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COMPILATION OF MEASURED NUTRIENT LOAD DATA FOR AGRICULTURAL LAND USES IN THE UNITED STATES[1]

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ABSTRACT: Measured field scale data are increasingly used to guide policy and management decisions based on comparative pollutant load information from various land management alternatives. The primary objective of this study was to compile measured annual nitrogen (N) and phosphorus (P) load data representing field scale transport from agricultural land uses. This effort expanded previous work that established an initial nutrient export coefficient dataset. Only measured annual N and P load data published in scientific peer-reviewed studies were included in the present compilation. Additional criteria for inclusion were: spatial scale (field scale or farm scale, minimum 0.009 ha); land use (homogeneous, either cultivated agriculture or pasture/rangeland/hay); natural rainfall (not rainfall simulation); and temporal scale (minimum one year). Annual N and P load data were obtained from 40 publications, resulting in a 163-record database with more than 1,100 watershed years of data. Basic descriptive statistics in relation to N and P loads were tabulated for tillage management, conservation practices, fertilizer application, soil texture, watershed size, and land use (crop type). The resulting Measured Annual Nutrient loads from AGricultural Environments (MANAGE) database provides readily accessible, easily queried watershed characteristic and nutrient load data and establishes a platform suitable for input of additional project specific data.
(KEY TERMS: databases; nitrogen; nonpoint source pollution; phosphorus; water quality.)

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INTRODUCTION

Growing demand for land use specific nutrient export information to inform regulatory and educational programs and to support water quality modeling has highlighted the need for a comprehensive database containing measured nutrient loss data. Water quality protection programs require comparative nutrient export information for land management alternatives to prevent excess nutrient loading and the resulting impacts of accelerated eutrophication and degraded aquatic habitat in downstream water bodies. Although estimated values from watershed models, regional relationships, or professional judgment can provide this information, measured field scale data are necessary to substantiate and/or improve these estimates.

Field scale nutrient load data are also needed to better understand nutrient transport mechanisms and sources of variability as affected by soil, land use, climate, topography, and management (Kissel *et al.,* 1976; Sharpley *et al.,* 2002). Small watersheds and field plots established to collect runoff from natural precipitation events are well suited for these investigations (Vervoort *et al.,* 1998, Gilley and Risse, 2000). Measured nutrient transport data are necessary to support nonpoint source model development, calibration, and evaluation. Models are an efficient method to evaluate nutrient loading mechanisms under various conditions, but they rely on monitoring data to improve performance and reduce uncertainty (Sharpley *et al.,* 2002). According to Sharpley *et al.* (2003),

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data are also urgently needed to test and validate nutrient management tools, such as the P Index that was designed to assess risk of phosphorus loss from individual agricultural fields (Lemunyon and Gilbert, 1993). Where such data are available, they should be applied to the fullest extent to support ongoing modeling efforts (Sharpley *et al.,* 2002). However, measured project specific or site specific data are typically not available due to the considerable time, expense, and effort required to collect field measurements (Beaulac and Reckhow, 1982; Gilley and Risse, 2000). In these situations, a comprehensive database containing measured field scale nutrient loss data and corresponding watershed characteristic information would be a valuable resource.

Although several excellent data management systems are available for hydrology and water quality information, they were designed to manage a wide range of data types collected on various scales. These systems include the U.S. Environmental Protection Agency (USEPA) Storage and Retrieval (STORET), U.S. Geological Survey (USGS) National Water Quality Assessment (NAWQA), National Water Information System (NWISW), similar state specific systems, and the recently developed Watershed Monitoring and Analysis database (Carleton *et al.,* 2005). These powerful tools assist in the storage, quality control, manipulation, retrieval, and transfer of data, but they do not typically provide measured field scale data with corresponding watershed characterization information. No comprehensive electronic database populated with field scale nutrient export data is currently available.

The initial effort to gather and compile such data was made in the early 1980s. In a study of lake eutrophication, researchers compiled measured nutrient export data for various sources, including forest, urban, cropland, pasture and grazing land, mixed agricultural areas, feedlot and manure storage areas, atmospheric contribution, septic tanks, and sewage treatment plants. The resulting reports used all available appropriate monitoring information and formed an excellent basis of knowledge on the magnitude and variability of annual nutrient losses (termed "export coefficients") for a variety of land uses (Beaulac, 1980; Reckhow *et al.,* 1980; Beaulac and Reckhow, 1982). This information, however, has not been updated with data collected in the past 25 years or reconfigured in an electronic format.

Based on the need for a current field scale nutrient export data compilation, the primary objective of this study was to compile measured annual nitrogen (N) and phosphorus (P) load data representing field scale transport from agricultural land uses. The resulting publicly available database provides nutrient load data and corresponding watershed characteristics from numerous field scale studies. Because of its format and design, this populated database should provide readily accessible, easily queried information to support water quality management, modeling, and future research design. The database also establishes a platform allowing user input of additional project specific data.

The original version of this database is being used in two current projects evaluating land management impacts on water quality. In 2003, the U.S. Department of Agriculture (USDA) began a national project, the Conservation Effects Assessment Project (CEAP), to assess the environmental benefits of conservation practices implemented under the Farm Security and Rural Investment Act of 2002. Within CEAP, USDA-NRCS, USDA-ARS, and Texas Agriculture Experiment Station scientists are conducting an assessment of conservation practice effects at the national scale (Mausbach and Dedrick, 2004). The database is being used in CEAP to create site specific datasets for calibrating and testing Agricultural Policy Environmental eXtender (APEX) model simulations (Williams *et al.,* 1998) representing National Resources Inventory (NRI) data point locations across the country. APEX is being used to estimate nutrient and sediment loading at these locations for the CEAP National Assessment. Furthermore, the breadth of data contained in the database provides a means of comparing physical relationships in observed data to those in simulated values.

The database is also in use for development and evaluation of a Bayesian version of the USGS SPARROW (SPAtially Referenced Regressions On Watershed Attributes) model (Smith *et al.,* 1997). SPARROW relates instream water quality measurements to spatially referenced characteristics of watersheds, including contaminant sources and factors influencing terrestrial and stream transport. The model empirically estimates the origin and fate of contaminants in streams and quantifies uncertainties in these estimates based on model coefficient error and unexplained variability in the observed data. The Bayesian SPARROW model introduces the dynamic modeling of nutrient transport between subwatersheds and uses a conditional autoregressive approach to explicitly account for spatial correlations not included in the stream networks (Qian *et al.,* 2005). The current Bayesian SPARROW application was based on noninformative prior probability distributions for all the model parameters. The database will provide the basis for the prior probability distribution in the Bayesian SPARROW model and provide information for the relative plausibility of the various source coefficient values (betas in the usual SPARROW notation), thus assisting in model implementation and/or data poor situations.

