Final Report

Project Title: Assessing the Effects of Conservation Practices and Fertilizer Application Methods on Nitrogen and Phosphorus Loss from Farm Fields – A Meta Analysis

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Introduction

Fertilizers increase crop yields but have consequences for society in the United States because they may be lost from agricultural fields and become pollutants to receiving water bodies (Sharpley 1995, Vagstad et al. 1997, Fuhrer 1999, Crain et al. 2006). Many models track the transport of nutrients in a watershed, including agricultural inputs (Robertson and Saad 2011). Detailed descriptions of site characteristics allow these models to account for factors such as soil type, crop type, and precipitation that can influence nutrient transport (Robertson and Saad 2011). However, incomplete descriptions often limit applying a model to novel locations. Additionally, site characteristics that differ from field to field are seldom taken into consideration.

The Measured Annual Nutrient loads from AGricultural Environments (MANAGE) database was created by the USDA to provide field scale information on nutrient losses, load, and concentration data from agricultural lands (Harmel et al. 2006, Harmel et al. 2008). This database provides support for models developed to address the nonpoint source transport of nutrients (Harmel et al. 2006). It includes land uses, rainfall quantities, soil loss data, and other site characteristics. This database is a compilation of data from several publications that contain field scale nutrient load and concentration data (Harmel et al. 2006). Data from each publication is input into all applicable tables that comprise the MANAGE database. In the most recent edition of MANAGE there are four different tables available – agricultural load, agricultural concentration, forest load, and forest data. The focus of this project is on the agricultural load table in the MANAGE database.

After the start of this project an addition table became available. Christianson and Harmel (2015) created an additional table, the MANAGE "Drain Load" database, to be added to the tables in the MANAGE database and published a summary of their findings based on the "Drain Load" table.

Since its creation, there have been 6 updates to the database and 4 articles have been published describing these updates and subsequent areas needing further research (Harmel et al. 2006, Harmel et al. 2008). However, Harmel *et al.* (2006) outlined criteria for adding papers to the MANAGE database which included only results published in peer-reviewed journals. This criterion creates a publication bias in the MANAGE database by omitting any other sources of information, including relevant agency reports (Easterbrook et al. 1991).

Harmel *et al.* (2006) found no significant decrease of nutrient loss with the implementation of conservation practices, but did not include important confounding factors such as land use and soil type (Harmel et al. 2006, Harmel et al. 2008). For example, the primary goals of conservation practices are to reduce runoff and nutrients leaving the field, thus we expect the practices to reduce nutrient loss (Duriancik et al. 2008). Other characteristics that influence nutrient loss include fertilizer application timing and method. Fertilizers are important to consider because they are applied with the intent to increase crop yields, but nutrients not taken up by crops can leach from fields and become pollutants (Smith et al. 2007).

This project aims to quantify the effects of conservation and fertilizer application practices on nutrient losses and crop yields. The October 2014 edition of the MANAGE database, created by the USDA, is used as the starting point for our statistical analyses because it contains the most information available in any edition of MANAGE up to this point. The database was created to provide field scale information on nutrient loss from agricultural lands and to assist farmers and managers to determine the most effective field management practices (Harmel et al. 2006, Harmel et al. 2008). Currently, summary statistics of the October 2014 edition and analysis of variables that have low data availability have been performed. This project and the funding provided by The Fertilizer Institute are the beginning of a student's Master's thesis that began in Fall 2014. As such, the final results of this project will be published in a student's thesis after the thesis defense. This is projected to occur in Spring 2016. The results included in this final report are the findings that have been accomplished thus far. In this report we summarize (1) the efforts of updating the MANAGE database, (2) the development of statistical methods for the proposed meta-analysis and (3) currents results from the proposed methods that estimate the effect that conservation practices have on the reduction of nutrient loss from agricultural fields.

