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Review

Surface and Subsurface Transport of Nitrate Loss from the Selected Bioenergy Crop Fields: Systematic Review, Analysis and Future Directions

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Abstract: Nitrate loss from bioenergy crop fields has attracted considerable attention during the last few years because of its potential negative impact on aquatic and human health. Both controllable and uncontrollable factors for nitrate loss have been the subject of several previous studies. Due to differences in climate, biophysical dissimilarities and land management characteristics in different parts of the world the factors affecting nitrate loss are often inconsistent and hence difficult to generalize. Therefore, reanalyzing the experimental field or plot scale studies to understand the nitrate loss factors in crop fields is useful and necessary in developing management strategies for reducing nitrate loss. This research synthesized and investigated 36 peer reviewed scientific journal articles related to selected bioenergy crop fields that included: continuous corn, corn in rotation with soybean, switchgrass and *Miscanthus* to conduct a meta-analysis of the available research. In this study, factors such as drain tile spacing, tillage practices, type and timing of the fertilization rate, irrigation and various other factors, which are challenging to represent in regression equations, were also systematically analyzed. In addition, various other agronomic characteristics that are attributed too nitrate loss are caused by perennially planted bio energized crops such as *Miscanthus* and switchgrass. Results indicated that 49% of nitrate loss through surface runoff from corn fields is directly related to the annual precipitation and fertilization rate. Multiple linear regression equations were developed to estimate the annual subsurface nitrate loss for the continuous corn fields with a R^2 value of 0.65, 0.58 and 0.26 for sandy loam, silty loam and clay loam, respectively. Our analysis resulted in the conclusion that corn has a 2 to 3 times higher nitrate loss in surface runoff compared to switchgrass. Likewise, continuous corn and corn in rotation with soybean contributed more than 9 times the subsurface loss of nitrate compared to the established subsurface loss attributed to the *Miscanthus* and switchgrass.

Keywords: nitrate loss; bioenergy crop; corn; switchgrass; *Miscanthus*

1. Introduction

Surface and subsurface nitrate loss from agricultural lands has been a substantial water quality concern globally [1–6]. Nitrogen added to the soil in the form of fertilizer or manure is a major cause of nitrate loss from the agricultural lands. Since nitrogen inputs on the agricultural land are not entirely consumed by plants a significant portion, in the form of nitrate, is lost into the ground and surface water. High nitrate concentration in surface and ground water is a concern because: It may lead to accelerated eutrophication in water bodies, it has a potentially harmful effect to children less than a year old as it can cause methamoglobinemia and it can be toxic for livestock.

Nitrate concentration in surface water has often exceeded the threshold recommended by the World Health Organization (WHO) drinking water standard of 10–11.3 mg·NO_3-N·L^{-1} [7] and the United States Environmental Protection Agency (USEPA) standard of 10 mg·L^{-1} [8]. For example, nationwide assessment of USGS reported that some wells in Midwest US exceeded the USEPA standard threshold [9]. Alarmingly, the nitrate lost from agricultural land in the American Midwest has been attributed to hypoxia in the Gulf of Mexico [10–12]. Researchers report that 43% of the total annual average nitrate flux into the Gulf of Mexico is contributed by the Upper Mississippi River Basin [13] with most of the flux coming from the American Midwest [14].

In the future, the American Midwest is expected to contribute significantly to the production of *Miscanthus* and switchgrass, which are cellulosic bioenergy crops [15], to meet the 136 × 10^6 m^3 of biofuel needs by 2022; a target set by the Energy Independence and Security Act (EISA, 2007). In addition, both grain and stover from corn fields are useful for biofuel production; whereas, grain is only useful for corn as needed for crop production. This suggests that management practices to be adopted while growing grain and biofuel are different. In this context, several past studies have evaluated the surface [1,16–22] and subsurface transport of nitrate loss from corn [23–32], *Miscanthus* [33–38] and switchgrass fields [39–42] and found that various controllable factors such as: the cropping system, the fertilizer type, rate and timing of fertilizer application, the nitrification inhibitor, the tillage system, and the drain tile spacing have been evaluated in different studies to understand nitrate loss. Similarly, the role of the independent or uncontrollable factors, such as precipitation and soil organic matter that contribute to nitrate loss, has been reported in several studies [43]. Nevertheless, these studies are not only limited to the American Midwest but have also been conducted in different parts of the world that have various climatic and soil conditions. Due to the site specific conditions, the factors affecting nitrate loss are often inconsistent and difficult to generalize. Hence, it is important to re-analyze the experimental field or plot scale studies and synthesize the data in various climactic and soil conditions to get general insights of the nitrate loss.