METHODS

Literature Survey (Data Compilation)

Data compilation involved a two-phased approach. First, data were compiled from the agricultural land use studies reported in Reckhow *et al.* (1980). Relevant studies conducted on cultivated agriculture and pasture/range/hay land uses were collected, and nutrient load data with corresponding watershed characteristics were compiled. Then an extensive literature survey was conducted on additional and more recent published studies that reported measured annual N and P data from agricultural land uses. Only studies that appeared in peer-reviewed scientific journals were collected, and thus the extensive amount of informal data (e.g., gray literature) was avoided. As a result, data included in the database appear in readily available studies that have received rigorous scientific review. In compiling relevant studies, a sincere effort was made to include all available studies conducted in the United States that meet the criteria outlined in Table 1.

Specifically, only measured annual N and P load data from field scale and farm scale studies were included. Nitrogen and phosphorus were chosen because they often control biological productivity, which impacts dissolved oxygen levels in streams and lakes and overall aquatic ecosystem health (Sharpley *et al.,* 1987). Nitrate and nitrite also impact drinking water quality and are listed as primary drinking water pollutants by the USEPA (2003). Data collected on periods shorter than one year were excluded because of the effect on nutrient export of temporal variability of weather, cropping patterns, and nutrient application. Data measured from watersheds with multiple land uses were not used because of the difficulty in determining the relative contributions from each land use; however, information on relative contributions, integrated effects, and downstream transport deserve further research. Data from rainfall simulation studies were excluded in an effort to address only field scale effects from natural rainfall and runoff mechanisms.

Database Development and Population

Watershed characterization, nutrient load, soil loss, and hydrology data were extracted from each publication that presented results meeting the previous criteria. These data were then entered into Microsoft Access 2000, and the resulting database was named Measured Annual Nutrient loads from AGricultural Environments, or MANAGE. Generally, each database record was created from a single publication, but occasionally multiple publications with data from the same watershed(s) were used to create a record. Each record in MANAGE represents a watershed or watersheds with similar land management over a given time period and contains the following categories (headings):

1. *Auto Number* – Automatically assigned identification number.

2. *Watershed ID* – Name of the watershed. If not specified, a watershed ID was assigned based on watershed management characteristics.

3. *Location (city, state)* – City and state or province of the study (occasionally only a county or region was specified).

4. *State* – U.S. state (or Canadian province) included to aid state specific queries.

TABLE 1. Criteria Used to Select Studies for Database Inclusion.

	Included	Not Included
Contributing Land Use	Single Land Use	Multiple Land Uses
Land Use Types	Cultivated Agriculture Pasture/Rangeland/Hay	Forest Urban
Contributing Area (ha)	> 0.009	< 0.009 ha
Nutrients	N P	K, Ca Mg, S
Study Design	Annual Nutrient Loads Natural Rainfall Measured Results Surface Runoff	Nutrient Concentrations Rainfall Simulation Modeled Results

5. *Location (latitude, longitude)* – Latitude and longitude of the study.

6. *Date* – Beginning and end of period with annual nutrient load data (not necessarily the entire study duration).

7. *Watershed Years (ws yr)* – Product of the number of monitored watersheds and the number of years with annual nutrient load data. Some temporal overlap occurred in studies at Chickasha, Oklahoma, and thus data from the coincidental studies were not separated.

8. *Land Use* – Identification of crop or vegetation type(s), crop rotations, grazing management, artificial drainage, and dryland or irrigated.

9. *Tillage* – Description of the tillage management divided into four options: no-till, conservation, conventional, or pasture. The first three options are intended to represent the dominant tillage management alternative for watersheds with cultivated crop production. Conservation tillage represents a range of practices design to leave crop residue on the soil surface. The pasture option represents rangeland, improved pasture and hay land; all of which may be grazed (indicated in the Land Use Category No. 8).

10. *Conservation Practice 1, Conservation Practice 2, Conservation Practice 3* – Description of conservation practices used in the study watershed(s) divided into five options: waterway, terrace, filter strip, riparian buffer, or contour farming. This category was repeated three times to account for multiple practices used in conjunction.

11. *Dominant Soil Type* – Soil textural class and soil series. If only the soil series was specified, the USDA-NRCS Official Soil Series Descriptions (OSD) (USDA-NRCS, 2005) available online at http://soils.usda.gov/technical/classification/osd/index.html was used to assign a textural class.

12. *Hydrologic Soil Group* – NRCS hydrologic soil group (HSG) classification (A, B, C, or D). The HSG was rarely specified, but it is an important general soil characterization that warranted inclusion. Therefore, the HSG was derived from Appendix 3B, Hydrologic Soil Groups (Haan *et al.,* 1994) and from the USDA-NRCS Official Soil Series Descriptions (OSD) (USDA-NRCS, 2005) if the soil series name(s) was specified. The HSG was estimated from NRCS definitions as presented in Haan *et al.* (1994) if only the soil texture was specified.

13. *Soil Test P (ppm)* – Maximum and minimum soil test P values for records with multiple watersheds or multiple years.

14. *Soil Test P Extractant* – Extractant used to determine soil test P.

15. *Land Slope (percent)* – Maximum and minimum land surface slopes for records with multiple watersheds.

16. *Watershed Size (ha)* – Maximum and minimum watershed sizes for records with multiple watersheds.

17. *Fertilizer Formulation 1, Fertilizer Formulation 2* – Type of fertilizer applied. This category was repeated twice to account for multiple fertilizer formulations. The common name, chemical name, and/or macro-nutrient composition (given as percent N-P-K) of the fertilizer(s) was input based on specified information.

18. *Fertilizer Application Method 1, Fertilizer Application Method 2* – Fertilizer application method divided into four options: surface, injected, incorporated, or other. This category was repeated twice to account for the multiple formulations presented in the Fertilizer Formulation Category No. 17.

19. Annual maximum, minimum, and average values are provided for the following categories when specified:

a. *N applied (kg/ha)* – The total annual amount of N applied to watershed(s) from all fertilizer sources.

b. *P applied (kg/ha)* – The total annual amount of P applied to watershed(s) from all fertilizer sources.

c. *Precipitation (mm)*.

d. *Runoff (mm)*.

e. *Soil Loss (kg/ha)* – The total measured soil loss from the watershed(s).

f. *Dissolved N (kg/ha)* – The total amount of N lost from the watershed(s) in a dissolved form.

g. *Particulate N (kg/ha)* – The total amount of N lost from the watershed(s) in a particulate form (associated with sediment).

h. *Total N (kg/ha)* – Total N load was specified in a number of the publications. If the total N load was not specified, it was determined as the sum of dissolved and particulate N loads, when both were specified.

i. *Dissolved P (kg/ha)* – The total amount of P lost from the watershed(s) in a dissolved form.

j. *Particulate P (kg/ha)* – The total amount of P lost from the watershed(s) in a particulate form (associated with sediment).

k. *Total P (kg/ha)* – Total P load was specified in a number of the publications. If the total P load was not specified, it was determined as the sum of dissolved and particulate P loads, when both were specified.

l. *Form* – Specific form or laboratory analysis technique used to determine dissolved, particulate, and total N or P composition in runoff.