Methods

Updating MANAGE

To understand the data availability and limitations of the October 2014 edition of MANAGE, we performed summary statistics using the statistical program R (R Core Team 2014). Summary statistics conducted included sum, mean, median, and aggregation of various attributes by other attributes. These summary statistics were chosen to compare the October 2014 edition to previous editions of MANAGE and to convey what is available to users. The statistical package reshape2 (Wickham 2007) in R was employed to assist with these calculations. In addition, arcGIS 10.2 (ESRI 2013) was used to map various attributes by state and create color gradient maps such as Figure 1. This map was created to characterize the geographic distribution of the entries in the October 2014 edition of MANAGE for users. Overall, the methods employed to summarize the efforts for updating the current edition of MANAGE, the first objective of this paper, include summary statistics using R and mapping using arcGIS 10.2.

Meta-Analysis Methods

We used the 2007 edition of the MANAGE database to test the proposed statistical methods – the propensity score matching analysis and the multilevel modeling approach. Both statistical methods are common for observational data in the social science field and are used to take confounding factors into consideration. Different field characteristics in MANAGE can act as confounding factors because they play a large role in determining whether a treatment is applied to a field and can influence the dependent variable being measured (Gelman and Hill 2007). We used these two methods to estimate the effects of conservation practices in reducing P loss from fields using the 2007 edition of MANAGE. In addition propensity score methods have been applied to the October 2014 update to MANAGE to estimate the effect of conservation practices in reducing total phosphorus (TP).

The first statistical method, propensity scores, will be used to find the average causal effect of a treatment (conservation practice) by comparing the treatment to a control (no conservation practices) (Rosenbaum and Rubin 1983, Gelman and Hill 2007). This method uses a logistic regression to create one number that will show the probability that the field in question will receive a treatment when all confounding variables are considered (Gelman and Hill 2007). Each confounding variable contributes to the likelihood of the field receiving a treatment and the propensity score quantifies each confounding variable's likelihood into one number (Gelman and Hill 2007). A field with the treatment will then be matched to a control field with the closest propensity score. These propensity scores will allow for controls (fields without a conservation practice) and treatments (fields with a conservation practice) to be compared while the averages of all other confounding variables are similar, analogous to what is done in lab experiments (Rosenbaum and Rubin 1983, Gelman and Hill 2007). Using the propensity score method is ideal because observational data differs from randomized experiments in that confounding variables cannot be normalized in observational data, while effects of confounding variables can be removed in randomized experiments (Gelman and Hill 2007).

The resulting scores will then be used to match a treatment field with a control field and create the two subsets that are, on average, more similar than the unmatched data. After sub-setting with propensity score, we will run a two sample *t*-test on the control and treatment groups to determine if the nutrient loss (average TP) is significantly different from each other, thus showing us if conservation practices have an effect on nutrient loss. Specifically we will be looking to see if the mean nutrient loss in the treatment group, fields with a conservation practice, is less than that of the control group. Next we will conduct regressions to look at the differences in slope of applied phosphorus (in fertilizer) between the treatment and control group to understand the effect of conservation practices on nutrient loss from a field. This regression will be used to determine the percent increase in TP leaving a field for every 1% increase in phosphorus from fertilizer application. Overall, the *t*-test and regression on our matched data will show the effect of conservation practices on nutrient loss.

The second proposed method, multilevel modeling, stratifies the data into groups with similar attributes and a regression model is then run on each group (Gelman and Hill 2007). This method is increasingly used for ecological data with interactions at difference scales because outcomes at one scale can be affected by events at a different scale (Qian et al. 2010). An example of this in MANAGE is how the effect of a conservation practice may vary by land use. The multilevel models will be run with fertilizer application and conservation practices as inputs when looking at the outcomes of total phosphorus. By running multilevel models I aim to quantify the effects that the inputs have on the outcome variables while considering confounding factors.

These proposed statistical analyses (multilevel modeling and propensity scores) will address the confounding factors noted in past studies, including crop type, study regions, soil characteristics, and runoff. Additionally, these analyses will determine the causal effect of the inputs (conservation practices and fertilizer application methods) on the outcome variables (nutrient loss). Analyzing the data with two different methods will increase the strength of the results if both tests determine the same overall average.

