Advances in Tillage Research in North American Cropping Systems

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SUMMARY. Numerous innovations in tillage systems have significantly altered agricultural production in North America. Mechanical, biological, and chemical innovations reduced labor requirements, increased yields and crop residues, and reduced pest impacts. Regional trends in tillage systems and equipment are the result of evolving design driven by soil, plant and climate factors that affect erosion, water conservation, and offsite nutrient control. Within the past three decades, technological advances led to an increased interest in conservation tillage systems to replace intensive conventional tillage practices. For agriculture to be sustainable, it requires improved soil tillage and residue management systems. New technology consisting of precision agricultural techniques

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The authors would like to acknowledge the helpful comments and suggestions from several colleagues and especially those who provided recent reprints for this review: Ken Potter, John Morrison, Henry Janzen, Martin Carter, Harold van Es, Con Campbell, Jeff Mitchell, Wayne Reeves, Warren Busscher, Roger Veseth, Denis Angers, J. R. Salinas-Garcia, Mike Lindstrom and many others who contributed to this chapter.

[Haworth co-indexing entry note]: "Advances in Tillage Research in North American Cropping Systems." Reicosky, D. C., and R. R. Allmaras. Co-published simultaneously in *Journal of Crop Production* (Food Products Press, an imprint of The Haworth Press, Inc.) Vol. 8, No. 1/2 (#15/16), 2003, pp. 75-125; and: *Cropping Systems: Trends and Advances* (ed: Anil Shrestha) Food Products Press, an imprint of The Haworth Press, Inc., 2003, pp. 75-125. Single or multiple copies of this article are available for a fee from The Haworth Document Delivery Service [1-800-HAWORTH, 9:00 a.m. - 5:00 p.m. (EST). E-mail address: docdelivery@haworthpress.com].

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10.1300/J144v08n01_05

and yield maps has already begun to change tillage systems. Agriculture's impact on global increase of carbon dioxide (CO_2) requires more sequestration and maintenance of high soil carbon (C) levels for enhanced soil quality. The best soil management systems involve less soil disturbance and more focus on residue management within a geographical location as driven by economic and environmental considerations.
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KEYWORDS. Physiographic regions, climate regions, management land resource areas, conventional tillage, conservation tillage, mechanical, chemical, and biological innovations and controlled traffic concepts, tillage systems

INTRODUCTION

Tillage or soil preparation has been an integral part of traditional agricultural production. Tillage is the mechanical manipulation of the soil and plant residue to prepare a seedbed where crop seeds are planted to produce grain for our consumption. Tillage fragments soil, enhances the release of soil nutrients for crop growth, kills weeds, and modifies the circulation of water and air within the soil. Intensive tillage can adversely affect soil structure and cause excessive break down of aggregates leading to potential soil movement via tillage/water erosion. Intensive tillage accelerates soil carbon (C) loss and greenhouse gas emissions, that impact environmental quality. New knowledge is required to minimize agricultural tillage impacts on the environment. This review emphasizes more precise definitions of "conventional" and "conservation" systems in various regions of North America. Emphasis will be placed on conservation tillage impacts on soil C management and environmental quality issues considering the general trend from intensive tillage to more conservation-based tillage practices over the last thirty years.

Tillage Terminology–Conventional versus Conservation

When most of the primary conventional tillage (CT) used the moldboard plow, the use of "conventional" terminology was not a problem. However, as technology changed and shifted toward "conservation" tillage, accurate terminology has become increasingly important. The term "conventional" is not universal in its meaning and "conservation" is an umbrella term that includes many other types of tillage [including no-till (NT)] and residue management systems that require specific definition of the tillage tools, soil interaction, and

residue response to the tillage operation. Conservation tillage encompasses combinations of cultural practices that result in the protection of soil resources while crops are grown (Allmaras and Dowdy, 1985). The definition of conventional versus conservation tillage also depends on the geographic location and specific soil conditions. As of 1994, Agriculture and Agri-Food Canada defined conservation tillage as "tillage methods that leave most of the crop residue (trash) on the surface of the soil (including minimum tillage methods)" and conventional tillage as "the tillage methods that incorporate most of the crop residue into the soil." This is in contrast to the commonly accepted US definition of 30% cover at seeding. Presently, reduced soil disturbance involving a combination of tillage and herbicides for weed control and land preparation for the next crop are being widely used in the Great Plains and could be appropriately called the conventional system for that region. In the Texas High Plains, Unger and Skidmore (1994) suggest that stubble mulching is now the conventional form of tillage replacing the moldboard plow and disk harrow. In South Carolina, Bauer and colleagues (personal communication, 2000) suggest that no soil surface disturbance has become conventional in the Coastal Plains replacing the disk harrow as the primary tool. In the Midwest region of the US, our observations suggest that fewer and fewer farmers use the moldboard plow and are now using deep chisel plows or combination tillage tools composed of residue cutting disks, chisel plows, "subsoil" shanks and covering disks. As new technology develops and new tillage and planting equipment become available, we should discontinue the use of the vague and nondescript terms of "conventional" and "conservation" terminology and provide explicit descriptions of equipment for tillage, residue management and planting. Terminology for conservation tillage practices became confusing when research agencies and manufacturing companies reporting and promoting "minimum-tillage," "reduced-tillage," "ridge-tillage (RT)," "mulch-tillage," "zero-tillage," and "NT" without defining attributes of soil and residue mixing. An accurate description requires listing all operations in the system and should be the prime consideration in discussing various conservation tillage systems. Because of the number and diversity of available conservation tillage systems across North America, following these guidelines will provide a clearer understanding of soil disturbance or mixing and residue management when the specific tillage tools used in the system are described.

Merits and Demerits of Conservation Tillage

The merits of conservation tillage systems are recognized throughout North America. Increased interest in conservation tillage arises from economic and environmental advantages of these systems over CT practices. Concern over tillage/water/wind erosion and increased pressure to farm land unsuitable for conventional tillage practices has led to the development of "reduced" tillage and residue management systems commonly referred to as conservation tillage systems. Both depth and frequency of tillage are reduced. The emphasis is placed on conserving crop residue and leaving 30% cover on the soil surface to protect the soil from raindrop or wind impacts and minimize soil erosion (CTIC, 1995). Mulch-till, no-till, and ridge-till are conservation tillage-planting systems because they fulfill the 30% surface residue cover requirement and they maintain crop residue in the upper 10 cm of the soil (Allmaras et al., 1998). The 30% cover is a function of tillage, but there are more functions that cannot be determined unless the tillage tools are known. A common problem related to 30% cover criterion as the only method to determine tillage is that less than 30% cover usually occurs with the moldboard tillage, but non-moldboard tillage after sparse crop residue can also produce less than 30% cover. Yet the crop residue environment below the surface is markedly different.

Some advantages of conservation tillage are improved timing of planting and harvesting and increased potential for double cropping and conservation of soil water through decreased evaporation and increased infiltration, and reduced fuel, labor, and machinery requirements. One disadvantage is that residue on the soil surface delays soil temperature increases which in temperate and cold climate regions impedes the germination and early crop growth and allows increased potential for insect and disease damage to crops. With conservation tillage systems, there is a need for more precise management of soil fertility and weed control to achieve maximum yields. One limitation for social acceptance of conservation tillage is an old aesthetics about the "trashy residue" on the soil surface relative to that of clean, tilled fields based on tradition, but this aesthetic is changing.

Definition of Tillage Systems

Tillage systems can be identified according to their overall objectives such as conventional or conservation, or systems can be described according to the primary tillage implement, e.g., moldboard plow, chisel plow, or disk harrow (Reeder, 2000). Defining tillage systems by objective gives a sense of why a particular system is being used and/or the desired outcome. Terms such as NT or RT refer to the system's basic strategy to meet an objective. Conservation tillage should include NT, zero till, direct seeding (drilling), slot plant, strip till, RT, and mulch till. Conventional till should include clean tillage, and may or may not include minimum till or reduced till concepts.

Conventional tillage is often thought of as two major operations: (1) primary tillage and (2) secondary tillage. Allmaras et al. (1998) suggest two categories to distinguish the use of the moldboard plow versus other tillage tools for primary tillage. Primary tillage displaces and shatters the soil as it reduces

soil strength and tends to bury and mix plant residues and fertilizers within the tilled zone. Primary tillage is more aggressive, deeper and leaves a rough surface relative to secondary tillage operations. Primary tillage tools are the moldboard plow, chisel plow and various types of combination disc-chisel-subsoil tools designed to disturb the soil to greater depths. However, depending on the features, options and operation of that implement, results of primary tillage will be different as soil conditions change. Secondary tillage varies widely with type and number of operations, penetration is nearly always shallower than with primary tillage tools. Secondary tillage provides additional soil breakup, levels and firms the soil, closes some air pockets and kills some weeds. Tillage equipment often associated with secondary tillage includes disk harrows, field cultivators, spring-tooth harrows, levelers, packers, and other types of finishing equipment. Interpreting tillage system results may be confusing or meaningless when little information about secondary tillage operations is available.

As a result of the potential terminology confusion in different parts of North America, a list of tillage system alternatives can be used to describe the type of tillage operation (after Morrison, 2000). Reeder (2000) and American Society of Agricultural Engineers (ASAE) Standards provided tillage implement descriptions and definitions of agricultural tillage implements (ASAE, 1998a; 1998b) and for soil engaging components of conservation tillage planters, drills and seeders (ASAE, 1999). Generalized definitions of tillage alternatives (based mainly on surface residue coverage) are provided by the Conservation Technology Information Center (CTIC) as follows (CTIC, 1995):

Conventional till (CT): Tillage types that leave less than 15% residue uncovered after planting, or less than 560 kg ha^{-1} of small grain residue equivalent throughout the critical wind erosion period. This generally involves moldboard plowing and sometimes a large number of tillage passes. Sparse crop residue can produce this cover with any tillage system.

Reduced till/Minimum till: Tillage types that leave 15-30% residue coverage after planting or 560-1120 kg ha^{-1} of small grain residue equivalent throughout the critical wind erosion period. This system fails to specify the tillage implements involved.

Ridge till (RT): The soil is left undisturbed from harvest to planting except for nutrient injection. Planting is completed in a seedbed prepared on ridges with sweeps, disk openers, coulters, or row cleaners. Residue is left on the surface between ridges. Weed control is accomplished with herbicides and/or cultivation. This full width tillage usually produces surface residue cover more than 30%, but maybe less when crop residue is sparse. Ridges are rebuilt during cultivation. Specified amount of surface residue is usually from 30 to 50%.

Mulch till: The soil is disturbed prior to planting using tillage tools such as chisels, field cultivators, disks (harrows), sweeps, or blades. Weed control is accomplished with herbicides and/or cultivation. Surface residue cover is usually greater than 30%, and the tillage is full-width.

No-till (NT)/Zero-till: The soil is left undisturbed from harvest to planting except for nutrient injection. Planting or drilling is accomplished in a narrow seedbed or slot created by coulter, row cleaners, disk openers, in-row chisels, or roto-tillers. Weed control is accomplished primarily with herbicides. Cultivation may be used for emergency weed control.

Strip till/Zone till: A modification of NT, sometimes similar to RT. Row width disturbance of less than 25% is necessary to fulfill the surface residue coverage. This variant of no till provides for traffic control in row crops.

The Economic Research Service had developed a tillage-system survey that identified the tillage tools, residue cover and depth of incorporated crop residue (Allmaras et al., 1998, 2000). It also identified surface cover based upon crop residue production.