20. *Total, Surface, Base Flow Indication* – Indication of the flow transport mechanisms addressed; however, annual loads were input only for runoff water leaving the watershed(s). Runoff may include storm runoff as well as base flow contributed by seepage (reemergence of lateral subsurface flow) and was identified as such when specified. Data on subsurface water quality were not analyzed but were indicated in this category. Results on "drainage" from artificially drained watersheds were included only in the notes section.

21. *Comments* – Additional information. Examples include: subsurface loads from areas with artificial drainage, supporting publications, data estimation procedures, and missing data.

22. *Reference* – Complete citation of each publication used to develop the database record.

The most difficult aspect of populating the database was working with the various formats of N and P load data presentation in the publications. In certain publications, nutrient loads were presented only in figures without corresponding numerical values. Although this format aided in visual comparison of treatments, it necessitated estimation of nutrient load values. The numerous and varied methods of tabular data presentation created additional difficulty. In the collected studies, data were reported with various formats of time (e.g., seasonal, annual, annual mean); watershed (e.g., individual watershed, treatment specific); nutrient form (e.g., dissolved/soluble N and P, particulate N and P, total N and P, NO_3-N, NH_4-N); and analytical method used. For "total" nutrients, it was often unclear whether the digestion or other analytical method was performed on the water, sediment, or the combined sample. Faced with these various formats, necessary calculations and estimations were made to produce mean, maximum, and minimum annual nutrient loads, which were entered into the database. Because of these difficulties and the possibility of errors in estimating values and gleaning data from publications, users should exercise caution when basing decisions and recommendations on these data. We suggest that data of interest be confirmed with the original source prior to drawing consequential conclusions.

Data Analysis

After relevant studies were collected and appropriate data were compiled and entered into the database, a limited number of general summary and comparative analyses were conducted. Watershed information was summarized to illustrate the distribution of study site characteristics. Specifically, location, land use (crop type), tillage management, conservation practices, soil textural class, watershed size, and fertilizer formulation were analyzed. The data distributions were tabulated based on watershed years (ws yr) because this format represented the data distribution better than alternatives such as number of studies, records, or watersheds. When percentage values are reported, they represent the percent of ws yrs represented by that characteristic, unless otherwise noted.

Annual nutrient load data were then evaluated by several methods. Where applicable, potential linear relationships between nutrient loads and selected field characteristics were evaluated with regression analyses. Nutrient loads were compared to watershed size to explore the impact of scale and were compared to nutrient application rate to evaluate the direct effects of fertilizer application. Dissolved, particulate, and total P loads were also compared to soil test P levels. The effects of tillage, conservation practices, soil textural class, and land use on annual N and P loads were also compared. Graphical procedures were used to examine and display potential differences for each treatment, and statistical differences in median annual loads were determined with Mann-Whitney tests.

All statistical tests were performed with Minitab 13 software and procedures described in Helsel and Hirsch (1993), Minitab (2000), and Haan (2002). All tests of significance were conducted at an *a priori*, $\alpha = 0.05$, probability level. As stated previously, annual nutrient load data were presented with a variety of formats in the various publications. From these varying datasets, annual mean, maximum, and minimum values were determined and used to populate the database. Because individual annual values were not available for all of the watersheds, the statistical comparisons do not strictly adhere to all rules and assumptions of standard statistical design. Therefore, the statistical results are presented for general comparative purposes only.

RESULTS AND DISCUSSION

Measured annual nutrient load data from 40 publications (listed in Table 2) were entered into a Microsoft Access 2000 database. The resulting 163-record MANAGE (v1) database contains approximately 1,100 ws yrs of annual N and P loads. The original MANAGE database and an updated version (v2) are available at no cost from the authors or online at http://www.ars.usda.gov/spa/manage-nutrient. Future, expanded versions will be available as updates are completed.

Study Site Characterization

Measured annual nutrient load data were obtained from 15 U.S. states (Table 3) and two provinces in Canada. The Canadian data were included to help fill in geographic gaps in the northeastern and northwestern United States. Texas and Oklahoma contributed the most data, but the southeast and central states were also well represented. No data were available from the Pacific Northwest, Rocky Mountains, or New England states. Watersheds established and/or operated by USDA-ARS, which were designed to provide long term data collection necessary to address temporal and spatial variability, provided more than 830 ws yrs (75 percent) of annual nutrient load data. A majority of the ARS data was collected from watersheds located in Treynor, Iowa; Coshocton, Ohio; Riesel and Bushland, Texas; Tifton, Georgia; Morris, Minnesota; and El Reno, Woodward, and Chickasha, Oklahoma.

Land use fit well into three general categories: cultivated crops, pasture/range/hay, and various rotations (Figure 1). Cultivated crops made up the largest category, contributing 41 percent of the data. Data from fields with corn production provided 22 percent of the annual nutrient load data; oats/wheat contributed 10 percent; and other crops including cotton, peanuts, soybeans, and sorghum contributed 1 to 2 percent each. The pasture/range/hay category, which includes uncultivated grazed, ungrazed, and hayed land uses, provided 33 percent. Data from pasture (assumed to represent improved pasture) provided 16 percent, native prairie grasslands 10 percent, managed rangeland 4 percent, and alfalfa 2 percent. The various rotations category, which represents a wide range of land use conditions, contributed 27 percent of the data. This category contains data that were presented based on rotation behavior as a whole; therefore, individual annual values representing each crop within the rotation were not specified.

TABLE 2. Refereed Publications Presenting Measured Annual N and/or P Load Data Meeting the Criteria Listed in Table 1.

Publication (short reference)
Alberts *et al.,* 1978
Alberts and Spomer, 1985
Angle *et al.,* 1984
Berg *et al.,* 1988
Burwell *et al.,* 1974
Burwell *et al.,* 1975
Chichester and Richardson, 1992
Drury *et al.,* 1993
Edwards *et al.,* 1996
Grigg *et al.,* 2004
Harmel *et al.,* 2004a
Harmel *et al.,* 2004b
Harms *et al.,* 1974
Jackson *et al.,* 1973
Jones *et al.,* 1985
Kilmer *et al.,* 1974
Kissel *et al.,* 1976
Lee *et al.,* 2003
Long, 1979
McDowell and McGregor, 1980
Menzel *et al.,* 1978
Nicholaichuk and Read, 1978
Olness *et al.,* 1975
Olness *et al.,* 1980
Owens *et al.,* 2003
Pierson *et al.,* 2001
Schuman *et al.,* 1973a
Schuman *et al.,* 1973b
Sharpley, 1995
Steinheimer *et al.,* 1998a
Steinheimer *et al.,* 1998b
Tate *et al.,* 1999
Thomas *et al.,* 1968
Udawatta *et al.,* 2002
Udawatta *et al.,* 2004
Vervoort *et al.,* 1998
Vories *et al.,* 2001
Weidner *et al.,* 1969
Wood *et al.,* 1999
Young and Holt, 1977

TABLE 3. Locations of Studies With Measured Annual N and P Load Data That Meet the Criteria in Table 1.