Results

Updating MANAGE

The October 2014 edition of MANAGE has the most available data for analysis out of any edition thus far. This edition is comprised of the 55 publications in the 2007 database as well as 10 additional publications, all of which equate to 330 entries and 1,980 watershed years. The watershed year variable is the total number of years monitored for each individual entry – for example a field monitored for 9 years would have 9 watershed years. Conversely, an entry in the MANAGE database represents an observation from a single field. Thus, one entry is a single field while the watershed years for that field is the number of years the field was observed for. A publication in MANAGE may contribute more than one entry because the study may have monitored more than one field. With these additional papers, the October 2014 edition of MANAGE has more data available to the public than previous editions.

To understand the nutrient information in this edition of MANAGE and the average load leaving the field, the area weighted average of phosphorus and nitrogen loading was calculated. The area-weighted average takes account of the size of the individual fields in the database. The area-weighted average of total nitrogen loading is 12.8 kg ha^{-1}. For the total phosphorus load, the area-weighted average is 2.1 kg ha^{-1}. Both calculations were taken from the entries with either phosphorus or nitrogen and watershed size data available. The area-weighted average was then calculated using the 2007 edition of MANAGE to allow comparisons between both editions of MANAGE. For total nitrogen the area-weighted average loading was 14.2 kg ha^{-1} and for total phosphorus 2.2 kg ha^{-1} was the area-weighted average loading (Harmel et al. 2006). Both values are similar enough to suggest that calculations were performed correctly and that the differences in the values can be attributed to the addition of 10 studies to the database.

The geographic balance of all editions of MANAGE, including the October 2014 edition, is not uniform and thus does not include all regions of the United States. The data is concentrated in the central region of the United States, where a large portion of the agriculture industry is located. In the original edition of MANAGE, entries mainly come from Oklahoma and Texas and equate to 42 percent of the watershed years (Harmel et al. 2006). The 2008 publication regarding MANAGE featured data that was largely from Oklahoma, accounting for 30 percent of the watershed years (Harmel et al. 2008). Following Oklahoma, Texas and Ohio featured the greatest number of watershed years with 16 percent and 15 percent of the total watershed years, respectively (Harmel et al. 2008). This trend is also consistent with the October 2014 update of MANAGE. In this edition, Oklahoma again has the most watershed years with 25 percent of watershed years in the database. Texas and Ohio also follow trends of past editions by occupying 16 percent and 14 percent of the total watershed years. The spatial aggregation of the 2014 edition of MANAGE can be seen in Figure 1.

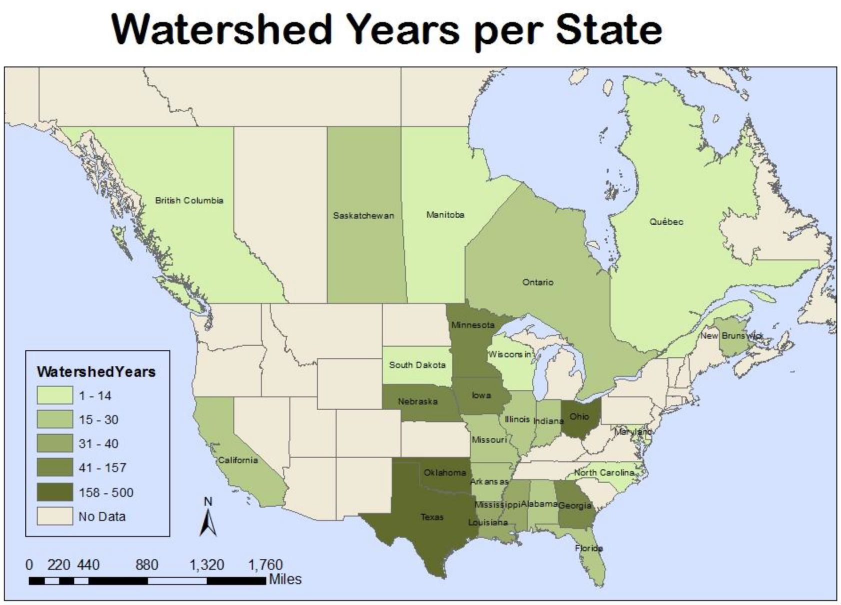


Figure 1. The number of watershed years per state in the October, 2014 edition of MANAGE.