Tillage Implements

Moldboard Plow

The moldboard plow was the most widespread and important implement of primary tillage in North America until the late 1960s. In humid climates, the soil inversion action is highly effective in burying and killing annual and perennial weeds as well as volunteer crops. The soil loosening action of the moldboard plow is excellent. When used during favorable soil conditions, moldboard plowing results in a clean surface that facilitates secondary tillage and precision seeding, but also leaves the surface susceptible to wind and water erosion. On light, sandy soils, there is a capacity to deeply plow under organic residues, manure and semi-liquid manure mixed with straw in order to amend the fertility status. As tractors and plows got larger, there was more of an effort to plow deeper to eliminate plow pans and subsoil compaction from previous tillage. The moldboard plow promotes pan formation that can limit root development. As horsepower (HP) of tractors and plow share size increased, plowing depth progressively increased to a depth of about 30 cm leaving the topsoil looser and the upper subsoil more dense than before. The direct impact of the moldboard plow is evidenced in the abrupt decrease in porosity at the plow pan (Logsdon et al., 1990). Moreover, loosening decreases the bearing strength of the tilled or topsoil layer. Together, increased load of common agricultural equipment, diminished surface bearing strength and trafficability caused increases in the depth of soil compaction under heavy machines particularly when the soils were wet (Logsdon et al., 1992; Voorhees, 1992).

Chisel Plow

A modified chisel plow in western US wheat (*Triticum aestivum* L.) lands replaced the moldboard and disc plows (Meyer and Mannering, 1961). Chisel plows bury about 40% of the crop residues and leaves the soil surface in a rough condition for infiltration of rainfall and protection from wind erosion. Point type and sweep type tools are used on chisel spring-shanks, which are typically staggered and spaced 30 to 40 cm apart for flow of residue between the shanks. Depth control wheels regulate operational depth. The chisel plow can be considered a reduced-tillage or minimum-tillage implement. The chisel plow is the dominant primary tillage implement in America in 2000. Johnson (1988) field demonstrated that the tool blade on chisel type implements had a marked influence on surface residue cover and surface roughness.

Blade Plow or Sweep Plow

A blade plow or sweep plow is used primarily in the western US Great Plains to cut roots of weeds following small grains. The implement has a large diameter coulter ahead of the shovel to cut residue; most residue remains on the surface. Several V-shaped sweeps (0.76 to 1.83 m wide) are mounted on standards attached to a tool bar or frame. Operating depth ranges from 6 to 13 cm controlled by both width of the sweeps and depth control wheels. Secondary tillage may consist of several rod weeding or harrowing operations for additional weed control and soil firming before planting. This system is called stubble-mulching in some regions.

Field Cultivator

The field cultivator was introduced as a light-weight secondary tillage and seedbed preparation implement with staggered, spaced spring-shanks (Nelson, 1997). Point type and sweep type tools are used on the shanks. Operation depth is regulated by depth control wheels. This implement continues to be the dominant secondary tillage implement. It also facilitates application of fertilizer and pesticides during secondary tillage.

Tandem Disk Harrow

The tandem disk harrow, established as a major tillage implement, was designed with angled gangs of concave disk blades to cut residues and soil and to bury 40 to 60% of the residues. The disk harrow is known to form a subsurface compacted soil layer, but it continues to be used as a major implement to cut crop residues, uproot crop stubble, roughen the soil surface, and to accomplish either primary or secondary tillage. The disk harrow is often considered a reduced-/minimum-tillage implement. It often replaces the chisel system in the more arid climates of the northern Great Plains (Allmaras et al., 1994).

Coulter Carts

Coulter carts consist of a multiple tubular steel mainframes for versatility mounted on a chassis for transport. The cart carries multiple coulters, residue movers and other tillage tools to enhance seeding under extreme residue and NT field conditions. Generally, seed drills and planters are attached to the coulter carts for a one-pass operation. Many of these carts are used in unique reduced tillage systems where zone till is used instead of pure NT or direct seeding. Under certain soil conditions, zone till will give better structure and seed-soil contact and help warm up the soil in cooler areas.

Trends in Tillage Equipment

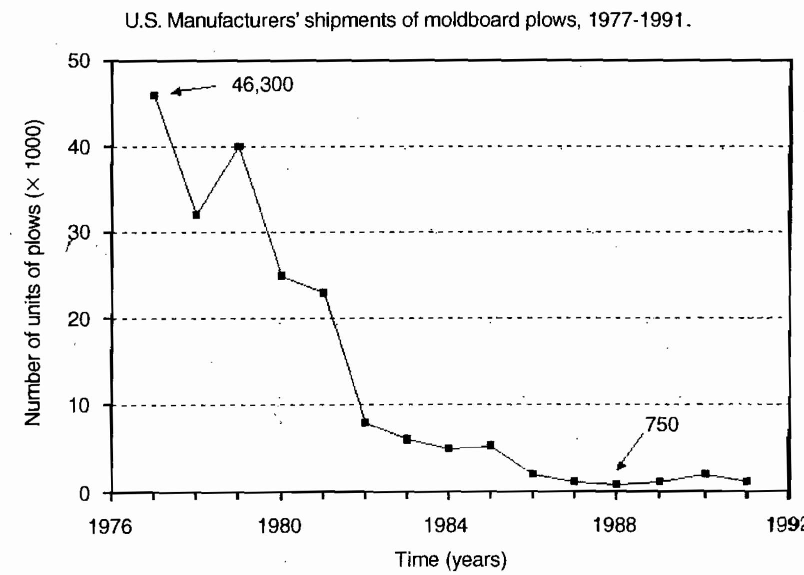
Over the past 60 years, the design of tillage systems and associated equipment has evolved to achieve once over field operations. New equipment design, new herbicides, more fertilizer application, genetically modified (GM) crops, short stature wheat, higher plant density, larger harvest equipment, and innovative farmers all interact to develop new tillage implements. The general trend is toward more surface residue management (Unger, 1999) and less soil manipulation mainly related to economic issues and partly related to the energy requirements and environmental issues. As plant populations and biomass production are increasing (Allmaras et al., 1998), there is more crop residue to manage. The combination of new computer-aided technology that incorporates precision agricultural techniques and yield maps will further change tillage equipment design in North America.

Allmaras et al. (1998) summarized changes in technology and resource conservation from 1940 to 1990. Advances in tillage and planting equipment have directly impacted management of crop residue for soil erosion control and other benefits to soil quality. Crop residues may provide excellent erosion control, both when on the surface or buried near the surface, but also present significant challenges for machinery system design. Adopted technology for soil and water conservation relates to crop residue return, conservation tillage and soil water response to tillage/residue management, crop rotation, machinery, weed management, crop improvement, fertilizer and cropping nutrition management, and disease management technology.

The early popularity of moldboard plows grew as crop production increased until the peak plow production in the US occurred in the 1950s and '60s when 75,000 to 140,000 units were shipped annually (USDA, 1965; USDA, 1977). Gradually, the moldboard plow was replaced by chisel plows, sweeps, combination tools, and disks for primary tillage. In the late 1980s to 1990, fewer than 3,000 moldboard plows were shipped annually in the US. The Department of Commerce reports that the number of moldboard plows shipped by manufacturers dropped from 46,300 in 1977 to 1,400 in 1991 (USDC, 1992) (see Figure 1). Some of the impetus for change came from the new farm bills and stewardship incentives that encourage conservation farming. The primary reasons given by the farmers for this transition away from the plow are efficiency, equipment width, and speed which the multiple combination tillage tools can be pulled through the soil. Other reasons for going away from the moldboard plow range from no more "dead furrows," no headlands, higher skilled operators, leaving residue on the surface for decreased erosion to overall economics. The moldboard plow may have special uses depending on soil type and wetness, but combination tillage tools have become more prevalent over much of the US.

Maintaining crop residue on the surface for erosion control has required a significant modification of seeding equipment; the most obvious change is increasing plant biomass associated with increased yields (Allmaras et al., 1998). Straw choppers and chaff spreaders on combines must uniformly spread the residue at harvest to improve subsequent residue management

FIGURE 1. Number of moldboard plows shipped in the U.S. from 1977 to 1991.



Source: Economic Research Service–U.S. Dept. of Commerce, 1982. [AERI/production inputs]

(Douglas et al., 1989). Seeding equipment requires more downward force in NT than other forms of reduced tillage because of soil strength and more soil engaging tools per seeded row. Devices have been added to seeders to move crop residues away from the openers and seed furrow. These include coulters to cut residue ahead of openers, scuffer wheels or angled disks and residue managers to move residue to the side (Morrison et al., 1988; ASAE, 1998a, 1998b). Coulter carts with triple disk openers, large diameter disks, offset double disks, and angled single disks have been incorporated to improve cutting through surface residue and soil (Tessier et al., 1991). This type equipment is mounted to precede the air seeders and enables rapid seeding of large areas.

As farms get larger and are managed by fewer people, the need for larger equipment is evident to keep all operations timely. Increased HP is required to pull the larger implement and to power the hydraulics needed to achieve once over operations. The average power of tractors sold in the US increased dramatically from 20 kW in 1950 to over 50 kW in 1982 (Allmaras et al., 1998). At present, various types of tracked or wheeled tractors are available that have average power well over 100 kW. The largest track tractors have a power rating of 306 kW (410 HP) and the largest 4WD wheeled tractors have a power rating of 317 kW (425 HP). These larger power units pull larger tillage, planting, transporting, and harvesting machines often at faster speeds. Numerous technological advances in the last 20 years have helped deliver engine power to the appropriate mechanical operation. These technological advances in tractor design also have impacted the adoption of conservation practices.

Axle weight, contact pressure and soil conditions are major factors controlling the degree of soil compaction (Voorhees, 1992). Axle weight of tractors has increased as much as 500% with tractor power in the last 60 years, but contact pressure of wheel tractors has not changed greatly. As a result, subsoil compaction has increased. This increased axle weight is often problematic in spring when soil is wet and more conducive to compaction. To minimize soil compaction, the use of triple wheels on all-wheel drive tractors or crawler tractors to pull the tillage equipment is now common. Many of these trends are driven by timeliness of operations for economic reasons; that include earlier seeding and ability to cover more land in less time. The weight of loaded harvest equipment and soil water content at harvest are big factors to minimize soil compaction.

Conservation tillage systems that leave more crop residue on the soil surface in wet, heavy soils may be more susceptible to compaction unless controlled traffic techniques are used (Reeder, 2000). Controlled traffic is a soil compaction management concept that separates traffic zones from cropping zones within a field. Compaction is managed, but not eliminated. Controlled traffic improves traction, flotation, and timeliness of planting, spraying, and harvesting while minimizing potential yield losses from compaction. Controlled traffic eliminates overlaps and skips during application pesticides and fertilizers and during seeding that typically waste 10 to 15% of chemicals, seed, fuel, and other operational expenses. The first requirement of this concept is to make all equipment cover the same width, or multiples of that width with common wheel and traffic patterns. Adapting controlled traffic is no simple change, but eliminating waste from overlaps, and reduced yields from any gaps in application, may quickly pay for the extra investment in controlled traffic (Reeder, 2000).

Today, most weed control is accomplished using herbicides instead of mechanical cultivation. A major change in tillage for weed control has occurred with the development of Genetically Modified Organism (GMO) that includes crops resistance to various herbicides. Alternative management practices that limit negative herbicide and environmental impacts provide more environmentally sound options. Similar GMOs with incorporated insect resistance also affect tillage decisions. The increase in flexibility and economic returns are a result of the decreasing cost of using this new technology to replace cultivation for weed and insect management.

Crop rotations are an integral of tillage systems. When cover crops and double cropping are used in climates where the cold season permits plant growth, the rotation cycle length includes cover crops, double crops, and full season crops. Crop rotation is highly regionalized whereas the adoption of tillage systems is not significantly regionalized (Allmaras et al., 1998). More of the non-moldboard systems are being used successfully in all crop rotations. Crop rotation is perhaps the most notable technology where practice and research recommendation differ. The additional benefit of cover crops is in the control of pests while continuing with conservation tillage innovations and reducing chemical use (Karlen et al., 1994a; Reeves, 1994).