	Watershed Years	Number of Studies
U.S. States		
Alabama	24	2
Arkansas	24	2
California	19	1
Georgia	93	4
Iowa	105	8
Louisiana	16	1
Maryland	6	1
Minnesota	109	3
Missouri	27	1
Mississippi	10	1
North Carolina	8	1
Ohio	132	2
Oklahoma	268	5*
South Dakota	14	1
Texas	200	6*
Canadian Provinces		
Ontario	24	1
Saskatchewan	24	1
Totals:	1,103	40

*One study analyzed nutrient losses from sites in both Oklahoma and Texas.

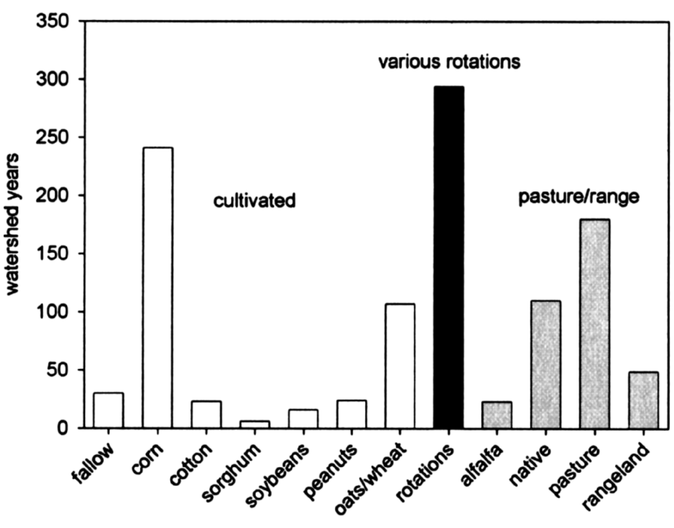

Figure 1. Distribution of Annual Nutrient Load Data Based on Watershed Years for Each Land Use Category and Crop Type.

Data for a wide range of tillage management conditions were obtained (Figure 2). Conventional tillage management sites provided the most annual nutrient load data (42 percent). Sites with conservation tillage provided 16 percent, and no-till provided 9 percent. Uncultivated sites in the pasture/range/hay land use category contributed 33 percent. Conventional tillage was used almost exclusively on studies from the 1940s through the 1960s. In the 1970s, data were collected under mostly conventional and conservation tillage but also under limited no-till management. By the 1980s and 1990s, conventional, conservation, and no-till management were all being actively studied. Summary data for conservation tillage are presented here and thus are not included in conservation practice discussion even though conservation tillage is widely accepted as an effective conservation practice.

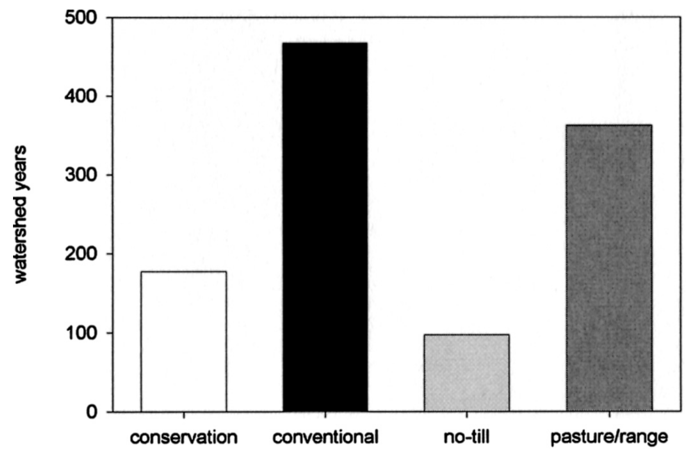

Figure 2. Distribution of Annual Nutrient Load Data Based on Watershed Years for Each Tillage Category.

Much of the nutrient loss data was collected on fields with no conservation practices (although 16 percent occurred under conservation tillage as discussed previously). Approximately 24 percent of the data occurred on areas with at least one conservation practice, and 15 percent occurred on fields with more than one conservation practice (Figure 3). Sites with contour farming provided 20 percent of the data, grassed waterways 14 percent, terraces 10 percent, and filter strips and riparian buffers less than 5 percent each.

Data were available for a wide range of soil textures, from heavy clays in the Texas Blackland Prairies to sandy soils in the Southern Coastal Plain. Sites with loamy soils contributed the most data (Figure 4). Soils in the loam and silt loam soil textural classes contributed 24 percent and 40 percent respectively, but sites with fine textured clay loam (9 percent) and clay soils (11 percent) also contributed substantial data. Similarly, the distribution of data was dominated by sites with hydrologic soil groups B (62 percent), which have moderate infiltration rates and textures, and D (18 percent), which have high runoff potential and fine textures.

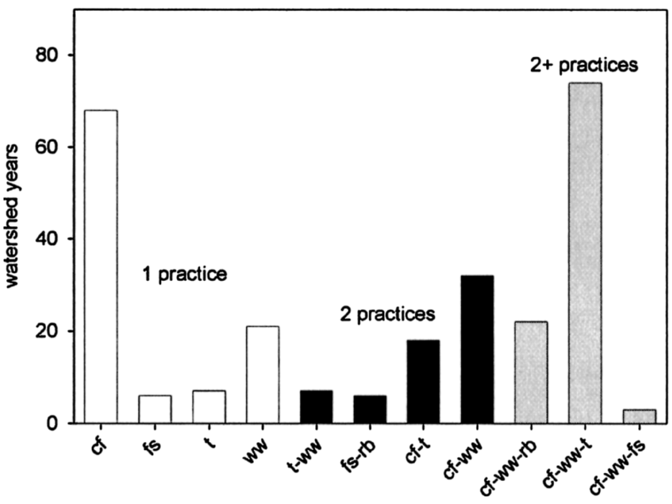

Figure 3. Distribution of Annual Nutrient Load Data Based on Watershed Years Occurring on Fields With Various Conservation Practices (cf, contour farming; t, terrace; ww, waterway; rb, riparian buffer; fs, filter strip).