To understand the availability of data in the 2014 edition of MANAGE, we have calculated the number of missing entries and watershed years for several variables of interest (Table 1). These calculations show variables that have a suitable sample size for analysis and others that may act to limit analyses. Two variables with limited sample size that can raise concerns when using them in analyses include conservation practices and crop yields.

Variable	Number of Missing Entries	Percent of Missing Entries	Number of Missing Watershed Years	Percent of Missing Watershed Years
Fertilizer Application Method 1	127	38.5%	803	40.6%
Fertilizer Application Timing 1	136	41.2%	868	43.8%
Conservation Practice 1	268	81.2%	1640	82.8%
Crop Yield	277	83.9%	1673	84.5%
Land Use	0	0.0%	0	0.0%

Tillage	3	0.9%	9	0.5%
Average Nitrogen Applied	114	34.5%	842	42.5%
Average Phosphorus Applied	59	17.9%	466	23.5%

Table 1. Number and percentage of missing entries and the associated watershed years for eight variables of interest.

The number of entries containing crop yield data in the MANAGE database are limited and can limit the sample size when using crop yields in analyses. This information is important when considering agricultural economics and nutrient uptake by plants (Vagstad et al. 1997). To better understand the crop yield information that is available the average crop yield for the primary crop on each field was calculated (Table 2). Of the entries with crop yield data, potato has the highest average crop yield. The yield data are difficult to compare among different crops. Furthermore, when comparing individual crops, sample size for each comparison will be too small for a meaningful statistical analysis.

Crop Type	**Average Crop Yield (Mg/ha)**
Alfalfa	12.4
Coastal bermudagrass	11.4
Corn	7.151538
Cotton	2.045
Pasture	5
Potato	27.485714
Soybeans	3.392
Wheat	2.64

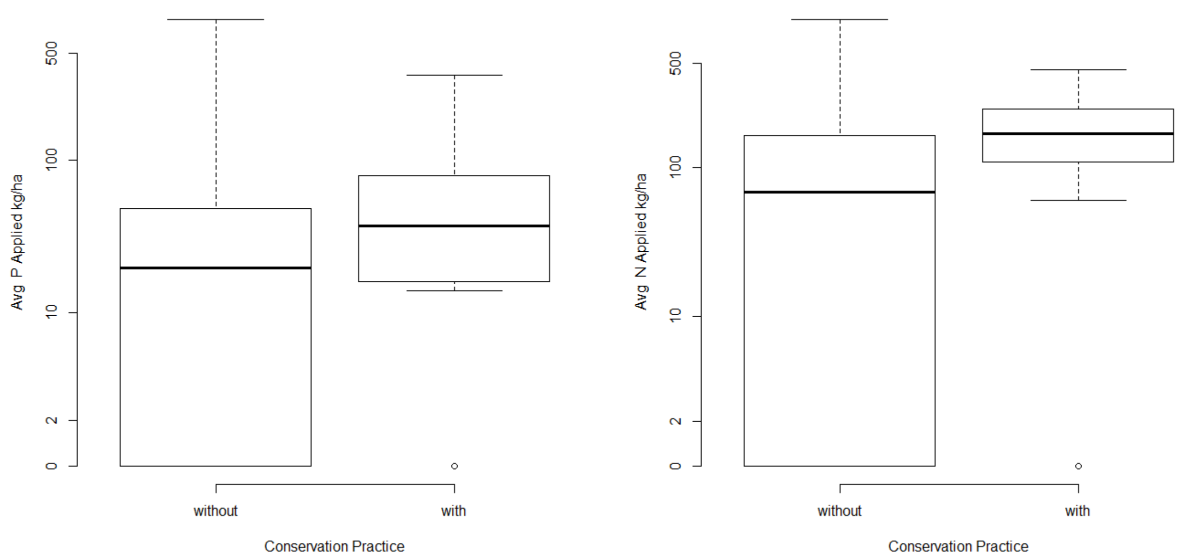
Table 2. Average crop yield by crop type in the October 2014 edition of MANAGE.

Considering the limited data available for crop yields, we propose to extend our study by exploring new modeling approaches and transforming the yield data into % of expected yield so that a meaningful comparison can be carried out. This part of the research will be conducted in the Fall of 2015 with additional funding from NOAA.