Tillage rotation is practiced somewhat in corn-soybean rotations (Hill, 2001). Uninterrupted NT ranged from 2.5 (Indiana) to 1.4 (Minnesota) years in soybean-corn rotations of the Corn Belt; 77% of farmers have tried NT in Indiana. The difference between Indiana and Minnesota is likely a thermal effect.

The amount of crop residue on the surface after tillage is influenced by the tillage tool. This information about surface cover is widely published (e.g., Unger, 1999). The residue burial pattern of depth distribution and concentration differs between tillage tools such at each tillage tool has a specific pattern (Staricka et al., 1991, 1992; Allmaras et al., 1988, 1996). These specific patterns persist when primary tillage is followed by secondary tillage (Allmaras et al., 1996). The moldboard plow causes about 75% inversion for each passage (e.g., each year in continuous moldboard systems) so that the older residue is placed near the surface while fresh residue is buried below about 15 cm. Other tillage tools including chisel and disk harrow buried the new residue with the old residue near the surface. These residue positions when using the same primary tillage tool year after year helped to explain erosion control based on soil surface roughness, surface residue and residue incorporated in the 0 to 15-cm depth.

REGIONAL OVERVIEW OF TILLAGE SYSTEMS IN NORTH AMERICA

Tillage and cropping systems are interdependent. The type of tillage depends on crops and crop rotations adopted in a given geographic region. The crops grown are selected based on climate variables, including water and temperature limits suitable for crop growth. The type of soil and tillage tool interaction depends on clay content and type of clay as it affects the cation exchange capacity, water holding capacity, soil organic carbon (C) and fluxes of water, air, and solutes. The spatial variation of the climate regions and soil types and their direct interaction in crop production require that we discuss advances in tillage research in North American cropping systems based on loosely defined geographic regions.

Any discussion of tillage systems must include purposes and tools used. A "tillage system" is a sequence of operations that manipulate the soil and residue to produce a crop. Reeder (2000) compiled an up-to-date discussion of tillage systems and related issues in the US. Morrison (2000) presented a brief review of the history of NT farming in America and discussed the recent developments in conservation tillage. Allmaras et al. (1991, 1994) discussed tillage management regions within the US based on soil types and management land resource areas. Allmaras et al. (1998) reviewed research technology inputs that have transformed American agriculture in the last 60 years to better understand the contributions of science and technology to soil and water conservation. In Canada, Carter (1994a) provided an excellent review on conservation tillage systems. In Mexico, Claverán et al. (1997) and Tapia-Vargas et al. (2001) summarized recent tillage system and erosion research. Excellent overviews of tillage and residue management are also presented by Unger and Skidmore (1994), Hatfield and Stewart (1994), Paul et al. (1997), Lal et al. (1998), Magdoff and van Es (2000), and Allmaras et al. (2000). All of these reports were heavily drawn upon in this review.

Allmaras, Unger, and Wilkins (1985) delineated nine tillage management regions in the US. The boundaries of these tillage management regions did not follow state boundaries, but instead geographical classification used common climate, topography, soils, land-use practices to solve conservation problems. Within a tillage management region, the technological problems and potential for development of conservation tillage should apply throughout the region. Several reviews (Allmaras et al., 1991; Allmaras et al., 1998) have shown conservation tillage to be adapted sooner in those tillage management regions

where more summer than winter crops are adapted. In 1998, reduced-tillage was used on 27% of America's farmland, while NT, strip-tillage, RT, and mulch-tillage totaled 37% of the land (CTIC, 2000). Moldboard plowing and an excessive number of operations ("conventional" tillage) were used on 36% of the land. Using statistics that identify the specific tillage tools, present day moldboard tillage is about 7% (Allmaras et al., 2000).

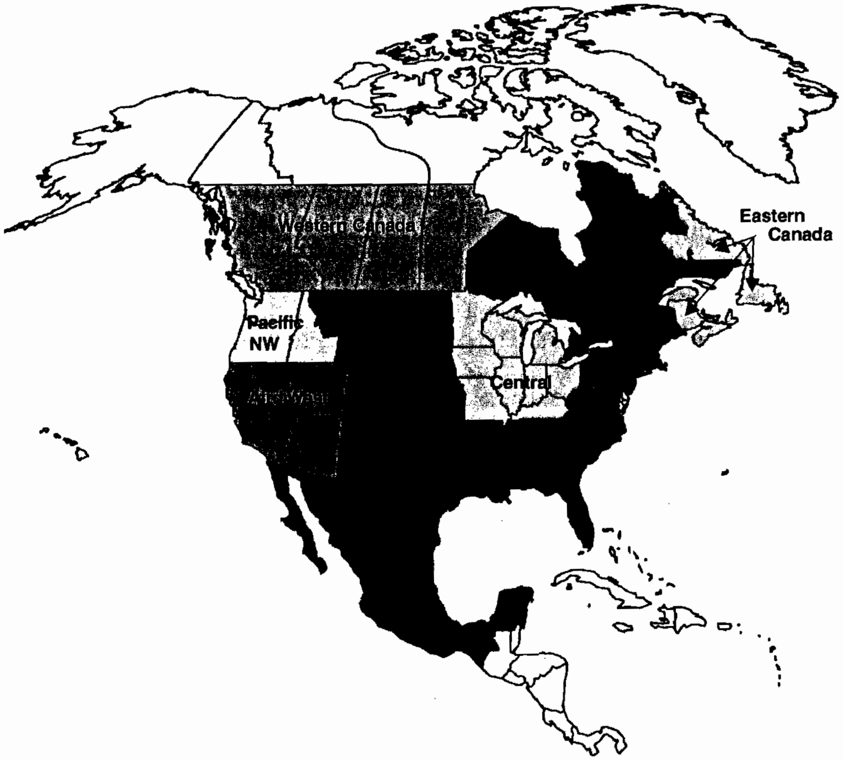
Factors influencing interaction of tillage tools and soil properties are the same factors that affect soil formation and variability across North America. The general forces of weather as described by Jenny (1941) are an active expression of the five major factors: climate, living organisms, parent material, topography and time, which largely control the kind of soil that develops and how that soil might interact in a tillage operation. These five factors for soil formation are critical in determining what types of tillage tools are required for achieving expected outcomes. The corresponding factors for determining tillage type required for a given soil are summarized by Reeder (2000). Selecting the most appropriate system for a particular soil and cropping sequence requires matching the operations to the elements that include crop sequence, topography, soil type, drainage, and weather conditions.

A specific agroecosystem depends on many factors that can be characterized using physical, chemical, biological, and socioeconomic principles. At present, there is not a unified approach to describe agricultural cropping or tillage systems that addresses the above factors. However, in most inventories of agricultural and tillage systems, climate and soil type are major factors. They play an important role in describing various tillage systems and any changes that have taken place in the last 20 years. Soil conservation problems and tillage management systems can be grouped geographically. Soil water and temperature must be managed in all regions. As a result of these complications, we will attempt to define tillage and crop production systems within geographic regions with similar soils and climate. Based on common climate, topography, soil, land use, and cultural practice for a given geographic area, the North American continent was divided along state or province boundaries. This report summarizes the findings for each of these regions to offer a glimpse at the regional characteristics and changes in tillage equipment associated with water and temperature regimes and natural variability across the continent. In many cases, research has been done on a regional level to solve problems within specific physiographic areas. Six geographic regions in the US, three in Canada and one in Mexico are defined (Figure 2) to discuss tillage systems.

Northeastern United States (ME, VT, NH, RI, CT, MA, NY, NJ, MD, PA, DE, WV, VA)

A general description of agriculture in the Northeast US was provided by Bennett (1977) and Blevins and Moldenhauer (1995). The soil properties and

FIGURE 2. Geographic regions of North America identified for advances in tillage research.



interaction with high intensity rainfall make the area susceptible to soil erosion in the Appalachian Mountains and the Coastal Plain. The soil degradation and loss that took place with CT has now been reduced with forms of conservation tillage. The Appalachian Mountains' rugged terrain makes the land less attractive for agricultural development because much cropland consists of small fields and narrow valleys. Livestock-based agriculture predominates on the steep hillsides. The Northeast generally receives adequate rainfall for crop production. This precipitation is not always uniformly distributed through the growing season. The growing season is short to intermediate in length, but is generally long enough for growth of major crops that include corn (*Zea mays* L.), wheat, soybean (*Glycine max* L. Merr.), and horticultural crops.

Row crops in the Northeast US traditionally have been produced under clean cultivation with moldboard plowing and disking for seedbed preparation

with several tillage operations after planting for weed control. However, on the sloping lands, wind and water erosion became a serious problem with continued clean cultivation. In the early 1960s, when the advantages of NT or reduced till became evident, researchers questioned the need for extensive secondary tillage as reliable herbicides and NT planting equipment were developed. Conservation tillage practices reduced wind and water erosion significantly compared to clean tillage. Double cropping with soybeans after barley (*Hordeum vulgare* L.) or wheat has become popular in the Piedmont area. Plowing and disking the soil in double cropping systems cause excess soil moisture losses due to additional exposure to sun and wind. Conservation tillage and NT significantly reduced the time between the small grain harvest and soybean planting resulting in a longer growing season for maximum grain production. Planting directly into small grain stubble, conserved soil moisture, reduced soil erosion and caused the soybean plants to set pods higher. The higher pod set aids in harvesting, particularly with wet soil conditions (Blevins and Moldenhauer, 1995).

Cool spring temperatures are major constraints to corn production in Northeast US and a NT system intensifies the problem. Cox et al. (1990) evaluated the influence of a fall moldboard plowed (CT), NT and RT systems on subsequent growth, development and yield of continuous corn. They found yields from NT averaged 10% lower and yields from RT average 5% lower than the CT treatments with drainage. In the undrained experiment, where some flooding occurred in the three-year experiment, grain yields were significantly higher under RT than under CT and NT. They suggested ridge configuration reduced duration of surface flooding from two days to one day, which resulted in increased plant survival, faster growth and development and higher grain yields that led to the conclusion that RT appeared to be a well adopted conservation tillage system.

Karunatilake, Van Es, and Schindlebeck (2000) evaluated the performance of reduced tillage systems after rotation from a perennial crop (alfalfa, *Medicago sativa* L.) on a clay loam soil in northern New York. They compared corn production with plow till, zone till, NT, and RT. They found corn yield was higher under plow till in one year but was similar to NT in the remaining years of the study. They concluded that reduced tillage systems can perform equally or better compared to fall moldboard plow tillage on this clay loam soil if adequate consideration is given to maintaining soil structure.

Tillage during winter is seldom possible due to frozen or excessively wet soil conditions. "Frost tillage" developed by Van Es and Schindlebeck (1995) was a primary tillage practice performed when a frozen layer exists at the surface and the underlying soil is tillable. The frozen layer needs to be sufficiently thick to support the field equipment (generally 5 to 10 cm thick), but still thin enough to be easily shattered by a tillage tool. Van Es, De Gaetano, and Wilks

(1998) determined and mapped the number of days frost tillage can be performed at various recurrence periods. Frost tillage resulted in a rough soil surface, even after thawing, thereby facilitating water infiltration. Soil drying was improved in certain years and residue cover was greater with frost tillage compared to spring tillage. Yields were similar in both treatments, suggesting that frost tillage may be an alternative management option to move more of the fieldwork into the winter months.