The primary objective of this study was to reanalyze the field scale experimental studies through various bioenergy crops such as corn, switchgrass, and *Miscanthus* fields, and compare their nitrate loss. Several previous studies were conducted in corn fields but limited data has been reported for *Miscanthus* and switchgrass; primarily because these are relatively new crops being targeted in response to the biofeedstock production goal set by EISA. A secondary objective of our study was to compare nitrate loss in energy crops to understand nitrate loss in various conditions based on well-studied crops such as corn. This is essential because the extent of differences in nitrate loss that exist between corn and other bioenergy crops is still not clear. More importantly, earlier findings were based on one study conducted in a single field site. Therefore, this is the first study to provide the comparative picture of nitrate loss of energy crops based on data compiled from 36 peer reviewed studies.

Many factors affecting nitrate loss are common for *Miscanthus* and switchgrass. However, some additional agronomic characteristics such as plant rooting density, nutrient recycling, fertilization requirements and mineralization play a substantial role in the nutrient loss process. Therefore, in addition to comparing nitrate loss from various bioenergy crop fields a discussion of additional factors for nitrate loss from perennial grasses is included. Potential reduction of nitrate loss through surface and subsurface pathways due to the production of *Miscanthus* and switchgrass is described.

2. Materials and Methods

2.1. Systematic Literature Search

Peer reviewed journal articles which reported nitrate loss from corn, *Miscanthus* and switchgrass were compiled. Search criteria developed to systematically capture peer reviewed journal articles using various search engines included: Scirus, web of knowledge, Science Direct, Agricultural Database (AGRIS), EBSCOhost, BioOne, Agricultural Online Access (AGRICOLA), Electronic Archive of International Organizations (WHO, FAO) and Worldwide Science.

Search terms included: "Nitrate and loss", "Nitrate and runoff", "kg/ha", "ton/ha", "t/h", "t/ha", "mg/lm" and "gm/m" using the keywords: Nitrate-nitrogen, corn, *Miscanthus*, and switchgrass; one at a time. Also, past publications were followed through the references section of the recent peer-reviewed articles selected for this study. The abstract and result section of all pertinent SprigerLink, Google Scholar, Journal Storage (JSTOR) and Purdue University Library Website research was carefully reviewed. The journal articles which furnished the experimental results in terms of annual loads or concentrations were used in the subsequent analysis.

2.2. Selection Criteria

To make consistent analysis of the data from the diverse set of studies reported in the literature a framework was developed. For example, articles discussing corn rotation with winter cover crops, or other than soybean, were not included in the analysis. Alternatively, continuous corn and corn with soybean rotation were included as part of analysis in this study. Similarly, articles which reported results using a simulation model were not considered for analysis although the findings from the simulation studies were included in the discussion. In brief, the chosen articles were thoroughly investigated using the following criteria:

- Articles must have been published in a peer-reviewed scientific Journal.
- Articles should discuss nitrate loss for at least one bioenergy crop such as corn, *Miscanthus* and switchgrass.
- Articles should discuss nitrate loss through experimental field studies.
- Articles should report annual scale study of nitrate loss with their full length of measurement covering the entire year.
- In all cases, articles should have reported nitrate loss with a sufficient description of experimental and environmental conditions.

Finally, 36 peer reviewed journal research publications were qualified for the continuous corn field. Similarly, 30 journal articles qualified for rotated corn field, and 8 journal articles qualified for perennial grasses (*Miscanthus* and switchgrass). The journal articles meeting the criteria were mainly from the American Midwest, Canada, China, Europe, and various other parts of the USA. Publication dates for these articles spanned from 1973 to 2013. Out of these articles, three articles discussed the nitrate loss from the artificial drainage. One article was about corn in rotation with soybean. Out of the two other articles, one article reported the nitrate loss in sandy loam and the other was in clay loam. The articles used for analysis in this study are available in the appendix as supporting information. Since nitrogen requirement and loss from the field vary depending upon the type of crops, this study focuses only on corn, *Miscanthus* and switchgrass. Hence, the study and information reported in this research is valid only for these bioenergy crops; the nitrate loss through other crop fields is beyond the scope of this article.

Once journal articles were selected, data from the entire publications were carefully synthesized into various categories. It was found that past experimental field studies were mainly focused on three major soil categories that included sandy loam, silty loam and clay loam. A database was developed in a systematic manner. Duplication of the same article and overlooking relevant information was avoided in the design of the database.