To understand the methods and timing of fertilizer applications included in the database, the most common method and timing were identified. Fertilizer application type and timing can impact nitrogen and phosphorus losses from agricultural fields. Precipitation and irrigation events carry nutrients from the field when they drain and make it important to consider the method and the timing of application. Surface applied fertilizers were the most common type of fertilizer application method included in the database, accounting for 30.5 percent of the data. With regard to fertilizer timing, the most common time of fertilizer application was "grass in growing season." Both the most common fertilizer application method and timing came from those entries in MANAGE that had data available. The percent of missing data for fertilizer application method was 40.6 percent and 43.8 percent for fertilizer application method (Smith et al. 2007). While the amount of missing data for fertilizer information was about 40 percent, this is considerably less than that of crop yields.

Data regarding conservation practices are also limited and can thus limit sample size when performing analyses that include conservation practice. Conservation practices can impact the nutrient loads that leave a field in runoff. The primary conservation practices considered in the MANAGE database include contour farming, filter strip, terrace, and grassed waterways. These conservation practices account for 17 percent of watershed years or 19 percent of entries in MANAGE. The other 83 percent of watershed years or 81 percent of entries do not have a conservation practice listed. This means one of two things – 1) the entries do not have a conservation practice applied to the field or 2) the publication containing the data does not list if there is or is not a conservation practice implemented. These two meanings of the missing data can have very different impacts when analyzing the database. The second meaning (the conservation practice data was not included in the publication) should be considered missing data while the first meaning (no conservation practice applied) is a separate category that should be included in analyses (Duriancik et al. 2008).

Current and past editions of the MANAGE database have provided field scale information on agricultural fields to public, but a number of the variables within the database are correlated with each other and can influence analyses (Harmel et al. 2006, Harmel et al. 2008). One particular of variable that exemplifies the trend is the amount of phosphorus or nitrogen applied to a field as it relates to whether the field has a conservation practice. Fields tend to have a conservation practice applied when there are high amounts of fertilizers applied, shown in Figure 2, thus these two variables are not independent of one another. For both phosphorus and nitrogen, the mean amount of fertilizers applied in Figure 2 is greater for fields with conservation practices than with fields without conservation practices. This relationship means that subsequent analyses will be impacted if this correlation is not taken into consideration.



<u>Figure 2.</u> Side by Side box plots of fertilizer application (Phosphorus Applied and Nitrogen Applied) for fields without a conservation practice and fields with a conservation practice. Both the left plot (Phosphorus Applied) and right plot (Nitrogen Applied) show a high mean fertilizer application in fields with conservation practices.

The current edition has additional attributes, including crop yield, that have a low percentage of available data and can thus limit the sample size available for analyses. Additionally, current and past editions have variables that need to be considered carefully because they can act as confounding factors. Although this is the case, the most recent update also has the highest number of publications and watershed years included in any edition of MANAGE thus far.

Methods Development

One objective of our project is to develop statistical meta-analysis methods for estimating the effect of agricultural conservation practices on reducing nutrient loss. The difficulty of the task lies in the nature of data available for such analysis. Almost all available data are observational data, which can be confounded by differing crop types and differing management practices. As we may not have the full knowledge of these confounding factors, conventional statistical meta-analysis methods are often ineffective. In this proposal, we discuss the use of two statistical causal analysis methods (propensity score and multilevel modeling) for quantifying the effects of water and soil conservation practices in reducing phosphorus loss from agricultural fields. With the propensity score method, a subset of the data was used to form a treatment group and a control group with similar distributions of confounding factors. With the multilevel modeling approach, the data were stratified based on important confounding factors and the conservation practice effect was evaluated for each stratum.

We applied both methods to the 2007 version of MANAGE database and estimated the conservation practice effect in reducing TP loss. Prior to applying our methods, we evaluated the effects of four different conservation practices (grassed waterways, contour farming, terraces, and riparian forest buffers/filter strips) (Qian and Harmel, 2015). This analysis suggested that the effect of individual conservation practices was similar to the effect of all conservation practices grouped together (Qian and Harmel, 2015). When applying our methods, the 18 percent of data with conservation practices listed were considered our treatment group – based on our previous analysis – and the 82 percent without a practice listed were used as our control group of “no conservation practice”. Our preliminary results are summarized in a manuscript submitted to *Journal of American Water Resources Association* (Qian and Harmel, 2015). The manuscript reported an average reduction of P loss of approximately 70 percent. In addition, both methods show evidence of conservation practices reducing the incremental increase in TP export per unit increase in fertilizer application.