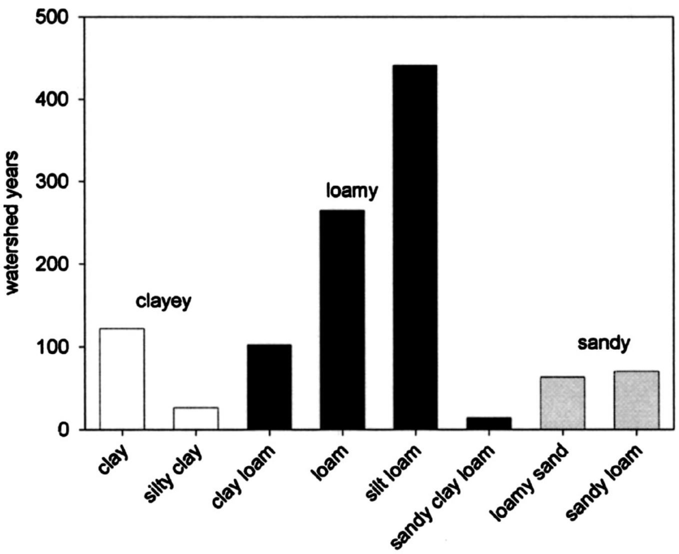

Figure 4. Distribution of Annual Nutrient Load Data Based on Watershed Years for Each Soil Textural Class.

Much of the compiled annual nutrient load data was collected on watersheds of less than 10 ha (Figure 5). This result is attributed to the single (homogeneous) land use criteria for including measured data in this database. Small plot and field scale studies are typically designed to evaluate conditions with homogeneous land use, which explains the predominance of small watersheds. The likelihood of heterogeneous land uses, which were excluded in this compilation, increases as watershed size increases.

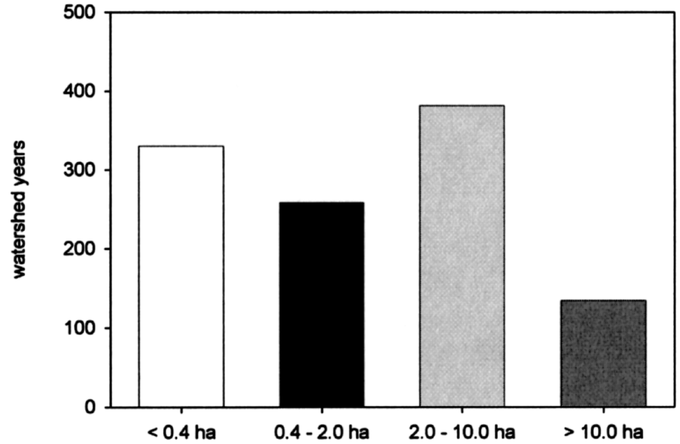

Figure 5. Distribution of Annual Nutrient Load Data Based on Watershed Years for Various Watershed Sizes.

Many fertilizer management strategies were used on the study sites, as illustrated in Figure 6. Inorganic fertilizers were most commonly applied (52 percent), but several different formulations were used, and the formulation was often unspecified (15 percent). Organic fertilizer (poultry litter, cattle manure) application occurred in only 8 percent of the ws yrs. No fertilizer was applied in many cases (26 percent) but mostly under fallow, grazed, and native prairie grassland conditions. Surface application without incorporation accounted for 25 percent and with incorporation for 23 percent, but often the method of fertilizer application was not specified (47 percent of ws yr). Fertilizer injection occurred in 5 percent of the ws yrs.

Nutrient Load Comparisons

Annual N loads exhibited no significant linear relationships with field size; however, dissolved, particulate, and total P loads all significantly decreased as field size increased. Although these relationships are significant, considerable variability existed (all adjusted R^2 values < 0.07). The results for N were expected because fields were defined in this study as units of homogeneous land use and management, particularly nutrient management. In contrast, reduction of nutrient loads, on a per area basis, would be expected for larger watersheds with mixed land uses, as the entire watershed would not typically receive fertilizer application. Possible causes for decreasing P loads with increasing watershed size include dilution as an increasing amount of base flow contributes to watershed export; landscape processes as infiltration, readsorption of soluble P in runoff, and redeposition of eroded sediment with particulate P increase; and channel processes as the role of channel sediments in regulating P concentrations increases as size increases (Sharpley *et al.,* 1999, 2002).

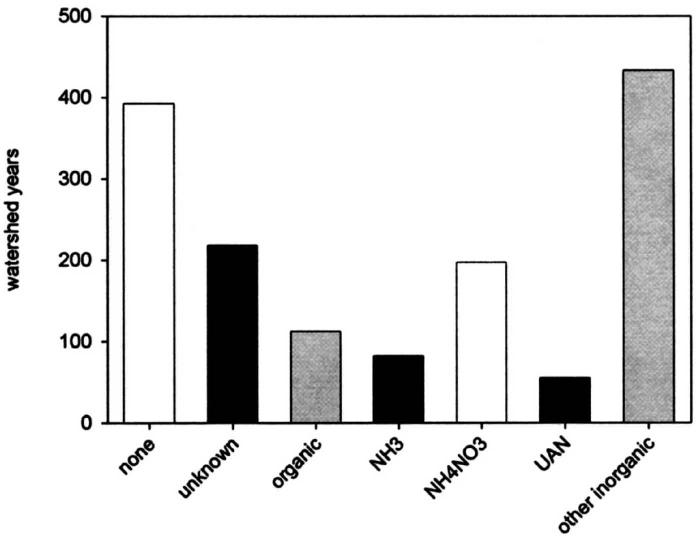

Figure 6. Distribution of Annual Nutrient Load Data Based on Watershed Years for Various Fertilizer Types. The sum of watershed years exceeds 1,103 because a combination of fertilizer formulations was often used.

In terms of annual loads, only dissolved N was significantly related to application rate. Considerable variability existed between all of the N and P forms and nutrient application rates (all adjusted R^2 values < 0.08), but annual dissolved N loads did increase with increasing N application. The lack of correlation between application rate and particulate N, total N, and all forms of P loads can be attributed to the overriding effect of soil erosion and transport on particulate N and P loss in certain situations (Sharpley *et al.,* 1987; Harmel *et al.,* 2004b). Particulate N and P losses contributed, on average, three times as much as corresponding dissolved forms. Differences in runoff volumes, soil interaction, plant uptake, watershed physical characteristics also have been shown to contribute to nutrient loss variability (e.g., Sharpley *et al.,* 1987; Pote *et al.,* 1996; Harmel *et al.,* 2004b) and to dampen the effect of application rate.