2.3. Database Preparation

The information regarding the environmental characteristics, soil characteristics and management practices were compiled from selected articles and organized into different subsets. Various soil types (silt, clay, loam) were categorized. The studies that included subsurface nitrate loss were divided into the three different soil categories of sandy loam, silty loam and clay loam. A careful review of the article to collect and compile information such as nitrate loss, mode of loss (e.g., surface or subsurface), tillage and no-till practices, fertilizer rate, slope of the field and annual precipitation was conducted. In other words, a list and discussion of each factor responsible for nitrate loss both quantitatively and qualitatively was conducted to explore several research questions related to nitrate transport including soil type, precipitation, and fertilization rate. Therefore, in addition to developing the regression equations, statistical analysis was conducted to find the difference in nitrate leaching under various conditions.

2.4. Multilinear Regression Modeling

Multilinear regression (MLR) is a statistical technique frequently used in water quality studies. In MLR, the best fitted linear equation will be developed using the response variables as a function of several explanatory variables. In this study, the MLR model was developed using the annual fertilizer and precipitation rate as explanatory variables, and nitrate loss as a response variable.

3. Results

First, possible factors for nitrate loss from continuous and rotated corn fields were analyzed. In the next step, additional factors associated with nitrate loss in perennial bioenergy crops such as switchgrass and *Miscanthus* were analyzed. Understanding the interaction of these factors is essential for the estimation of nitrate loss based on geomorphologic characteristics, fertilization rate and likely precipitation. In this study, the fertilizer application rate varied from 0 to 336 KgN/ha, whereas annual precipitation varied from 258–1366 mm for the studies considered in this research. Since annual temperature varied within the range of 40 °F to 50 °F, we did not include in the regression equations as the effect of annual temperature was very nominal.

4. Nitrate Losses from Corn Fields

4.1. Surface Nitrate Loss

The studies reporting nitrate runoff losses from the surface and subsurface loss were compiled since nitrogen loss through surface runoff is nominal compared to loss through subsurface runoff [1]. The majority of studies conducted in different parts of the world focused on subsurface nitrate loss. Figure 1a,b indicate the variation of nitrate on surface and subsurface runoff at different fertilization rates. Results suggest that nitrate in surface runoff (R^2 = 0.27) is more influenced by the fertilization rate than subsurface loss (R^2 = 0.14). This is consistent with findings by [21], which suggest that nitrate loss, especially through subsurface loss, is often difficult to correlate with fertilization rate due to nitrogen interaction within the soil and water in the presence of crop.

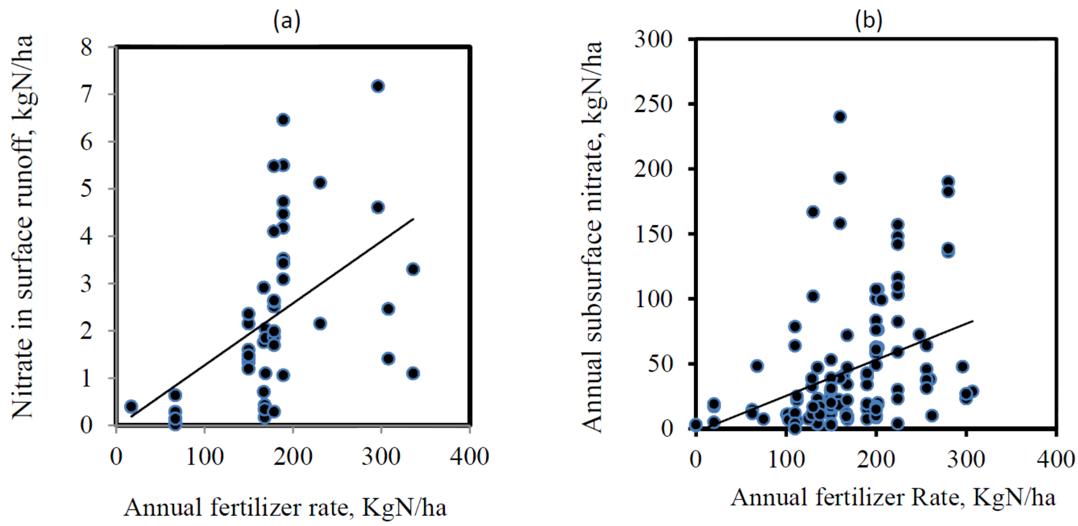

Figure 1. Nitrate in surface runoff (**a**) and nitrate leaching through subsurface runoff (**b**).