The propensity score method has also been applied to the October 2014 edition of MANAGE. The linear model created to calculate propensity score includes average phosphorus applied, average nitrogen applied, average runoff, average soil loss, dominant soil type, hydrologic soil group, land use, tillage, fertilizer application methods and an interaction term for fertilizer application methods and land use as covariant for the calculation of each score. Similarly as in Qian and Harmel (2015) values with a total phosphorus load of 0 were replaced with 0.002, half of the lowest reported value, to allow these entries to be kept for analyses. In the development of propensity score, conservation practices were combined to increase the sample size of the treatment group and the control group included all entries without a conservation practice listed. This allows for the two groups to have similar variance and maximizes the sample size after matching. The model produced a subset with 58 observations – 29 for the control and 29 for the treatment. The sub-set data shows that the two groups are more similar on other covariates than they were prior to matching. Figure 3, below, shows two overlaid histograms of the distribution of runoff, a confounding variable. The figure shows that the treatment and control groups are less skewed from each other with the matched data than with the original data. The increased similarity of the two groups after matching achieves what we aimed to do with the propensity score because the treatment and control groups are closer to having the same distribution like we would find in a laboratory experiment.

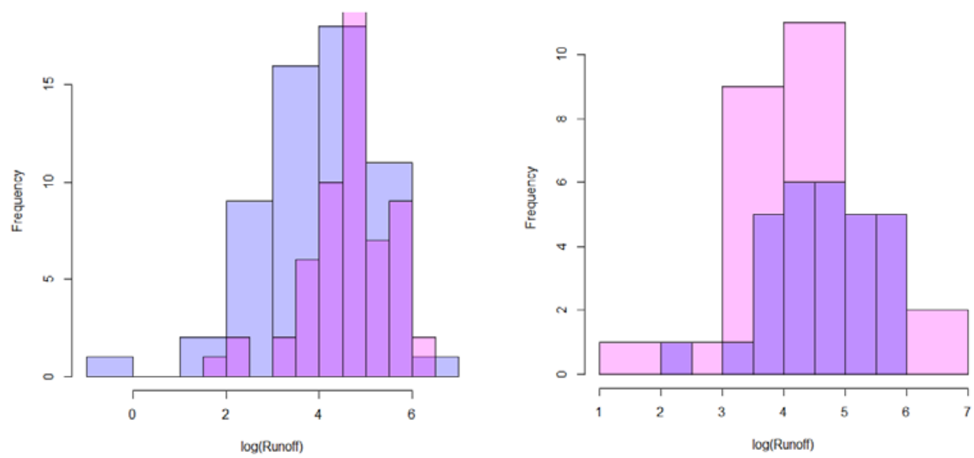


Figure 3. Overlaid histogram of runoff before (left) and after (right) matching. Pink represents no conservation practice and blue represents with conservation practice.

After matching the data using propensity score as described above, we then conducted a two sample t-test to compare the log-mean nutrient losses of the treatment group versus the control group. The results of this t-test showed a significant decrease ($p<0.01$) between the mean of the control group, no conservation practice, and treatment group, having a conservation practice. Taking this understanding a step further, we used the difference in the log means to calculate the percent reduction in total phosphorus loads. The estimated effect was calculated as ▯ =-0.7861 ($p<0.01$). To calculate the multiplicative effect we used $▯^{-0.7861}$=0.4556. This equates to a 54 percent reduction in the total phosphorus load leaving the field. These results show that conservation practices did reduce the amount of total phosphorus leaving a field when accounting for the confounding variables. Our results also support the findings of Qian and Harmel (2015) – that conservation practices made a significant reduction in the amount of total phosphorus leaving a field (Qian and Harmel 2015).