Significant linear relationships were evident between soil test P and dissolved, particulate, and total P loads, although the variability was quite large with adjusted $R^2 < 0.19$ (Figure 7). Although numerous researchers have determined that soil test P is related to P in runoff (e.g., Pote *et al.,* 1999; Sharpley *et al.,* 1999; Torbert *et al.,* 2002), such studies focused on P concentrations, not P loads, because load analysis is subject to the confounding influence of differing runoff volumes (e.g., Pote *et al.,* 1996). Recent manure/litter applications also have been shown to temporarily weaken or overwhelm the relationship between soil test P and runoff P concentrations (Sharpley and Tunney, 2000; Pierson *et al.,* 2001), although two recent field scale studies yielded

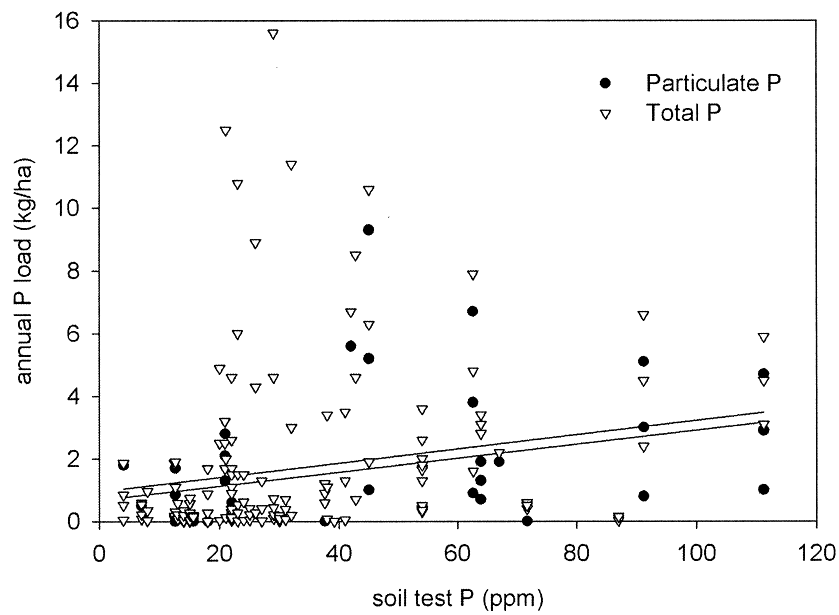

Figure 7. Scatter Plot and Regression Lines for Soil Test P Levels and Particulate and Total P Loads.

contrasting results regarding the relative importance of manure applied P and soil test P on annual dissolved P loads (DeLaune *et al.,* 2004; Harmel *et al.,* 2005). The relative contribution of recently applied nutrients and nutrients in the soil profile affects the environmental impact of agricultural P and thus deserves further research and management consideration (Sharpley *et al.,* 2002).

Several results differed from commonly accepted behavior in the comparison of median annual nutrient loads for the various management practices. These unusual results, however, were not surprising because nutrient loads were grouped across widely varying site characteristics including soil texture, slope, crop, tillage, fertilizer, rainfall, and conservation practices. The studies compiled also differed in the type of nutrient load data collected. Specifically, numerous combinations of dissolved, particulate, and total nutrient load data and various analytical tests were reported. Differences in runoff also tend to confound nutrient load results; thus nutrient concentrations are commonly examined. Although these confounding influences created difficulty in drawing strong conclusions across varying conditions, they support the need for a database such as MANAGE that allows users to select only relevant data.

The influence of tillage on nutrient loads is shown in Table 4. Median particulate N loads for sites with conventional tillage exceeded those from conservation tillage and no-till sites, as expected with increased soil erosion (Figure 8). In contrast, particulate P loads did not differ significantly in conventional, conservation, and no-till tillage management. Dissolved N and P loads were highest for no-till management, probably because fertilizer is not incorporated. Median N and P loads from cultivated conditions tended to exceed those from pasture/range/hay because the noncultivated sites typically received less fertilizer and have permanent vegetative cover. Figure 9 illustrates the potential of extreme dissolved P loads when excessive manure is surface applied (unincorporated) in pasture settings. These large P loads occurred in years with high poultry litter application rates and continued due to residual soil P in years when only N was applied (Pierson *et al.,* 2001). Large P loads also can occur in cultivated conditions despite incorporation when high rates of manure are applied (Weidner *et al.,* 1969).

The effects of conservation tillage were discussed above among other tillage management options; therefore, conservation tillage is not included in the following discussion of conservation practices such as waterways, terraces, riparian buffers, and filter strips. The influence of conservation practices on nutrient loads was more variable than tillage impacts (Table 4). In this analysis, the data were expected to show reduced total and particulate nutrient loads with conservation practices; however, while conservation practices did reduce nutrient loads in specific studies (e.g., Udawatta *et al.,* 2002; Lee *et al.,* 2003), no clear tendency was shown in the overall data (Figure 10). The reduced impact of conservation practices

TABLE 4. Median Annual Dissolved, Particulate, and Total N and P Load Values (kg/ha) for Selected Treatments.

Treatment*	Total N (kg/ha)	Dissolved N (kg/ha)	Particulate N (kg/ha)	Total P (kg/ha)	Dissolved P (kg/ha)	Particulate P (kg/ha)
Tillage						
Conventional	7.88a	2.41a	7.04a	1.05a	0.19b	0.64a
Conservation	7.70a	2.30ac	3.40c	1.18ac	0.65ac	1.00a
No-Till	1.32b	4.20c	1.80bc	0.63c	1.00c	0.80a
Pasture/Range	0.97b	0.32b	0.62b	0.22b	0.15b	0.00b
Conservation Practice						
None	2.19a	1.60a	1.70a	0.41a	0.26ab	0.64ab
One Practice	6.73b	1.33a	14.80a	0.61ab	0.14a	0.37a
2+ Practices	8.72b	2.61b	3.30a	1.22b	0.50b	0.75b
Soil Texture						
Clay	4.93a	4.47a	2.00a	0.92a	0.50a	0.55a
Loam	4.05a	1.64b	5.78b	0.41b	0.18b	0.93a
Sand	2.74a	1.70ab	–**	1.50ab	0.07ab	–**

*For each nutrient form within a treatment, medians followed by a different letter are significantly different ($\alpha = 0.05$).
**No particulate N or P data were available for sandy soils.

can be attributed to varying site characteristics, differences in load data collected and analytical tests used, and probably most importantly, the tendency to establish practices in conditions vulnerable to erosion and nutrient loss.

effectiveness, the need to quantify and better understand their watershed scale performance is crucial. This need is illustrated by a recent USDA commitment and initiation of CEAP as described in Mausbach and Dedrick (2004).