We developed a multilinear regression model to estimate nitrate in surface runoff based on fertilization rate and annual precipitation, see Figure 2. Annual temperature as an explanatory variable was included but it is not statistically significant as the annual temperature did not vary much from location to location. Results of the data indicated that only 49% of nitrate in surface runoff is described by annual precipitation and fertilization rate. Since every factor for nitrate loss is not possible to incorporate in regression equations quantitatively, the remaining factors besides precipitation and fertilization will be discussed qualitatively in the subsequent sections.

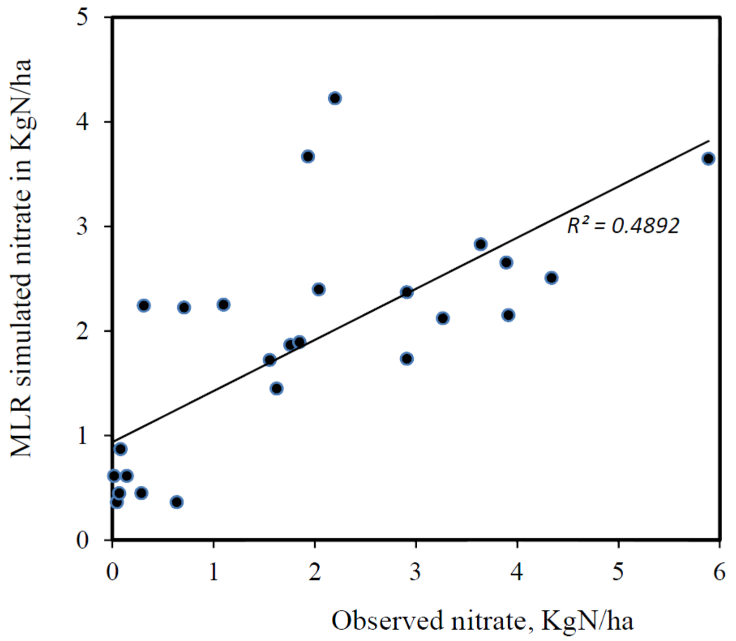

Figure 2. Annual nitrate in surface runoff using Multilinear Regression Model as rainfall and fertilizer as predictors.

Spatial and temporal characteristics of precipitation including precipitation intensity and duration might be more crucial than the net precipitation depth as the intense precipitation may accelerate more loss through the surface runoff. Similarly, precipitation pattern and the effect of the growing season precipitation will be vital on nitrate loss rather than annual precipitation [43]. The reason for higher loss due to growing season precipitation is attributed to the immediate wash out of nitrate. Also, the timing of fertilizer application is equally important for nitrate loss through surface runoff. For example, more nitrogen loss is anticipated if the fertilizer is applied prior to the wet period [4]. Nitrate loss in a wet year is expected to be higher than dry years [44], so a separate analysis for wet and dry years will be recommended. Some other factors for loss could be the growing season temperature [2], the type of the fertilizer application, and the type of tillage system adopted. Various tillage systems may have a different loss rate, such as higher loss may be encountered in ridge tillage [1]. Also, reduction in nitrate loss may be encountered with using no tillage (NT) rather than conventional tillage [23] due to the higher denitrification under NT [45]. Possible variations in nitrate loss due to various management practices were not incorporated in regression equations.

4.2. Subsurface Nitrate Loss

The factors associated with nitrate loss through the subsurface are essentially like the factors associated with the surface nitrate loss. Several studies suggest that the subsurface loss of nitrate will be amplified due to the higher rate of fertilization application [45–47]. Figure 1b indicates that for the same range of fertilizer application there are wide ranges of nitrate loss. This indicates that management practices could be influential in nitrate loss rather than the fertilization rate [48,49].

Though precipitation is one of the most prominent factors for nitrate loss as it drives nutrient loss and transport process, higher nitrate loss is not always correlated with higher precipitation. In some areas, during relatively dry growing seasons, precipitation may enhance nitrate uptake due to increased corn yield, resulting in a reduction in nitrate loss [50]. Nitrate loss is also affected by the precipitation and climatic conditions (dry or wet year) of the preceding year [51] because nitrate accumulated in the dry season will be susceptible to loss in the rainy season [31]. That is, greater nitrate loss can be expected in wet years following dry years [6]. In addition, loss is particularly influenced by the temporal characteristics of precipitation within a given year indicating that the same amount of precipitation has different influences over the seasons of Fall, Spring and Winter [42]. Relatively, higher nitrate loss is expected during the early growing season [52]. The reason for this is that during the early stages of growth nitrogen uptake is small and more nitrogen is available for loss in the soil profile early in the season compared to later stages.