Discussion

The various editions of the MANAGE database provide accessible data to the public that can be used to support nonpoint source models and aid decision makers (Harmel et al. 2006, Harmel et al. 2008). The most recent edition – edited in October 2014 – provides data on fertilizer application, conservation practices, rainfall, runoff, land use, and nutrient loads leaving a field. This edition of MANAGE includes 10 more papers than the previous edition equating to a total of 65 papers. The data from these 65 papers provide 330 entries or 1980 watershed years as data for analysis by users.

Past analyses of MANAGE have yielded interesting results that can be partially attributed to confounding factors that were not accounted for (Harmel et al. 2006, Harmel et al. 2008). These confounding factors, which are factors that are not the independent variable but influence the outcome of the dependent variable, include field characteristics such as land use, soil characteristics, precipitation, and seasonal variations. In addition to confounding factors not considered previously, there are a number of attributes in the MANAGE database that have limited data available. As noted by previous publications, there is a definite gap in the amount of concentration data versus the quantity of nutrient load data (Harmel et al. 2008). Additionally, there is a limited number of entries that have crop yield information. Only 16 percent of the data in the October 2014 edition of MANAGE possess crop yield quantities. This imbalance of data availability can cause difficulties when using MANAGE to find trends involving these limited variables, especially when taking the confounding factors into consideration. To address this limited data availability, we are reviewing the current entries for crop yield information that may not have been included, as well as ensure that additional entries contain this information.

The propensity score results from both Qian and Harmel (2015) and current analysis on the October 2014 database have shown significant reductions in TP loads leaving a field when conservation practices were implemented. Qian and Harmel (2015) showed a 70 percent reduction in the amount of TP leaving a field using the 2007 version of MANAGE while current analysis of the October 2014 edition showed a 54 percent reduction in TP leaving the field. These reductions both signify that the application conservation practices to a field reduce the amount of nutrient loss leaving a field.

The next steps of this project include further statistical analyses to find the causal effect of conservation practices and fertilizer application on nutrient loss. These analyses will be conducted by using multilevel modeling in addition to the current application of propensity score. Intermediate goals proposed have been met to achieve the overall objective to quantify the effects of conservation practices and fertilizer application practices on nutrient loss. These intermediate goals include incorporating changes to MANAGE and adding grey literature and government research to the next edition of MANAGE. Adding grey literature will help to address limited sample sizes and any publication bias that exists. Since the 2007 edition 10 additional studies have been added as well as variables such as fertilizer formula and fertilizer application timing. The summary statistics performed in 2014 highlighted additional tasks that need to be addressed so the most accurate analysis of the effect of the two agricultural practices on nutrient losses and crop yield can be quantified.

Interpretive Summary

This project has made notable advancements towards the objective of quantifying the effect of conservation and fertilizer application practices on nutrient loss and crop yield, listed in the project proposal. Initial summary statistics were used to find attributes with limited sample size and overview the data in the October, 2014 edition of the MANAGE database. Crop yield and conservation practice – important variables for achieving the project outcomes – were both found to be variables with limited sample size. Additionally, initial statistics showed that the entries are spatially aggregated toward the central region of the United States. Ohio, Oklahoma, and Texas account for 1,092 of the 1,980 watershed years in the database. To address attributes with limited sample size, plans have been made to review the 65 papers included in the database. In addition, we plan to add grey literature to MANAGE to address any publication bias. The project has achieved the intermediate objective to update the MANAGE database and is in the process of achieving the objective of finding the effects of the two noted agricultural practices on nutrient loss. The first proposed statistical method of propensity score has been implemented on both the 2007 edition and the October 2014 edition of MANAGE and has yielded significant reductions in the amount of TP leaving a field when conservation practices were implemented. These results will then be compared to multilevel modeling results to ensure the validity of both statistical methods.

This project supports one graduate student (Ms. Stephanie Nummer) in the Department of Environmental Sciences, The University of Toledo. Part of the research is used in developing Ms. Nummer's master's thesis. Initial results summarized in the paper by Qian and Harmel (2015) were presented at the Annual Conference of the American Water Resources Association in Washington D.C. (November 2014). In addition, results from this research allowed us to apply for additional support from the Federal government to expand the scope of our initial proposal.

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