Southeastern United States (NC, SC, TN, GA, AL, LA, MS, AR, FL)

The Southeastern US historically has had severe soil erosion and subsequent surface water quality problems. Many soils have root restrictive genetic horizons and hardpans or are underlain by shallow limestone, sand or heavy clay. From a physiographic perspective, the Coastal Plains are flatter than sloping land of the Piedmont and Appalachian Plateau and do not possess a severe soil erosion hazard as described by Campbell, Reicosky, and Doty (1974), Tyler et al. (1994), and Langdale and Moldenhauer (1995). These unique soils have many restrictions that have been exacerbated through moldboard plowing and from compaction with heavy farm equipment. Generally, the coarse textured A_p horizon holds small amounts of soil C (Hendrix, Franzluebbers and McCracken, 1998), plant available water and the hardpan restricts root growth into the subsoil, thereby, limiting water and nutrient uptake of cotton (*Gossypium hirsutum* L.), corn, and soybean.

Conservation tillage is relatively new in the Southeast with many of the aspects not fully understood because soils, climate and farms differ widely across the area. The design of one tillage system to fit all conditions is unrealistic. Annual deep tillage requiring more energy, usually in-row subsoiling, is often necessary in southeastern Coastal Plains hardpan soils to maintain a suitable rooting environment (Busscher et al., 1995). They found that residual "slit" tillage (shallow subsoiling to 15 cm) did not out yield NT the following year. Most of the slits did not persist with only 10% identifiable one year after tillage. Lack of slit persistence in the soil was due to soil collapse and infilling by sand particles. Even though the slits did not persist, slit tillage may be better than deeper subsoiling (46 cm) if performed annually because it conserved energy and maintained yields. Chiseling and subsoiling to increase the rooting depth is rapidly gaining popularity in the Southeast particularly in the Coastal Plains' soils. Yield responses are weather dependent with increases most likely in dry years when water stress occurs at critical stages of plant development. Equipment locally referred to as the "ripper hipper" received some acceptance. This in-row subsoiler loosens hard pans and allows deeper root penetration for water and nutrient extraction. The bedding component of this tool improves water and soil temperature relations for seed germination in the

early spring. Results with the "super seeder," which subsoils under the row with a minimum disruption of surface residue, were also weather dependent (Karlen et al., 1991). It maintained residue on the surface to protect the soil from raindrop impact and minimize soil erosion.

Because of a longer growing season, double cropping soybean after wheat harvest is a viable alternative to monocropped soybean production in the Southeast US. The amount of soil fracture by in-row subsoiling may not be sufficient for soybean grown in narrow rows. Frederick et al. (1998) evaluated the yield response of double crop soybean to surface tillage (disk harrow twice to 18 cm) and deep tillage (four-shank Para Till[1] to 41 cm) when grown in 19- and 76-cm row widths. Soybean seed yields were normally higher for narrow row widths. Seed-yield increases due to deep tillage were greatest when plots were deep tilled before planting both crops and when no surface tillage and narrow rows were used. More recently, Busscher, Frederick, and Bauer (2000) found that spring-only deep tillage maintained lower cone indices in the following double-cropped growing season than fall-only deep tillage. Compared to non-disked treatments, disked treatments produced equal or higher mean-profile cone indices (a measure of penetration resistance). They concluded that if producers deep till only once a year, spring tillage appears to be better for the Goldsboro loamy sand.

Research on rainfed crop production in Coastal Plain soils indicate some form of deep tillage is needed for roots to efficiently extract subsoil moisture. For cotton production using conservation tillage, researchers have reported equipment and cultural practice effects (Burmeister, Patterson, and Reeves, 1995; Naderman, 1993), on soil strength (Busscher and Bauer, 1995), irrigation and tillage (Camp, Bauer, and Busscher, 1999; McConnell et al., 1995). With deep tillage, Frederick and Bauer (1996) reported 25% greater winter wheat yield with no surface tillage in a dry year and no effect in another year with adequate rainfall. They concluded that the probability of yield increases from deep tillage should be greater with no surface tillage than with disking.

Central United States (OH, IN, MI, IL, WI, MN, IA, MO)

The Central US is referred to as the Corn Belt. The soils in the western portion of the Central US are predominantly Mollisols with Alfisols on the eastern edge. Characteristics of tillage interactions with soils and cropping systems are provided by Griffith, Mannering, and Moldenhauer (1977), Allmaras et al. (1994), Lal et al. (1994a), Moldenhauer and Black (1994), Moldenhauer and Mielke (1995), Amemiya (1997), and Reeder (2000). Soils in the northern three-fourths of the region are derived from glacial till while many of the soils in the western part of the region are derived from loess deposits. Corn and soybean are the principle crops in each of the states and account for 75% of total cropland in the Central US, which is prone to accelerated erosion with risks of both off and on-site damage. Nearly 40% of the land in Minnesota was moldboard plowed before soybean planting in the early 1990s (Allmaras et al., 1994). The remainder of planted land was moldboard plowed or NT or RT depending on the soil type. This marked change in tillage management occurred because moldboard plowing was the primary tillage for corn and soybeans as late as 1975. Permanent pasture and small grains have increased in the southern sections with a limited number of horticulture crops grown in the northern states.

Tillage systems used in the Central US vary widely in terms of equipment type, tillage depth, and amount of soil disturbance. Griffith, Mannering, and Moldenhauer (1977) stated that tillage systems during the early 1970s used moldboard plowing in the fall and spring with various forms of secondary tillage using field cultivators or disk harrows. Other forms of spring plowing followed by wheel track planting were employed in some areas, but no longer used. Lal et al. (1994a) discussed the gradual transition from intensive tillage to conservation tillage. They reported that about 45% of the land area in the Central US was in some form of conservation tillage that included NT, RT, strip till, mulch till, and "reduced" till. The principle advantage of using conservation tillage was soil erosion control. Conservation tillage was adapted primarily because reduced time and labor in seedbed preparation. Types of conservation tillage adapted depended on crops, rotations, specific soil type, climate, and drainage conditions. This was illustrated by Iqbal et al. (1995) who studied in-row soil disturbance effects from the use of NT, a single coulter or triple coulters in NT. The triple coulter unit produced the zone of lowest bulk density and penetration resistance, but corn plant emergence and growth rate was the slowest, apparently as a result of soil compaction at the base of the coulters. The results showed the planting method was not compatible with a strip tillage technique and existing soil properties. Conservation tillage methods are generally easier to adapt for crops on soils that are well drained (Allmaras et al., 1991).

The RT system was often used in soils with slow internal drainage (Fausey, 1991; Eckert, 1990). In Ohio, RT was considered appropriate for poorly drained, heavy textured soils where crop growth was limited by cool soil and anaerobic conditions (Erickson, 1982). Data of Fausey and Lal (1989a, 1989b) showed that mean daily maximum soil temperatures measured in April were highest atop the undrained ridges. Ridge tillage and raised beds further away from the drain had higher maximum temperatures than moldboard plow tilled or NT methods of seedbed preparation. An overview by Lal (1990) states that RT reduced labor costs, enhanced soil fertility, improved water management, improved water and wind erosion control, as well as facilitated multiple cropping, enhanced rooting depth and improved pest management. Given all these benefits, why was RT used on less than 4% of the total cultivated land in the Central US (ERS 1994)?

Hatfield et al. (1998) discussed RT research that evaluated trace chemical movement from site of application within the soil to groundwater aquifers. The environmental impacts were generally positive, but depended on soil and climatic factors. Ridge till changed soil temperature and soil water patterns compared to NT and full width moldboard plow/chisel plow and/or disking for the primary tillage. These changes led to improved environment for crop emergence and early growth because of warmer soil temperatures in cool climate and better water relations in moderately or poorly drained soils. Hatfield et al. (1998) concluded that crop production would likely be enhanced by RT systems. Similar benefits were noted on a sandy soil in Minnesota (Lamb et al., 1998).

In humid climates with corn/soybean cropping systems, the moldboard plow system has been the traditional tillage system. Karlen et al. (1994b) found in 12 years of tillage system comparisons with continuous corn, the NT and chisel systems accumulated C in the 30 cm soil layer relative to the moldboard plow system. Carbon return from the primary production was nearly the same for all three tillage systems. Similar results were found in other long-term tillage comparisons of continuous corn and a corn/soybean sequence in Ohio (Lal, Mahboubi, and Fausey, 1994; Dick and Durkalski, 1997; Dick et al., 1998; Huggins et al., 1998). Wander, Bidart, and Aref (1998) demonstrated that tillage methods impacted the depth distribution of soil organic matter (OM) differently in three Illinois soils. Generally, NT increased soil C and particulate OM 25 and 70% compared to CT (moldboard plow after corn and chisel plow after soybean) in the surface 5 cm at the expense of soil C in the 5 to 17.5-cm depth. The results demonstrate the importance of soil type variation and tillage tool interactions in C accumulation.

Deep soil compaction sometimes requires subsoiling clay or clay loam soils to modify soil properties and enhance crop growth (Wu et al., 1995). Evans et al. (1996) found that subsoiling in Minnesota had very little effect on plant growth and no effect on grain yield over three cropping seasons. Subsoiling to 41 cm had significant effects on bulk density and volumetric water content the year after tillage, but in subsequent years, these effects were not significant with random field traffic. Volumetric soil moisture content generally increased in relation to soil bulk density increases. Subsoil tillage impacted crop residue accumulation, but did not affect soil bulk density, volumetric water content or grain yield. Results indicated that subsoiling does not necessarily improve yields or soil moisture availability particularly if pre-existing compaction does not limit root development.

Great Plains of the United States (ND, SD, KS, NE, OK, TX, CO, WY, MT)

The Great Plains has become an important agricultural region in the US because of N fertilizers, weed control, and less summer fallow. This region extends from the Canadian border to southernmost extremes of Texas. The area is often characterized by relatively low rainfall occurring most of which occurs during the summer months. The moisture environment ranges from moist subhumid in the east to semiarid in the west. There is a wide range in temperature from very cold in the north to moderate temperatures in the south. Soils and cropping system characteristics for this area have been reviewed by Fenster (1977), Unger, Wiese and Allen (1977), Unger and Skidmore (1994), Moldenhauer and Black (1994), Stewart and Moldenhauer (1994), and Allmaras et al. (1994). The soils are mostly deep Mollisols with smaller areas of Alfisols in the southeastern portion. Irridisols occur more frequently in the western parts where the cropland is often a small percentage of the total land area. Corn and soybean are the major crops in the western Corn Belt and eastern Great Plains while wheat is the major crop in the drier areas. Allmaras et al. (1994) reported primary tillage with a chisel, disk or a sweep plow was used on most land planted to wheat, corn, and soybean. The sweep plow has been a primary tillage tool since the 1940s in the wheat fallow rotations of the semiarid regions. In the more humid regions, various forms of conservation tillage are more widely used which improves water conservation and reduces soil erosion and degradation. The main limitations of crop production in these semiarid areas are water supply and soil water storage capacity.

Winter wheat and grain sorghum (*Sorghum* ×*alum* [L.] Moench) are the major crops of this region. Cotton is another major crop in the southern portions of the Great Plains, which is often irrigated if ground water is available. Other important crops include corn, sugar beets (*Beta vulgaris* L. subsp. *vulgaris*), various vegetable crops in the southern regions and alfalfa, peanuts (*Arachis hypogaea* L.) and some soybean and a limited amount of oats (*Avena sativa* L.). Crop selections in a rotation depend on water availability and the potential for irrigation.