Table 1 shows the cross correlation of fertilization and annual precipitation of the preceding year. The multi-linear regression model (MLR) was developed considering annual precipitation and fertilization as the predictors of nitrate loss for continuous corn and the three different soil categories; (i) sandy loam; (ii) silty loam; and (iii) Clay loam, see Table 1. We found that R^2 values for sandy loam, silty loam and clay loam soils were 0.65, 0.58, and 0.26, respectively. Analysis indicates that the sandy soil shows better correlation with annual precipitation and fertilizer, and clay loam soil shows the least correlation with precipitation and fertilization.

Table 1. Cross correlation of fertilization and annual rainfall of former year with nitrate leaching of current year for continuous corn.

Soil Type	Annual Rainfall (t-1)	Annual Rainfall (t)	Fertilization (t-1)	Fertilization (t)	R^2 From MLR	Adj-R^2	Remarks
Sandy Loam	−0.32	−0.19	0.57	0.51	0.65	0.42	
Silty Loam	0.19	0.40	0.55	0.38	0.58	0.42	
Clay Loam	0.02	0.34	0.34	0.29	0.26	0.2	Some silt are mixed,

Evapotranspiration (ET) is also another potential factor because this loss of nitrate may be correlated with the net moisture content difference between precipitation and ET [53]. The increase in precipitation may not necessarily increase nitrate loss if the ET rate from the field is higher [54]. In the meantime, nitrate loss may continue even if ET is higher than precipitation, indicating that nitrate loss in a current year is associated with the nitrogen applied in the previous year [53]. Therefore, higher nitrate loss in some seasons prior to fertilization application can be expected due to nitrogen loss from the previous year [51].

Growing season temperature is another factor which was not incorporated in the regression equation but can play a role in nitrate loss. Research shows higher loss when temperatures exceeded 60 °F [42]. Similarly, soil texture and soil moisture conditions are some of the key factors to influence loss. For example, loss might be accelerated even for a nominal precipitation season if soil reaches the field capacity [42]. Nitrate loss through various soil conditions has been described under two categories of corn field; (i) continuous corn; and (ii) corn in rotation with soybean.

4.3. Continuous Corn versus Corn in Rotation

Several studies indicate that nitrate loss from continuous corn is relatively higher than the loss from rotated corn. The main reason for higher nitrate loss from continuous corn is the fertilization input. Fertilizer is applied every year for continuous corn, whereas it is applied every other year for corn in rotation with soybean. Figure 3 shows the plotting of data collected from diverse studies indicating that the greater nitrate loss is expected from the continuous corn rather than the rotated corn. Figure 3 also indicates that the interquartile range of nitrate loss through continuous corn is higher than that of the rotated corn including the extreme reported case of loss (240 kgN/ha) through continuous corn. The majority of past studies have reported that the continuous corn field contributes significantly greater loss with reduced crop yield, whereas rotated corn requires less nitrogen input resulting in lower nitrate loss and potentially increased crop yield. The study by [55] is an exception which reported that rotated corn had substantially higher nitrate loss (91 kg·ha^{-1}) than continuous corn (52 kg·ha^{-1}). Our analysis was based on data collected from both sources of the study; (i) independent study of continuous corn and rotated corn in various fields; and (ii) studies conducted simultaneously in continuous corn and rotated corn over the same field.