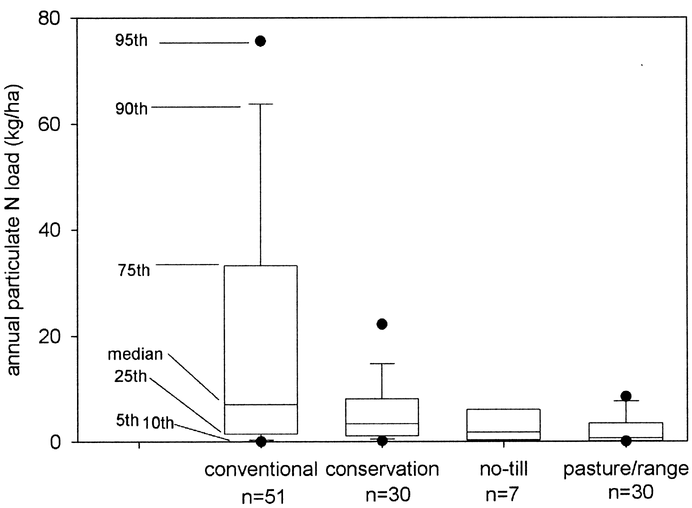

Figure 8. Annual Particulate N Loads Under Various Tillage Management Alternatives.

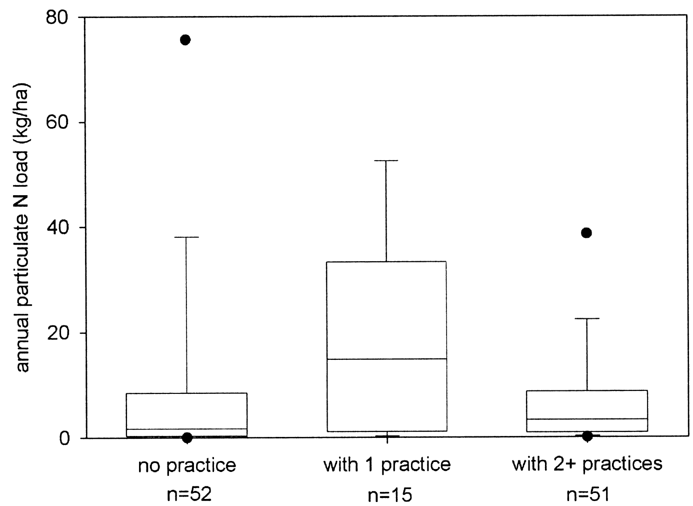

Figure 10. Annual Particulate N Load Data With and Without Conservation Practices.

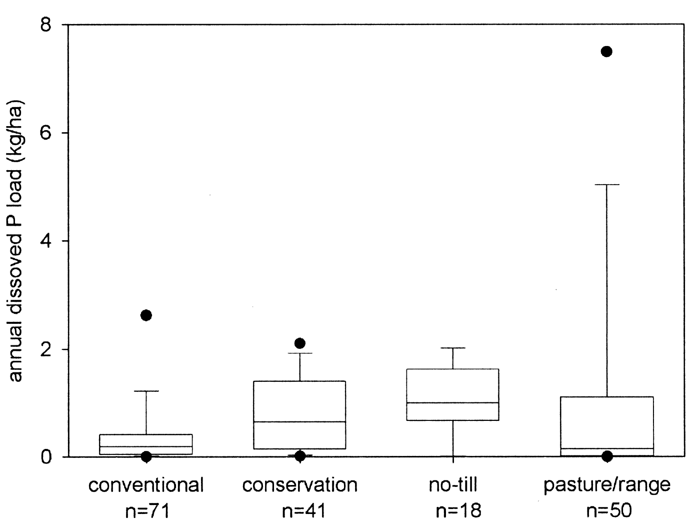

Figure 9. Annual Dissolved P Loads Under Various Tillage Management Alternatives.

Gitau *et al.* (2005) compiled an interactive database tool for determining best management practice (BMP) effectiveness based on site characteristics. The present database linked to such BMP tools would provide measured data with which to estimate and compare conservation practice effectiveness. Although considerable data are available on conservation practice

In terms of the effect of soil texture on nutrient loss, the same interesting result occurred for dissolved N and P and total P. In each case, neither clay and sand nor loam and sand differed significantly, but clay and loam were significantly different (Table 4). It was expected that clay and sand would differ most in behavior because of drastic differences in particle size distribution and nutrient transport mechanisms.

The comparison of nutrient loads across the various land uses (crop types) was made difficult by differences in the amounts of data available for each land use. As shown in Figure 1, corn, oats/wheat, various rotations, and pasture/range/hay all provided substantial data (each in excess of 100 ws yr). Each of the other land uses provided less than 30 ws yrs. These differences in data availability should be considered in the following discussion. For dissolved N, sites in corn production tended to have quite large and variable annual loads (Figure 11). Cotton, soybeans, and various rotations also had relatively high dissolved N loads. The largest median particulate N loads occurred under corn, cotton, and soybean production (Table 5), but the largest variability occurred under fallow conditions (Figure 12), which is attributed to the extreme erosion potential for clean cultivated fallow conditions. Annual total N loads were largest for corn, cotton, and oats/wheat.

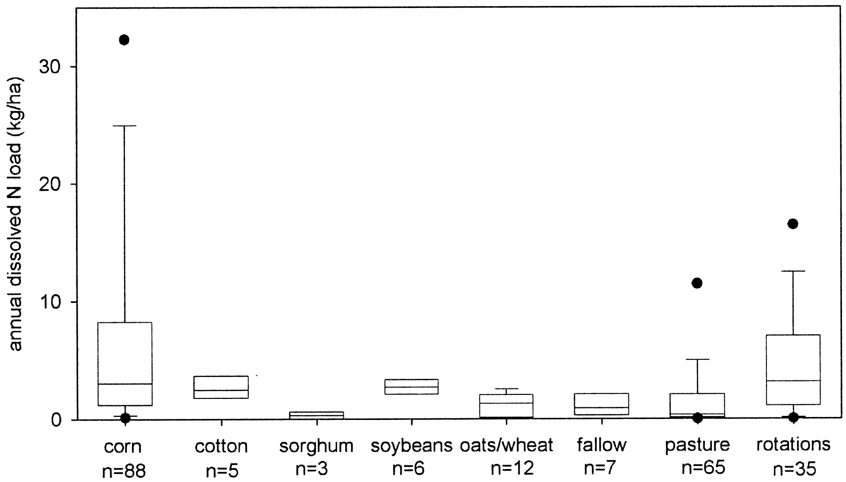

Figure 11. Annual Dissolved N Loads for Each Land Use Category (no data were available for peanuts).

TABLE 5. Median Annual Total N and P Load Values (kg/ha) for Land Use (crop type) Treatments.