As in other regions, tillage in the southern Great Plains once considered "conventional" changed with advances in technology. "Fallow" treatments were designed to conserve water by plowing and frequent shallow tillage during the season without a crop. With subsequent wind and water erosion on fallow areas, straw mulching became the "conventional" system in that area (Jones and Johnson, 1983; Unger and Skidmore, 1994). A combination of limited tillage and herbicides for weed control is now widely used and could be appropriately called the conventional system for growing dryland wheat and grain sorghum in the region. With the new straw mulch tillage, large sweeps or blades undercut the soil surface at 5 to 10 cm while retaining most of the crop residues on the soil surface. Straw mulch tillage is effective for controlling wind erosion, provided adequate crop residues are available. Chisel plows are widely used for dryland wheat production, but tillage systems involving the chisel plow seldom retain enough residue on the surface in parts of the region to be classified as conservation tillage (Unger and Skidmore, 1994). For irrigated wheat, the land is usually disked, chiseled and perhaps disked again and furrowed to control irrigation water flow. Moldboard plowing was used by some producers, but has been on a decline (Unger and Skidmore, 1994).

Field experiments in Oklahoma on continuous winter wheat over a 10-year period, compared six different tillage systems: the moldboard plow, chisel plow, disk harrow, sweep, and NT (Epplin, Al-Sakkat, and Peeper, 1994). Wheat yields from moldboard plow tillage systems were consistently greater and showed less variability than yields from three intermediate tillage systems and NT. The lowest yield was from NT. Yield was inversely related to the amount of crop residue cover on the field prior to planting. The yield declines were attributed to rootborne and soilborne pathogens, secondary toxins, and increased weed competition associated with higher crop residue cover. Raun et al. (1998) showed substantial N fertilizer effects on soil C and N in continuous wheat related to biomass and grain yield.

Cropping systems involving fallow are sometimes used in drier regions and can influence soil C storage (Paustian, Elliott, and Carter, 1998). Fallowing has decreased as the role of carbon (C) became more important in maintaining soil physical properties. Salinas-Garcia et al. (1997) evaluated long-term and seasonal changes in soil organic C, soil microbial biomass, soil microbial N, and mineralizable C and N in continuous corn under several different tillage systems in Texas. The tillage treatments examined were CT (shredding and disking stalks after harvest, followed by lifting out the crown stubble in old plant rows and re-bedding with row middles and beds cultivated during fall and winter to control weeds); moldboard plow (shredding and disking stalks after harvest, followed by moldboard plow to 30 cm and field cultivation, then bedding, with row middles and beds cultivated during fall and winter to control weeds); chisel plow (the same operations as moldboard plow but using a chisel plow to 30 cm instead of the moldboard); and "minimum" tillage (shredding and disking stalks after harvest, followed by root and plant stubble lifting and forming low-profile beds with herbicides for weed control); and NT (shredding stalks and spraying herbicides as needed for fall and winter weed control). They found that seasonal distribution of soil microbial biomass C and mineralizable C were consistently greater in non-moldboard plowed tillage systems, averaging 22 and 34% greater than moldboard plow treatments at planting. The greater amount of crop residues remaining with "minimum" tillage and NT may have provided available substrate for maintenance of the larger soil microbial biomass pool and the higher C and N mineralization in the

0 to 20 cm depth during the growing season. Reduced tillage systems that promote surface residue accumulation provided opportunities for increasing C sequestration and mineralizable nutrients within the soil microbial biomass (Franzluebbers, Hons, and Zuberer, 1998).

Potter et al. (1997, 1998) compared NT and stubble mulch management on four dryland cropping systems and found that fallow limits C accumulation. They found NT treatments resulted in significant differences in soil organic carbon (SOC) distribution in the soil profile compared to stubble mulch tillage. The SOC differences were largest in continuous cropping systems. No-till management with continuous crops sequestered more C compared to double mulch treatments. Similarly, Dao (1998) found that with continuous winter wheat, greater SOC storage occurred in NT compared to moldboard plow tillage. Carbon storage in the top 20 cm with NT was increased as available wheat residue increased, but soil C storage in the moldboard system was never sensitive to the amount of wheat residue returned. Peterson et al. (1998) noted smaller SOC losses in NT versus non-moldboard plow tillage in the Great Plains for wheat or sorghum/fallow, continuous wheat or sorghum, and some wheat/fallow/sorghum cropping systems. Differences in the net primary production (C input) can also modify the relative organic C storage in these non-moldboard tillage systems (Wienhold and Halvorson, 1998). Reeder, Schuman, and Bowman (1998) described soil C and N changes in Conservation Reserve Program lands in the Great Plains without tillage for at least 10 years, suggesting some C input from native grasses.

Strip-tillage/zone-tillage was promoted and rapidly adopted in the 1990s for soils which were not friable and benefited from localized loosening and drying in the seed zone prior to seeding. Halvorson and Hartman (1984) reported that as much as 20% of the area of sugar beet production, used shallow powered row-zone tillers (7 to 10 cm deep) with no yield differences compared to conventional and NT systems. Sugar beet strip-tillage systems were also compared on a very fine sandy loam by Smith et al. (1995) who found that both minimum tillage and powered tiller row-zone systems reduced total energy requirements by 60% over conventional moldboard plow systems. Placing fertilizers in the soil prior to seeding is one of several alternatives for strip-tillage (Morrison, 1999). Tillage (10 to 20-cm wide strips) is accomplished with various tools such as knives, sweeps, or rotary tillers. Residue rakes, rolling coulter blades, residue wheels, or other tools may precede the tillage tool to clear a path through residues and control depth. The tilled strips are somewhat similar in condition to the seedbed produced by CT, so that conventional row-crop seeders can be used without the need for excessive ballast weight or downforce springs. Residue rakes are usually attached to the seeders to clear any loose residues from the path of the tillage tool. Compared to NT, strip-tillage usually requires one more field operation to facilitate conservation tillage on

difficult soils. Strip-tillage technology promises to be readily accepted by farmers and useful for many years. As equipment designs are improved and more experience is gained more and more tillage operations become less intensive and more effective for controlling both wind and water erosion in the Great Plains. The continued improvements in conservation tillage in a stepwise matter will lead to even better ways to minimize soil erosion and enhance soil physical properties.

There is uncertainty about conservation tillage in furrow irrigated fields with ample surface residue because the residue "dams" irrigation furrows and prevents uniform water distribution (Carter, Berg, and Sanders, 1991). Research was conducted to compare the agronomic and economic performance of conservation tillage during the establishment years with conventional tillage in furrow-irrigated cropping systems of corn, soybean, winter barley (*Hordeum vulgare* L.), and dry bean (*Phaseolus* spp.) in western Colorado (Ashraf et al., 1999). They found conservation tillage can be used successfully in furrow irrigated cropping system to control soil erosion. Surface residues can be managed without adversely affecting crop yields. They concluded that successful adoption of conservation tillage under furrow irrigation would require growers to adopt new production management practices and possibly purchase new equipment to operate in high residue conditions.

Pacific Northwest United States (ID, WA, OR)

The Pacific Northwest US supports significant areas of both irrigated and rainfed agriculture (Papendick and Miller, 1977; Sojka and Carter, 1994; Papendick and Moldenhauer, 1995). Much of the region's cropland is dry farmed, but significant areas in the Columbia Basin and the Snake River Plains are irrigated. The topography varies from nearly level valleys to steep, sloping uplands interior. Much of the steeper land is located in higher precipitation zones susceptible to soil erosion. Up to 80% of cropland in dry land farming commonly has slopes from 8 to 30% with some exceeding 50%. As a result of the topography and soil properties, water erosion and wind erosion are major concerns. Winter wheat is the major non-irrigated crop and other cereal grains and pea (*Pisum sativum* L.) are also important in areas of high precipitation. Major irrigated crops include potato (*Solanum tuberosum* L.), sugar beets, alfalfa, beans, corn, small grains, and various tree fruits. The climate ranges from humid to subhumid and semiarid on various parts of the mountain areas. The surrounding mountain ranges modify local climate so much that seasonal and annual precipitation in areas of a few kilometers apart may differ by as much as 50% (Papendick and Miller, 1977). Some soils are developed from loess and some are derived from glacial drift. Nearly all of the upland soils contain varying amounts of volcanic ash in the surface layers. Many of the coastal area soils are mainly alluvial. Most of the soils are permeable, well drained. Some are not sufficiently deep to store precipitation for a wide range of crops. Soils in the low precipitation zones typically are fine, sandy loams or silt loams.

Most wheat/fallow or sorghum/fallow rotations in semiarid environments showed soil organic C decline related to tillage systems (Rasmussen et al., 1998). The C storage ranked by tillage method showed NT > non-moldboard tillage > moldboard tillage (Smith and Elliot, 1990; Allmaras et al., 1998; Rasmussen, Albrecht, and Smiley, 1998). Primary tillage with a disk or a sweep plow provided a soil organic C storage superior to a moldboard based system. In an adjacent field trial with wheat/pea, Rasmussen, Albrecht, and Smiley (1998) reported aggrading soil organic C with the non-moldboard system but continued decline with a moldboard system that lasted for more than 30 years. Only the treatment with regular applications of animal manure maintained a stable C content throughout the study.

Tillage for soil conservation on irrigated row crops may not always be NT or even residue maintenance on the soil surface. Subsoiling in furrow or sprinkler irrigation, and small damming basins under sprinkler irrigation are examples of tillage practices that may replace otherwise conventional tillage systems to improve infiltration, reduce runoff, and prevent erosion. Only in the past 8-10 years have NT systems been introduced to irrigated land in the Pacific Northwest (Sojka and Carter, 1994). No-till systems for irrigated land were developed and evaluated by Carter and Berg (1991) and Carter, Berg, and Sanders (1991). They showed cereal or corn can be grown following alfalfa, corn following cereal or corn and cereal following corn without tillage using the same furrows for irrigating the subsequent NT crop. Both erosion and sediment losses were greatly reduced and in many cases completely eliminated. Crop yields were nearly identical without tillage as with traditional tillage. No-till conserved soil by reducing erosion and sedimentation and increased net income as a result of reduced tillage cost. The work of Carter and Berg (1991) and Carter, Berg, and Sanders (1991) demonstrated that conservation tillage can be successful on furrow-irrigated land and is currently the best approach for soil and water conservation in the Pacific Northwest.

Tillage erosion, movement of soil downslope by a mechanical implement, may not be as spectacular or destructive as water erosion from intensive rainfall events. Though recognized as a problem on the steep slopes in the Pacific Northwest, effects of tillage erosion are more subtle and accumulate over long periods of time. Tillage erosion is very severe on the steep slopes especially with moldboard plowing (Papendick and Miller, 1977). On irregular terrain, it is more practical to contour than to farm up and down the hill or across the slopes. Repeated plowing downhill moves large amounts of soil down slope. Plowing accelerates the removal of soils from the hilltops and results in translocation down slope and degradation. Today's faster and more powerful tractors compound this problem by moving the soil even faster and farther with conservation tillage tools.

Arid West (Irrigated) (UT, NV, CA, NM, AZ)

The irrigated valleys of California and Arizona produce numerous high value row crops including many fruits, vegetables, and cotton. Cropping practices are characterized by frequent fertilizer and irrigation inputs and intensive tillage for bed formation. Aggressive tillage practices and associated loss of soil OM have led to recent concerns about soil degradation in the region (Mitchell et al., 1999). Much of the intensive tillage is used to loosen the soil so that it can be reshaped into 1.53 m center-to-center beds for planting various vegetable crops requiring irrigation. Other types of tillage methods are used with emphasis on RT to enable furrow cultivation for the high value irrigated cash crops. An important alternative for potentially reducing such degradation and overall production costs is the use of reduced tillage. In recent years, several conservation tillage systems have been developed including NT, strip till, and RT that are commonly used in the irrigated valleys (Mitchell et al., 1999).