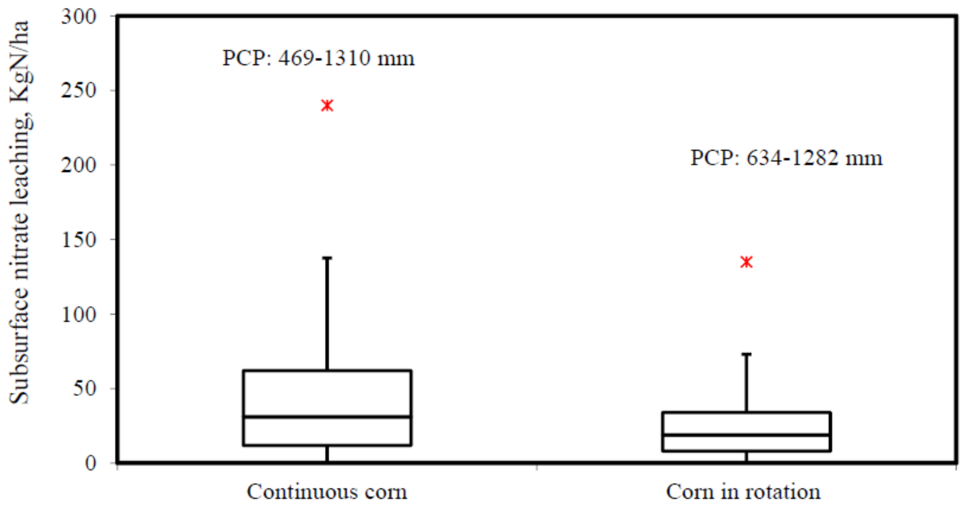

Figure 3. Subsurface nitrate leaching in continuous corn and corn in rotation within various ranges of precipitation (twenty nine and sixteen journal articles were used for continuous corn and corn in rotation, respectively). PCP: Precipitation.

4.4. Soil Types and Nitrate Loss

The nitrate loss in continuous corn is higher for the higher rate of fertilizer used, but a significant range of variability in nitrate loss was realized at the medium range of fertilization (165–200 KgN/ha), especially for fine loamy soil, see Figure 4. The range of precipitation corresponding to respective nitrate loss and associated fertilizer rate is identified and shown in Figure 4. For this, in the first step, nitrate loss at the various rates of low, medium and high fertilizer applications was categorized. In the second step, ranges of annual precipitation for each category was identified.

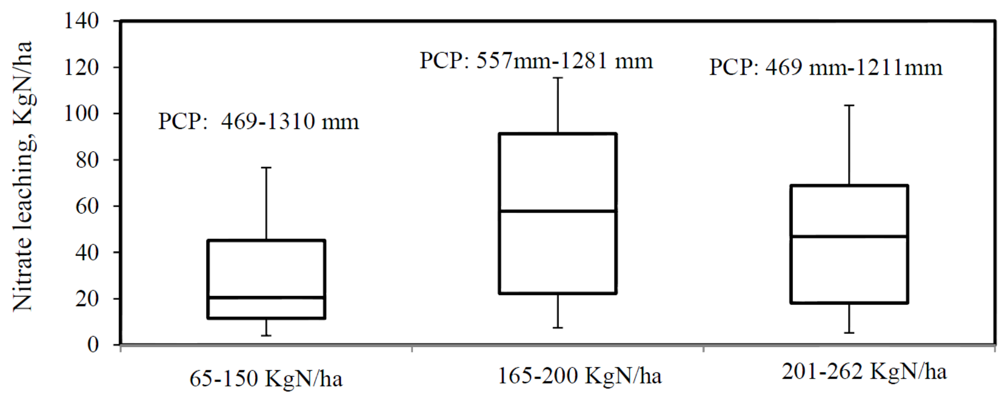

Figure 4. Subsurface nitrogen leaching from fine loamy soil for continuous corn at various ranges of precipitation (seven journal articles were used for analysis). PCP: Precipitation.

Figure 5 indicates the annual subsurface nitrate loss from the silty loam for continuous corn. Relatively, the fertilization rate has better correlation with nitrate loss in silty loam compared to the fine loam soil. Similarly, Figure 6 indicates nitrate loss at the subsurface level through sandy loam at various fertilizer application rates in a continuous corn field. Compared to the other two soil types, sandy soil shows an entirely different pattern of nitrate loss. The nitrate loss was linearly increased for the increase in fertilization rate, indicating that nitrate loss through sandy loam is better correlated with the fertilization application rate. Irrespective of the soil types, there is a significant difference in the nitrate loss when comparing the low fertilizer application rates to the medium range of fertilization. However, there is no distinct pattern in nitrate loss corresponding to the medium and high range of fertilization application, especially for the fine loamy soil and the silty loam soil. This is not surprising because fertilizer amount is not the only factor for the increased nitrate loss. In fact, the type of fertilizer and its timing of application are also equally important. In addition, several other management factors including mineralization of soil content and environmental factors related with the crop yield also contribute to the variation of nitrate loss.

