-specified wage rate gives the annual labor cost.

An additional cost associated with the dairy animal is the milk hauling and marketing fee charged for selling the milk produced. This fee is based upon the units of milk sold. The annual cost is the user-specified fee times the number of units of milk produced and sold from the farm.

Custom Operations

When a custom operation is selected, all costs of owning and operating the equipment in that operation are ignored. Instead, a cost is charged as assigned by the model user. The annual custom operation cost is the number of units performed multiplied by the price per unit. The type of units used varies with the type of operation performed. Operations such as tillage, planting, mowing, tedding, raking, and grain harvest are all calculated using units of dollars per unit of land covered. For baling and forage chopping, the units are dollars per unit of forage harvested. For manure hauling, the units are dollars per hour of hauling time. The number of units (hectares, tonne, hours) each operation uses is determined in the **Tillage and Planting**, **Crop Harvest**, and **Manure Handling** components when an operation is designated for custom hire.

Revenue and Net Return

Farm income consists of revenues from the sale of field crops, milk, excess feeds, and animals. Milk sale is the product of milk production and milk price. Milk production is determined by the animal component as a function of the quantity and quality of available feeds (See the **Herd and Feeding** section). The milk price set by the user should reflect a long-term average annual price in current dollars.

Animals sold can include culled cows, bred heifers, and calves for a dairy operation and culled cows, weaned calves, yearling calves, stocker cattle, and finished cattle for a beef operation. The number of cows sold is set by the user-specified percentage of first lactation animals. The number of animals in this portion of the herd minus the death loss (5% per year for dairy; 2% for beef) gives the number sold. The income from cows sold is the number sold times the average weight times the user-specified price for a cull animal. Bred heifers sold are the number of heifers on the farm over one year old (reduced by 2% mortality) minus the number of first lactation animals needed. Young stock (heifers or stockers) sold are the number raised on the farm minus a 2% mortality minus the number needed for replacements in the next age group. Income is the number of animals sold times the user-specified price per animal. For simplicity on a dairy farm, the price of a young heifer is set at half the price of a two-year old bred heifer. For feeder cattle on a beef farm, an adjusted sale price can be used that considers animal body weight, condition score, frame size, gender, and the time of year (see the production cost section above). Finally, calves are sold. The number of calves on the farm is set assuming a 4% rate of twins and 10% mortality (8% mortality on beef farms). The difference between those available and the number of young heifers and/or weaned calves raised on the farm gives the number sold.

The final revenue is from the sale of field crops for a crop farm and excess feed and bedding products from dairy or beef farms. To allow each simulated year to be independent from other years, no crop or feed is held over for the next year. On a crop farm, all harvested crops are sold. For animal operations, everything produced is either consumed by the herd or sold as excess. The excess or surplus feed in any given year is the difference between that produced and that consumed by the herd. Straw may also be sold if that produced exceeds that needed on the farm for bedding material. Normally, surplus feed and straw sales occur only in high yield years unless crops are produced specifically for off-farm sale. Income from crop sales is the amount sold each year times the user-specified price.

A net return is determined as the sum of all revenues minus the sum of all costs of production. This net return represents the potential profitability of the farm. This value provides a good basis for comparing the profitability of farm systems, but it is not necessarily a good representation of the profit of a given farm. This analysis does not include the impacts of income taxes and other government payments that may affect the profitability of the business.

Other accounting measures on a dairy farm include the net feed cost per unit of milk produced and the net feed cost as a percentage of milk income. These measures provide a common denominator, which reflects the economic value of all resources expended in feed to produce a given quantity of milk. A net feed cost is determined by summing all costs for producing all crops on the farm along with the cost of all purchased feed and subtracting the value of any feeds sold off the farm. These economic measures of the animal/forage system reflect the interface of the cropping and animal systems without including the other costs associated with production.

Table 16.1- Feeder Cattle Price Adjustments

Monthly price adjustments (multipliers) for feeder cattle (adapted from Meyer, 1997).

Month	Small Feeders (<270 kg)	Large Feeders (>270 kg)
January	1.000	1.020
February	1.030	1.005
March	1.073	1.025
April	1.043	0.995
May	1.010	0.975
June	1.003	1.000
July	0.987	1.015
August	0.997	1.025
September	0.970	1.005
October	0.950	0.970
November	0.963	0.975
December	0.970	0.985

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