California law requires complete burial of cotton residue to minimize carry-over of the boll worm (*Heliothis armigera*). Typically, four to seven CT passes over the field are required to get complete incorporation of the cotton residue to meet legal requirements. Recently, the Rome-Pegasus[1] plow (Lyle Carter, 2000, personal communication) has been invented as a one-pass cotton tillage tool. After the cotton has been picked, the unit opens the furrow, cuts the tap roots, trenches the standing cotton stalks followed by closing discs for a one-pass cotton residue burial and tillage application. The equipment benefits are cost savings in fuel, operator time, and other farm energy costs. The tillage tool greatly reduces field compaction when compared to current conventional farm practices and also reduces dust emissions and topsoil loss. The incorporation of the cotton residue enhances the soil profile and field trials have shown that boll-worm control is equal to or better than that of conventional moldboard plow tillage. The one-pass operation provides a unique form of residue management. It complies with legal requirements and also leaves the field with ridges for the following crop. The one-pass operation also cleans out the irrigation furrows so that the next crop can be easily irrigated and is equivalent to a RT operation.

In New Mexico, Christensen et al. (1994) observed more soil C storage in NT than in sweep-blade tillage systems applied to a sorghum/fallow/wheat system. Both treatments were converted from long-term moldboard systems without change in cropping systems. They noted a 25% increase in stored C

1. Names are necessary to report factually on available data; however, the USDA neither guarantees nor warrants the standard of the product, and the use of the name by USDA implies no approval of the product to the exclusion of others that may also be suitable.

within five years that indicated a short-term advantage for NT and sweep-blade systems over the moldboard tillage system.

The impact on soil OM and nutrient cycling are increasing in importance with a current renewed focus on agricultural sustainability. In many parts of the world, rice (*Oryza sativa* L.) straw is burned for disease and pest control and for labor and energy savings. However, air quality concerns have dramatically reduced or banned rice straw burning in California. A search for alternate residue management techniques is essential. Eagle et al. (2000) found that straw management affected grain yield in zero N fertilizer plots. They used a heavy roller to roll, crush and flatten the straw into the soil surface prior to winter flooding. The straw effect was mainly due to the greater yields in the straw retained treatments (incorporated and rolled) compared to the straw removed treatment (burned and baled). This unique form of residue management increased the soil N supply and led to a reduction in N use efficiency in the N fertilized plots suggesting that N fertilizer can be reduced when the rice straw is retained.

Eastern Canadian Provinces (NB, NF, NS, PE)

In eastern Canada, soil is traditionally prepared for seeding field crops after fall moldboard plowing followed by a spring secondary tillage. Ketcheson (1977) and Vyn, Janovicek, and Carter (1994) provide a general description of the soils and climate for the eastern Canadian provinces. Much of the area has a continental climate that is modified by the Great Lakes. Glacial deposition is the parent material for the majority of the soils in eastern Canada. Prompted by concerns about soil erosion and high capital and labor investments with intensive tillage, grain and oil seed producers are increasing the adoption of less intensive tillage systems. The main limitation of many of the soils is imperfect or poor internal drainage that may limit crop production. Many fine textured soils in annual crop production areas are systematically tile drained. Some agricultural soils in Prince Edward Island have major limitations of low fertility and poor soil structure mainly evident as dense subsoil. The combination of poor subsoil structure with humid climate conditions causes excessive soil moisture especially in the spring and autumn. Thus, many of these soils are susceptible to soil compaction. Much of eastern Canada's climate supports a wide range of crops including corn, soybeans, potatoes, cereal crops, hay, and pasture.

Carter (1992) determined the physical condition of the soil profile under reduced tillage conditions for winter wheat in eastern Canada. He assessed the response of winter wheat to different tillage treatments in regard to plant survival and grain production. Three tillage treatments were employed: direct drilling (NT), shallow tillage (two passes with a rotary harrow at 10 cm deep), and moldboard plowing to 25 cm followed by a furrow press to reconsolidate the loosened soil. The latter tillage treatment is a one-pass system that eliminates the need for secondary tillage. All tillage treatments retained straw and stubble from the previous crop that was spread during the harvest operation. Direct drilling increased plant survival but not grain yield in the first year compared to other tillage systems. Leaf diseases significantly reduced crop performance under shallow tillage and direct drilling in the second year. None of the tillage systems had adverse effects on the soil strength and field capacity over the 35 cm soil profile depth. Auxiliary measurements indicated relatively large macro pore-volumes under moldboard plowing followed by a furrow press were less efficient in conducting air than macropores under direct drilling that were most prevalent at the lower soil depth.

Fall moldboard tillage is the conventional primary tillage used with potatoes in eastern Canada. Carter, Sanderson, and McLeod (1998) compared spring moldboard plowing and fall chisel plowing in the potato phase of a 3-year rotation. They evaluated the degree of soil loosening, soil macro-structure, soil density, strength and permeability and crop yield and quality. Although moldboard plowing provided an additional 2 to 10 cm of loose soil at the lower depth compared to chisel plow, there were no differences in soil permeability in sandy loam soils. The total potato yield and marketable yield were not influenced by differences in primary tillage over the 3-year period. Use of spring primary tillage and replacement of moldboard plow with a chisel plow, within the potato phase of the 3-year rotation, caused little change in soil physical quality compared to the CT systems. The use of the chisel plow appears to be a suitable alternative to enhance conservation tillage techniques for sandy loam soils.

With the current interest in C cycling processes and the need to assess soil C stocks, Carter et al. (1997) determined potential storage of soil C and N for a wide range of soils under different agricultural management systems. Information was obtained from agricultural soils under intensive tillage over the last 25 years. Some soils in eastern Canada possessed a relatively high potential for OM storage when the appropriate tillage methods were used. Angers et al. (1997) concluded for a range of soils under continuous corn and small grain cereal production in Eastern Canadian conditions, reduced tillage systems did not increase the storage of soil OM in the entire profile, at least in a 5 to 10 year period. Where crop production and residue inputs are not affected by tillage, they found no differences between tillage treatments in total organic C and N storage down to 60 cm. In the surface 0 to 10 cm, C and N contents were higher under NT than under moldboard plow whereas in the deeper levels (20 to 40 cm), the reverse trend was observed. Placement of the residues was a major factor influencing C and N distribution in the soil profile, especially when erosion and deposition occurred (Gregorich et al., 1998).

Vyn, Janovicek, and Carter (1994) reviewed tillage requirements for predominant annual crops in eastern Canada. They focused on tillage systems for corn, small grains, soybeans and evaluated tillage-induced change in soil properties and their effect on soil erosion and crop performance. The autumn moldboard plow tillage system was used as the conventional treatment and compared to other forms of conservation tillage and NT. They showed that reduced grain yields in NT compared to autumn plowed tillage systems could not be attributed to differences in rates of emergence or corn plant population. They concluded that inferior crop performance in the NT system has been attributed to either increased pest and disease problems or poor seedbed conditions. No-till soils have been characterized as having higher bulk densities, higher soil penetration resistance, lower macroporosities, and seedbeds with a greater proportion of coarse aggregates. These inferior soil conditions could inhibit root growth and water availability over the growing season. They further noted that corn performance was unaffected by tillage systems used for the preceding soybean crop.

Little is known about micronutrient availability under different tillage systems. Carter and Gupta (1997) studied the effects of several minimum tillage methods on micro- and secondary nutrient content of barley and soybean. They identified incipient deficiencies and detrimental tillage-induced changes in plant nutrient accumulation in a fine sandy loam Podzol. They evaluated various forms of spring and fall moldboard plow, paraplow (slant-legged soil loosener) followed by rotary harrow, disk harrow, chisel plow, and direct drilling. Reduced tillage had various effects on micronutrient concentration in plant parts, which were probably related to pH changes in the surface soil. Overall, grain micronutrient concentrations in barley and soybean were in the sufficiency range for optimal yield.

Vyn, Janovicek, and Carter (1994) also discussed the development and evaluation of strip tillage systems on corn yields. They evaluated various combinations of in-row soil loosening, in-row surface residue removal and RT planting systems. They found that on sandy loam soils, strip tillage yielded similarly to the autumn moldboard plowing treatment and were generally greater than the NT systems. On silt loam soils, strip tillage yields were intermediate to an autumn moldboard plowing system. On a clay loam soil, strip tillage used as a secondary tillage operation after autumn offset disking resulted in corn yields between those with moldboard plow and NT systems. The ability of strip tillage systems to significantly improve corn performance relative to NT alone indicated that suitable soil conditions can be attained by loosening a relatively small volume of soil (Janovicek, Vyn, and Voroney, 1997). Similarly, Raimbault, Vyn, and Tollenaar (1991) used powered rotary tiller units to produce shallow 12-cm wide tilled strips into herbicide-killed rye (*Secale cereale* L.) cover crop.

The success of reducing tillage is dependent upon the crop, soil type, and the preceding year's crop residue left on the surface. The diversity of crops and soil types associated with many farming operations in eastern Canada make the selection of a single tillage system very difficult. In these soil types and the cool climates, Vyn, Janovicek, and Carter (1994) concluded that with proper management, few situations exist where an autumn moldboard plow tillage system was necessary to ensure economic crop yields. While the particular tillage system may be specific for a crop and slightly different for soybean versus small grain versus corn, use of less intensive tillage and conservation tillage techniques has merit. Due to frequent and often intense rainfall events combined with the relatively complex topography in eastern Canada, conservation tillage techniques that leave residue on the surface are required to decrease severe water erosion.

Soil compaction, in the surface 0 to 20 cm, is common on light textured sandy soils due to vehicular traffic, animal traffic, and natural soil bulk density that is marginal for crop growth. Carter and Kunelius (1998) evaluated non-inversion tillage using a para plow (a slant legged cultivator that loosens the top 10 to 20 cm) on permanent pasture productivity. Penetrometer resistance profiles showed that the loosened soil condition persisted for three to four years. However, the non-inversion soil loosening caused a negative pasture yield response attributed to root injury following the tillage operation.

Sijtsma et al. (1998) evaluated tillage costs in eastern Canada. They assumed similar crop productivity and input costs in two rotations and found that fuel usage for seedbed preparation and crop establishment was lower with several reduced tillage practices (10.0 to 23.7 l ha^{-1}) than conventional moldboard plowing (27.6 l ha^{-1}). The conventional moldboard plowing combined with secondary tillage was the most costly system in both rotations. Replacement of the moldboard plow with various combinations of alternative tillage systems provided annual tillage cost savings of 44 to 60% for the three-year potato rotation and 10 to 40% for the barley-soybean rotation. They concluded that the adoption of various reduced tillage practices would be more economical than a conventional moldboard plow system.

Central Canadian Provinces (ON, QC)

Central Canada contains a large portion of Canada's agricultural land, where soil is traditionally prepared for seeding field crops using fall moldboard plowing followed by a spring secondary tillage. The agroecosystems in the central Canadian provinces have been described by Ketcheson (1977) and Carter et al. (1997). Major crops are corn and soybean with cereals, pasture, and some forages. Approximately 65% of agricultural land in eastern Québec is under cereal and forage production. Most of this land is still being cropped with conventional methods, including primary tillage in fall and secondary tillage in spring, just prior to seeding. Although some progress has been achieved, particularly in the southwestern part of the province, adoption of conservation tillage practices is still lagging compared with other areas of North America.

Constraints to the adoption of conservation tillage in Québec potentially include cool, wet springs, short growing seasons, and variable precipitation patterns. Légère et al. (1997) considered the interactive effects of rotation, tillage, and weed management intensity simultaneously in the cereal cropping system. Their objective was to determine effects of conservation tillage practices and weed management intensity on populations and dry weights of crop and weeds at midseason and on final grain yields in two rotations of barley and red clover (*Trifolium pratense* L.). Tillage treatments were moldboard plow in the fall (15 to 18 cm), followed by spring secondary tillage; chisel plow in the fall (12 to 15 cm), followed by spring secondary tillage; and NT or direct seeding. Spring secondary tillage consisted of two passes of a rigid-tooth finishing harrow. Yields produced under NT were comparable to those in moldboard plow treatments and did not require a major increase in herbicide use. Their findings demonstrate implementation of conservation tillage for spring barley production is feasible in eastern Québec. However, the benefits of conservation tillage practices can only be fully realized if the proper attention is given to crop establishment and weed management.