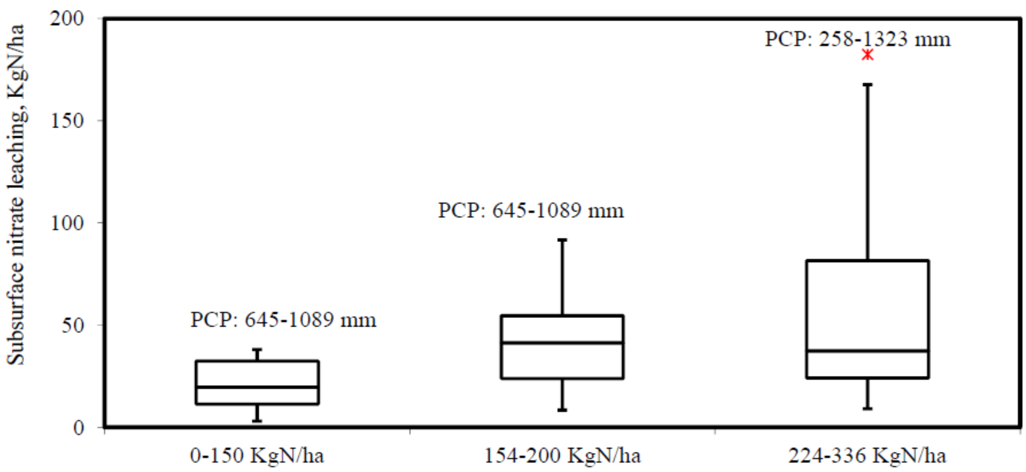

Figure 5. Subsurface nitrogen leaching from silty loam for continuous corn at various ranges of precipitations (six journal articles were used for analysis). PCP: Precipitation.

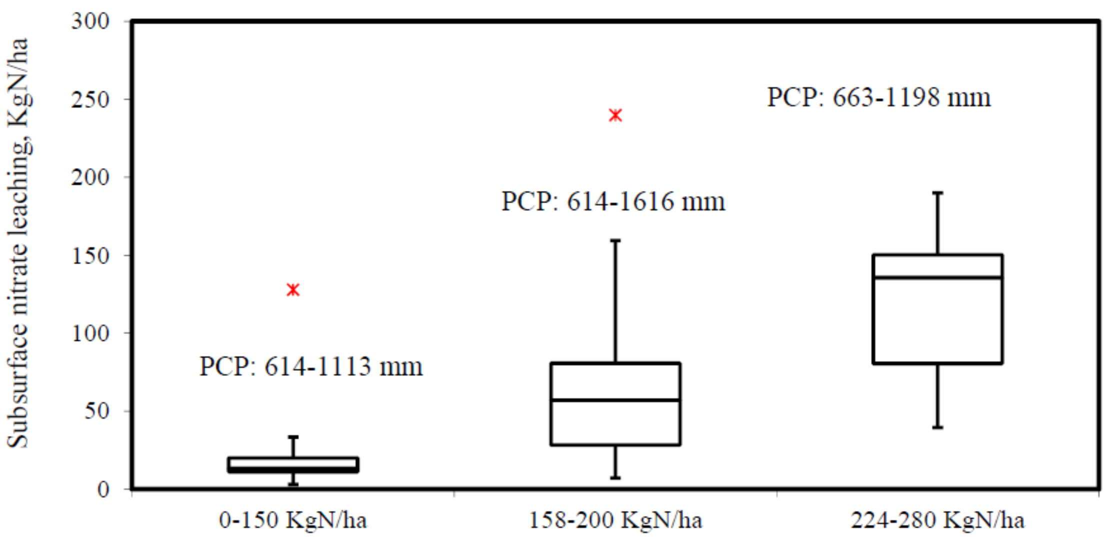

Figure 6. Subsurface nitrogen leaching from loamy sand for continuous corn (seven journal articles were used for analysis).

Several studies in the past indicate that significant nitrogen loss is expected during the winter season (early spring season) especially due to mineralization and the contribution of residual soil nitrate from the prior crop [56]. Also, nitrate loss through mineralization depends on the preceding year crop type, nutrient uptake by the crop [57] and in some cases temperature [58].

Likewise, we documented various studies conducted in rotated corn fields with different soil types. The studies at various locations were mainly focused on two types of soil categories; silty loam soil and fine loamy soil. Figure 7 indicates that there is no significant difference in nitrate loss through fine loamy soil for the two ranges of fertilizer application rates. Similarly, for silty loam soil, nitrate loss through medium range fertilization rate is relatively higher than that of the low range of fertilization rate, see Figure 8. However, the high range of fertilizer application does not necessarily result in greater loss than that of the medium range of fertilizer application.