Treatment*	Total N (kg/ha)	Dissolved N (kg/ha)	Particulate N (kg/ha)	Total P (kg/ha)	Dissolved P (kg/ha)	Particulate P (kg/ha)
Land Use						
Corn	18.70	3.02	7.27	1.29	0.22	0.85
Cotton	7.88	2.47	9.13	5.01	0.68	5.60
Sorghum	3.02	0.30	–	1.18	–	–
Peanuts	–	–	–	–	0.05	–
Soybeans	–	2.70	21.9	0.45	0.60	9.60
Oats/Wheat	6.61	1.31	5.90	2.20	0.30	3.45
Fallow Cultivated	3.00	0.90	2.70	1.08	0.48	0.45
Pasture/Range	0.97	0.32	0.62	0.24	0.15	0.00
Various Rotations	3.68	3.12	1.36	0.59	0.80	0.60

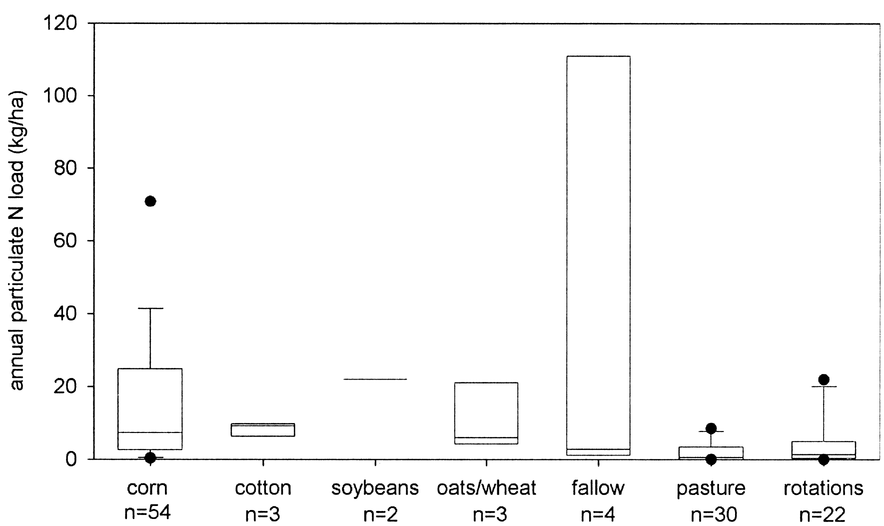

Figure 12. Annual Particulate N Loads for Each Land Use Category (no data were available for peanuts or sorghum).

Land use had relatively little impact on median annual dissolved P loads, as values were less than 1.0 kg/ha for all land uses (Table 5). In contrast, land use did affect the variability of dissolved P loads (Figure 13). Dissolved P loads for the various-rotations category were quite variable due to the diversity of cropping systems included. Dissolved P also exhibited considerable variability for pasture/range/hay because of the differing fertilizer management, ranging from none applied on rangeland to high litter application rates on improved hay/pasture. Particulate P loads were quite large for cotton, soybeans, and oats/wheat, but these results were based on two or fewer data points (Figure 14). The fallow sites again demonstrated the potential for high erosion and corresponding particulate P loss. Total P loads were largest for cotton and oats/wheat, but large annual loads occurred from several land uses.

SUMMARY

Several interesting results were evident in the evaluation of N and P load data included in the MANAGE database. Certain results were expected, but

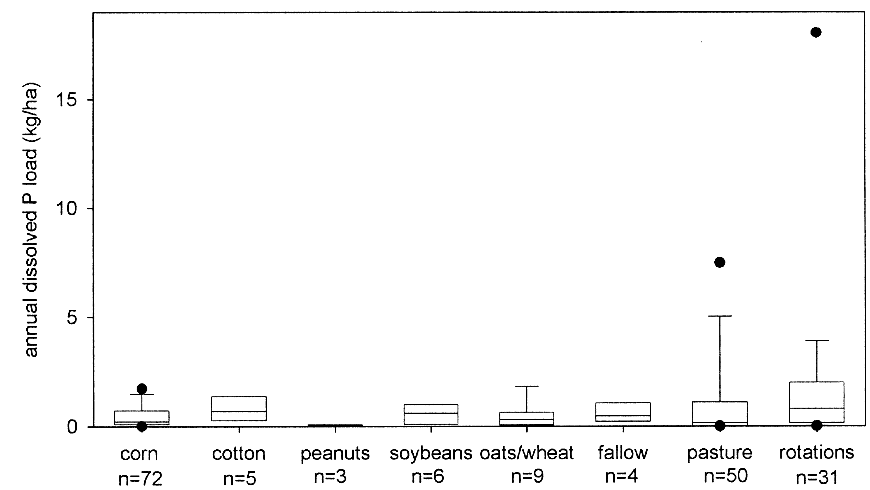

Figure 13. Annual Dissolved P Loads For Each Land Use Category (no data were available for sorghum).

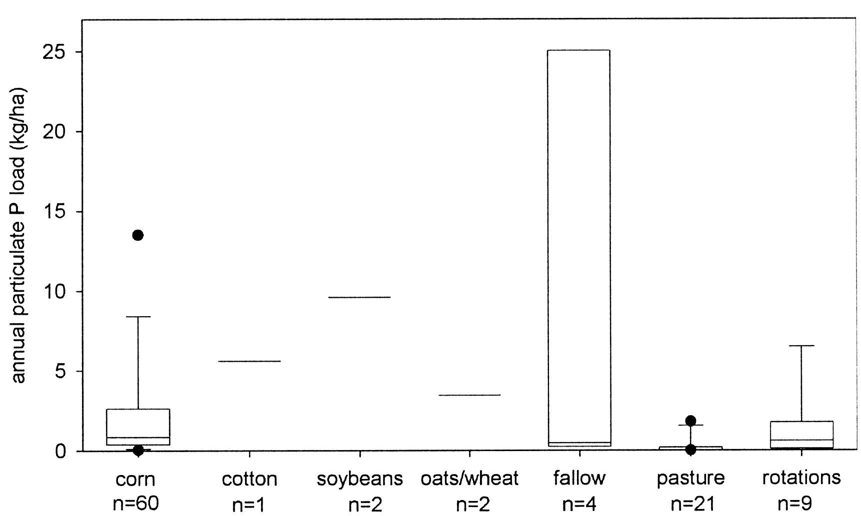

Figure 14. Annual Particulate P Loads for Each Land Use Category (no data were available for peanuts or sorghum).

others differed from commonly accepted ideas about nutrient transport behavior. These unusual results are attributed to grouping nutrient load data across widely varying hydrologic and management conditions and to differing data availability for various management alternatives. The compiled studies also differed in the types of annual nutrient load data collected (dissolved, particulate, and/or total). While these confounding factors contributed to unusual results, they supported the need for such a tool that facilitates the selection of data representing conditions of interest.

Although selected statistical analyses of nutrient loads are presented in this study, the primary value is its presentation of a publicly available database compilation of a majority of the measured annual nutrient load studies conducted on agricultural land uses in the United States. Our goal was that MANAGE will facilitate the evaluation of model performance in watersheds or conditions with limited measured data and thus improve model reliability; provide user-friendly data query capabilities that readily produce comparative measured data for site specific applications; illustrate the type and quantity of data available for watersheds, regions, and conditions of interest; establish a platform that allows the user to input additional project specific data; and direct future nutrient transport research.

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