The adoption of NT systems on clay soils in North America has been hampered by reports of delayed emergence and growth and reduced grain yields, especially following winter wheat in a rotation. Opoku, Vyn, and Swanton (1997) evaluated several conservation tillage and wheat residue management systems that provided favorable seedbed conditions for emergence, growth, and yield of corn following winter wheat on clay soils in Ontario. They found NT yield potential was affected by the amount of wheat residue present. Modifying the spring NT planting system by adopting fall zone till or fall tandem disk produced corn grain yields no different from fall moldboard plow or fall chisel plow treatments. Similar results were observed for soybean by Vyn, Opoku, and Swanton (1998). No-till soybean growth was delayed and yields were reduced with increasing wheat residue left after planting. They recommended fall zone till and fall tandem disk systems as the best conservation tillage alternatives to fall moldboard plowing.

Tillage operations such as plowing are known to increase loss of soil OM (Janzen et al., 1997). Conversely, reduced tillage frequency and increased surface residue increase soil OM. Angers, N'dayegamiye, and Côté (1993) conducted a silage corn production study to determine the influence of reduced tillage practices on soil OM in particle-size fractions and microbial biomass. The three tillage treatments were "minimum" tillage which consisted of two passes of a field cultivator (spring tines) in the spring; RT in which ridges were reformed each spring before planting; and moldboard plow in the fall followed by harrowing in the spring. Moldboard plowing was performed at 18-cm and spring cultivation at 7-cm depths. The ridges were 15 cm high after formation. Silage yields were essentially the same and were not influenced by tillage. Total organic C did not differ among the tillage treatments at any depth sampled. The study demonstrated that, even in cropping systems involving almost no return of aboveground residue to the soil (typical of silage corn production) a reduced tillage intensity can maintain or increase the more labile fractions of soil OM.

Crop rotation and tillage practices can alter OM accumulation and mineralization by changing the structure of the soil through soil disturbance and mixing. Angers, Samson, and Légère (1993) studied changes in water-stable soil aggregation under different tillage and rotations during a 4-year study. They evaluated two rotations of barley and three tillage treatments. The three tillage methods consisted of fall moldboard plowing (15 to 18 cm) with spring secondary tillage, fall chisel plowing (12 to 15 cm) followed by spring secondary tillage and NT. The mean weight diameter of water-stable aggregates did not vary significantly with time under the NT treatment, but decreased significantly under the moldboard plow and chisel plow treatments. The effect of water content on mean weight diameter was less apparent under NT, suggesting that these aggregates were less susceptible to slaking. In a companion study, Angers et al. (1993) found ratios of microbial biomass C and carbohydrate C to total organic C suggested that there was a significant enrichment of the OM in labile forms as tillage intensity was reduced. The ratio of both mild-acid and hot-water soluble carbohydrates to total organic C was greater under NT than under moldboard plowed soil after only three cropping seasons suggesting an enrichment of labile carbohydrates in OM under reduced tillage. Four years of conservation tillage resulted in greater OM in the topsoil layer compared to more intensive tillage systems.

Western Canadian Provinces (MB, AB, SK, BC)

Agroecosystems in western Canadian prairie provinces have been described by Johnson (1977), Larney et al. (1994), and Janzen et al. (1998). Much of this agricultural land is semiar\id and lies east of the Canadian Rockies with a semiarid climate. Soil erosion remains the dominant threat to long-term sustainability of farming and has had an impact on long-term soil productivity via its effect on soil quality. "Plowless summer fallow" whereby crop residues are kept on the soil surface as protection against evaporation and wind erosion has been practiced in western Canada since the area was brought into cultivation. This technique is also called "trash cover farming" or stubble mulching. It is considered CT but has undergone major improvements.

The main crop in the Canadian prairies is spring wheat with barley, canola (*Brassica napus* L.), and flax (*Linum usitatissium* L.) occupying significant portions of the area. Winter wheat is also grown. Mixed farming is prevalent in many provinces and rotations include various proportions of forage legumes and grasses for pasture and hay. A limited amount of irrigation is utilized in southern Alberta where the two main crops are soft spring wheat and alfalfa. Crops grown in selected areas of the Red River Valley in Manitoba include sugar beets, potatoes, corn, field peas (*Pisum sativum* L. subsp. *sativum*), beans, and other specialty crops. Thus, the tillage system used depends on the crop and soil type.

Janzen et al. (1998) reviewed C storage in long-term research sites and found that significant gains in soil C storage occurred with practices such as limited summer fallow, increased use of forage grasses, improved fertility management, and reduced tillage intensity. Cultivation of grassland and forest soils on the Canadian prairie has caused about 20 to 30% loss of soil organic C, apparently related to use of intensive tillage equipment, the disk harrow, chisel plow, and the V-blade plow. Larney et al. (1997) detected a soil organic C increase under NT when compared to intensively tilled systems, but no benefits were apparent relative to the widely used stubble-mulch system.

Hao et al. (2000) studied effects of conventional and reduced till systems on soil physical properties and crop residue conservation for two crop sequences. For wheat and annual legumes, CT consisted of chisel plowing and double disking in fall and light-duty cultivation and harrow packing in spring. Reduced tillage consisted only of light cultivation and harrow packing in spring. For sugar beets, CT consisted of moldboard plowing, double disking, light cultivation, harrow packing, and ridging in fall and spring while reduced tillage consisted of chisel plowing, harrow packing, and ridging in both fall and spring ridging. They found no significant differences between minimum tillage and CT in soil bulk density and penetrometer cone index data. Reduced tillage over CT improved residue cover sufficient to reduce to wind erosion. Crop sequence is crucial to successful implementation of reduced tillage systems for irrigated cropping.

Data from four long-term studies in Saskatchewan were examined for evidence that N fertility was a constraint under NT compared with tilled systems (McConkey et al., 2002). Changes may be needed because of greater water conservation, slower N mineralization, and greater denitrification losses under NT compared to CT. Tillage methods studied were CT systems that involved late fall cultivation and a single pre-seeding cultivation, generally less than 15 cm. In the early years of the study, a disk harrow was used as primary tillage. The reduced tillage system involved only one cultivation prior to seeding. On the CT fallow treatment, one to five tillage operations were performed during the summer with a heavy-duty cultivator and/or rod weeder to control weeds. Herbicides followed by one or two operations with a wide V-blade cultivator or a heavy-duty cultivator provided weed control in reduced tillage fallow. A single pre-seeding cultivation was made on the fallow in the reduced and CT tillage systems. For NT systems, all weed control was accomplished with herbicides and seeding with narrow openers to minimize soil disturbance. They concluded that current fertilizer N recommendations, which were formulated for tilled systems, may be inadequate for maximum wheat production with acceptable grain protein under NT.

Using similar tillage methods, Campbell et al. (2001) found most soil quality responses could be associated with treatment effects on crop residue production and soil inputs. Most of the labile soil quality attributes, e.g., microbial biomass C, light fraction C, light fraction N, and N mineralization were increased by fertilizers, cropping frequency, and by including legumes and rotations with green manure or hay crops with limited impact of tillage method. The greater amount of crop residues and less soil disturbance resulting from changing crop management probably contributed to the observed increase in water stable aggregates after 10 years of NT. As a result of intensive tillage, soils have been degraded and considerable erosion has taken place. Increased adoption of conservation tillage system is seen by many as one of the few options to ensure long-term sustainability and economic viability of the farms across the Canadian Prairie provinces (Dumanski et al., 1986).

Mexico (All States)

Tillage systems and agricultural research in Mexico has largely been driven by crop production as a means to achieve business profitability and a better standard of living for farmers. Claverán et al. (1997) and Tiscareño-López et al. (1999) summarized Mexico's agricultural productivity and much of the recent tillage systems research. Nearly 20 million ha are dedicated to food and fiber production. Agriculture is the main economic livelihood for 25% of the population living in rural areas. Eighty percent of the cropland is cultivated under rain-fed conditions in a gradient of rainfall north-south that ranges from 200 to 2000 mm during the growing season. The dominant soil types are Andisols and some Vertisols. The soils in Mexico are easily eroded under dry or wet conditions due to its lack of structure. At the same time, 85% of the country is classified as arid or semiarid, where potential evapotranspiration exceeds total annual precipitation, so drought imposes a high risk of crop failure. Cropland is also limited by topography such that with intensive tillage, erosion is a major problem. During the 1970s and 1980s, state agencies encouraged expansion of arable land wherever necessary and possible. As a result of such political decisions, temperate and tropical forests have been reduced by 30 and 75%, respectively, since 1960. Today, 65 to 85% of land has been identified as undergoing a degradation process due to soil erosion, nutrient losses, agrochemical pollution, and lake eutrophication. The need to identify appropriate technology to optimize tillage systems and crop production has been realized along with the necessity of implementing soil and water conservation practices to protect the land.

After decades of conventional agriculture based on traditional intensive tillage practices, the steep sloped lands are becoming less productive because soil erosion and nutrient losses have been greatly accelerated. Tiscareño-López et al. (1999) reported on soil conservation methods used with steep slope agriculture conducted at the Lake Patzcuaro Watershed in Central Mexico. Twelve soil and residue management treatments were implemented to evaluate maize with CT (disking stalks after harvest, followed by disk plowing and disk harrowing, then bedding), reduced tillage (shredding stalks and disk harrowing, then bedding), and NT (shredding stalks only) under varying percentages of soil crop residue coverage. In CT, the primary tool was the disk plow. Application of conservation tillage as NT and/or reduced tillage represented a feasible technology to reduce water erosion by 80% and reduced nutrient losses by 60%. They noted that mechanical soil movement from traditional intensive cultivation of the uplands accelerated sedimentation of the lake, with an annual surface area reduction of 70 ha. Conservation tillage technology increased productivity by 24% compared to CT and motivated 1500 farmers to form a regional program to promote NT and crop residue management following a participatory research approach.

Some aspects of crop residue management associated with conservation tillage may be difficult to adopt, especially when farmers need crop residues to feed animals. Any recommendation to leave crop residues in the field requires appropriate shredders or residue cutters for easy residue management and conviction that residue cover is vital for soil protection. However, the largest factor in acceptance of conservation tillage was social limitations, including a strong tradition for farmers to use CT methods. Valdivia and Villarreal (1998) developed the "The Farmer Researcher" program to increase maize productivity in several regions of Mexico with a potential for high productivity.

Salinas-Garcia et al. (2000b, 2001) characterized soil microbial activity, N mineralization, and nutrient distribution in Vertisols and Andisols under rainfed corn production from three tillage experiments located in Michoacán, Mexico. They evaluated CT (disking stalks after harvest, followed by disk plowing and disk harrowing, then bedding), minimum tillage (shredding stalks and disk harrowing, then bedding), and NT (shredding stalks only) under varying percentages of soil crop residue coverage. Reduced tillage and NT treatments significantly increased crop residue accumulation on the soil surface. For all treatments, soil organic C, microbial biomass C and N, N mineralization, total N, and extractable P were higher in 0 to 5-cm depth and decreased with depth, apparently related to residue incorporation. Over the 0 to 20-cm depth of disk plow tillage, the same parameters were generally lower, but more

evenly distributed. Salinas-Garcia et al. (2000b, 2001) concluded that soil OM enhancement with conservation tillage was probably the most important beneficial change in those soils.

Conservation tillage in semiarid lands increased the water available to plants, reduced soil erosion and reduced N loss in runoff. Salinas-Garcia (1997) showed the best conservation tillage response when 33 to 66% residue cover is left on the soil. Soil erosion on irrigated semiarid croplands was reduced by 40 and 49% under chisel plow tillage and NT, respectively, in comparison to disk harrow tillage. Conservation tillage production costs were 15 to 30% lower than those of CT. Additional information on economics of conservation tillage in Mexico was presented by Erenstein (1997) and Islas Gutiérrez (1997). The effect of different tillage methods on corn insects (Carrillo Sánchez, Aguilera, and Lourdes Garcia, 1997) and on the water balance (Scopel and Chavez Guerra, 1997) shows numerous benefits of conservation tillage that lead to sustainable production and economic stability.

In Mexico, it is common to grow two cash crops per year on the same piece of land. This decreases the time available for residue degradation and large quantities of residue can build up, especially in irrigated areas. A common practice is to first burn the residue and then till the soil with the moldboard or disk plow. Smoke from burning residue increases air pollution and raises other environmental concerns suggesting a need for alternative residue management systems. Salinas-Garcia et al. (2000a) found that high quantities of surface residue did not allow the coulters and seed openers to penetrate the soil consistently. The residue was pushed into the soil and folded up on either side of the seed to provide a microenvironment that prevented seed germination. This phenomena has been defined as the "taco effect" since the seed is contained inside a residue shape resembling a taco shell. In the Midwest US, this phenomenon is referred to as "hair pinning" of crop residue. This occurred despite cleaning wheels, coulters, and disk furrow openers on the planter. They suggested need for new management or machinery system techniques to leave only the quantity needed on the soil surface for specific objectives such as erosion and evaporation control.

SOIL EROSION

While tillage is often considered necessary in many agricultural production systems, the associated soil erosion and degradation can lead to increased soil variability and yield decline. Three types of soil erosion are defined: tillage, water, and wind erosion where erosion implies soil movement by some external force. Traditional approaches to characterizing wind and water erosion are highly dependent upon climate (rainfall) and soil type (Lal, 1999). While intensive tillage loosens the soil for greater response to erosive forces of wind and water, the tillage process itself also moves the topsoil downslope.

Tillage erosion or tillage-induced translocation, the net movement of soil downslope through action of mechanical implements and gravity acting on loosened soil, has been observed for many years. Papendick, McCool, and Krauss (1983) reported original topsoil on most hilltops had been removed by tillage erosion in the Pacific Northwest. The moldboard plow was identified as the primary cause, but all tillage implements will contribute to this problem (Govers et al., 1994; Lobb and Kachanoski, 1999). Tillage erosion has become an important factor in soil management considerations and is often confused with water erosion.

Soil translocation from moldboard plow tillage operations has been identified as a cause of soil movement from specific landscape positions that can be greater than currently accepted soil loss tolerance levels (Lindstrom, Nelson, and Schumacher, 1992; Govers et al., 1994; Lobb, Kachanoski, and Miller, 1995; Poesen et al., 1997). Soil is not directly lost from the fields by tillage translocation, rather it is moved away from the convex slopes and deposited on concave slope positions. Lindstrom, Nelson, and Schumacher (1992) showed that soil movement on a convex slope in southwestern Minnesota could result in a sustained soil loss level of approximately 30 t ha^{-1} yr^{-1} from annual moldboard plowing. Lobb, Kachanoski, and Miller (1995) estimated soil loss in southwestern Ontario from a shoulder position to be 54 t ha^{-1} yr^{-1} from a tillage sequence of moldboard plowing, tandem disk and a C-tine cultivator. In this case, tillage erosion, as estimated through resident Cesium137, accounted for at least 70% of the total soil loss. Tillage speed increases nonlinearly the rate of tillage erosion.

The relationship between soil productivity and erosion is complex. Soils are not the sole factors controlling crop yields. The degree to which crop yield losses are related to soils is a function of several interacting factors including soil physical, chemical and biological properties, landscape position, crop grown, management practices, and weather conditions before and during the growing season. Schumacher et al. (1999), used modeling procedures to show that tillage erosion caused soil loss from the shoulder position while soil loss from water erosion occurred primarily in the mid to lower backslope position. The decline in overall soil productivity was greater when both processes were combined compared to either process acting alone. Water erosion contributed to nearly all the decline in soil productivity in the backslope position when both tillage and water erosion processes were combined. While there are many other reasons for intensive tillage, tillage sets up the soil to be loose, open and very susceptible to high intensity rainfall and subsequent erosion. The net effect of soil translocation from the combined effects of tillage and water erosion

was an increase in spatial variability of crop yield and a likely decline in over all soil productivity (Schumacher et al., 1999).

TILLAGE MANAGEMENT AND ENVIRONMENTAL CONCERNS

Concern for environmental quality and greenhouse gas emissions (carbon dioxide (CO_2), methane, nitrous oxide) requires new knowledge to minimize agriculture's impact. The link between global warming and atmospheric CO_2 has heightened interest in soil C storage in agricultural production systems. Agricultural soils play an important role in C sequestration or storage and thus can help mitigate global warming (Lal et al., 1998). The moldboard plow has been the symbol of US agriculture over the last 150 years. Intensive tillage in the US has mineralized or oxidized between 30 and 50% of the native soil C or soil OM since the pioneers brought the soils into cultivation (Schlesinger, 1985). Tillage processes and mechanisms, e.g., tillage-induced CO_2 losses, lead to C loss and are directly linked to soil productivity, soil properties, and environmental issues (Paustian, Collins, and Paul, 1997). Soil C dynamics can have an indirect effect on climate change through net absorption or release of CO_2 from soil to the atmosphere in the natural C cycle. Carbon comes into the system through photosynthesis and is returned to the atmosphere as CO_2 through microbial respiration and anthropogenic intervention. Good soil C management is vital because of its role in maintaining soil fertility, physical properties, and biological activity required for food production and environmental quality. Good soil C management is also needed to partially offset greenhouse gas emissions from manufacture and use of acid fertilizers, liming, and fossil fuels as well as to minimize the release of more potent nitrous oxide and methane. Minimizing agriculture's impact on the global increase of CO_2 requires that we sequester and maintain high soil C levels through decreased tillage intensities and improved residue management.

Sustainable agriculture requires good crop production and rotations using tillage systems and soil management focused on lower inputs and energy use. Moldboard plow tillage is unique in that it inverts the soil sufficiently to adversely affect soil physical, chemical and biological properties, and processes. Less intensive conservation tillage may reduce problems of soil erosion, OM losses, and structural degradation (Carter, 1994b). Conservation tillage, particularly no-till or direct seeding, has potential to reduce negative effects of plow tillage and to allow better C sequestration. Recent technology advances have led to combined tillage and planting operations (NT) as well as herbicide applications that can replace mechanical cultivation (Allmaras, Unger, and Wilkins 1985; Carter, 1994b; and Reeder, 2000).

Tillage affects soil microbial activity, OM decomposition, and soil C loss in agricultural systems. Much of the C is lost as CO_2, which is the end product of microbial feeding on soil OM. Reicosky and Lindstrom (1993, 1995) showed major short-term gaseous loss of C immediately after moldboard tillage that partially explains long-term C loss from tilled soils. Gas exchange was measured using a large, portable chamber to determine CO_2 loss from various types of tillage. Moldboard plow immediately before CO_2 measurement was the deepest and most intensive tillage, and produced more CO_2 loss than other tillages immediately preceding the CO_2 measurement. No-till or no soil disturbance before CO_2 measurement lost the least amount of CO_2. Repeated moldboard plowing allows rapid CO_2 loss and oxygen entry because it loosens the soil and inverts both soil and residue. Much of the CO_2 released initially is from entrapment and storage, and the remainder from accelerated microbial respiration when oxygen entry is accelerated. Long-term plowing accelerates microbial decomposition in the 15 to 30 cm layer and the lack of shallow residue causes aggregate breakdown to ultimately decrease surface soil C content. Ellert and Janzen (1999) and Rochette and Angers (1999) found similar results for different soils and less intensive tillage methods. This interaction of soil and residue mixing enhances aerobic microbial decomposition of incorporated residue to decrease soil organic C (Reicosky et al., 1995). Allmaras et al. (2000) reviewed many field trials that show the moldboard plow tillage system stores less soil organic C than all other tillage systems. They also found that farmers have now reduced their use the moldboard plow to about 7% of the land prepared for corn, wheat, and soybean.

Reicosky (1997) reported that average short-term C loss from four conservation tillage tools was 31% of the CO_2 from the moldboard plow. The moldboard plow lost 13.8 times more CO_2 as the soil not tilled while conservation tillage tools averaged about 4.3 times more CO_2 loss. The smaller CO_2 loss from conservation tillage tools was significant and suggests progress in equipment development for enhanced soil C management. Conservation tillage reduces the extent, frequency, and magnitude of mechanical disturbance caused by the moldboard plow and reduces the large air-filled soil pores to slow the rate of gas exchange and C oxidation.

Strip tillage tools are designed to minimize soil disturbance (Morrison, 1999). Different strip tillage tools and moldboard plow were compared to quantify short-term tillage-induced CO_2 loss relative to tillage intensity (Reicosky, 1998). Less intensive strip tillage reduced soil CO_2 losses. No-till had the lowest CO_2 loss and moldboard plow had the highest immediately after tillage. Forms of strip tillage had an initial soil CO_2 loss related to tillage intensity intermediate between the extremes of plowing and NT. The cumulative CO_2 losses for 24 hours were directly related to the soil volume disturbed by the tillage tool. Reducing the volume of soil disturbed by tillage should enhance soil and air quality by increasing the soil C content. This suggests that soil and environmental benefits of strip tillage be considered in soil management decisions. The CO_2 released immediately after moldboard plowing suggests little C sequestration. Conservation tillage methods that leave most of the crop residue on the surface with limited soil contact yield better C sequestration to enhance environmental quality.

Tillage, through its effect on traffic and soil OM, affects water quality and water use efficiency (Betz et al., 1998). Water is often the most limiting factor for crop production in North America. The soil's capacity to hold water is a function of the amounts of sand, silt, and clay and the OM content. Water holding capacity of soils having the same sand, silt, and clay contents showed that for each percent increase in OM, the water holding capacity of the soil increases by 3.7% on a volume basis (Hudson, 1994). The inverse relationship between intensive tillage and soil OM content leads to the question of tillage impact on water use efficiency. While the role of tillage on infiltration and runoff is generally understood, we are now getting a better understanding of the impact of tillage and soil C on plant available water holding capacity. The contribution of soil OM to water holding capacity and water quality cannot be underestimated. Both of these are key factors in agricultural watersheds for maintaining environmental quality.

CONCLUSIONS

Traditional agricultural production has involved at least five separate operations: (1) tillage, (2) planting, (3) cultivating, (4) harvesting, and (5) processing, transporting, and storage before final consumption. Tillage is on this list because it has historically been an integral part of the production process. Over the last 30 years, new technology is redefining these operations where tillage and planting are combined in conservation tillage and where mechanical cultivation is being replaced by herbicides. Modern, large farm equipment can perform these operations easily and quickly with one pass. Historically, the moldboard plow was an essential tool for the early pioneers in settling the prairies of central and western US and Canada. The moldboard plow allowed the farmer to create a soil environment in which grain crops could thrive and meet the needs of the increasing population. At the same time, the moldboard plow degraded soil from increased water, wind, and tillage erosion as well as biological oxidation of soil OM. In the drier areas, other types of chisel plows and large sweeps are primary tillage tools based on the crops and available water. Tillage is intimately related to the cropping rotations that are limited by soil and water resources within the physiographic region. New tillage systems with emphasis on crop residue management and soil conservation will encompass new technology and continue to evolve around the best systems within a given geographic location as driven by economic and environmental considerations. As new agricultural tillage and planting practices are developed across North America, their impacts on the environment and energy use will need to be evaluated critically to ensure their compatibility and sustainability with society's needs.

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