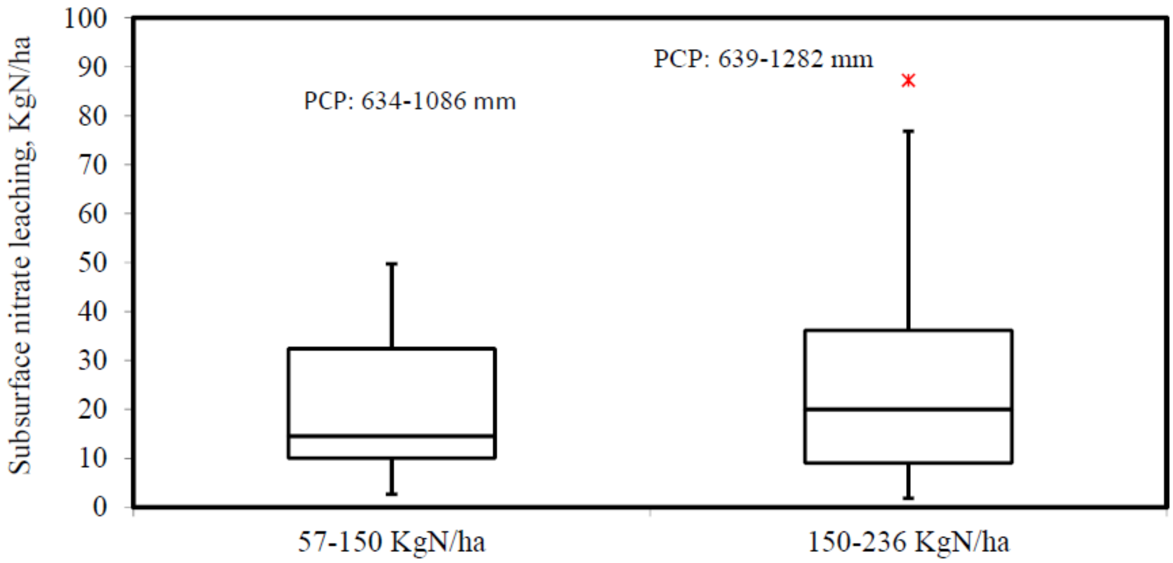

Figure 7. Subsurface nitrogen leaching from fine loamy soil in rotated corn (twelve journal articles were used for analysis).

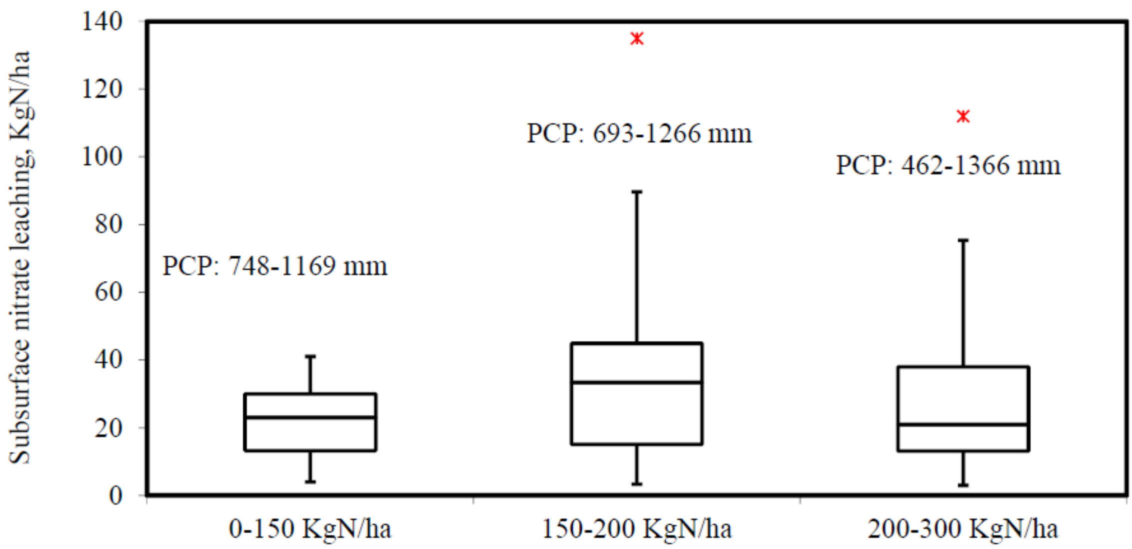

Figure 8. Subsurface nitrogen leaching from silty loam soil in rotated corn (eleven journal articles were used for analysis).

Figure 9 shows the differences in nitrate loss from continuous corn and rotated corn through silty loam soil. The data for rotated corn pertains to the nitrate leaching data considered only for the corn year. Average loss in rotated corn is relatively less compared to continuous corn regardless of the range of fertilization application rates, see Figure 9. Similarly, Figure 10 shows greater nitrate loss through continuous corn compared to the rotated corn in silty loam soil for various ranges of fertilizer application rates. The variation of nitrate loss through the corn field is affected by various factors which have been systematically described in the following section.

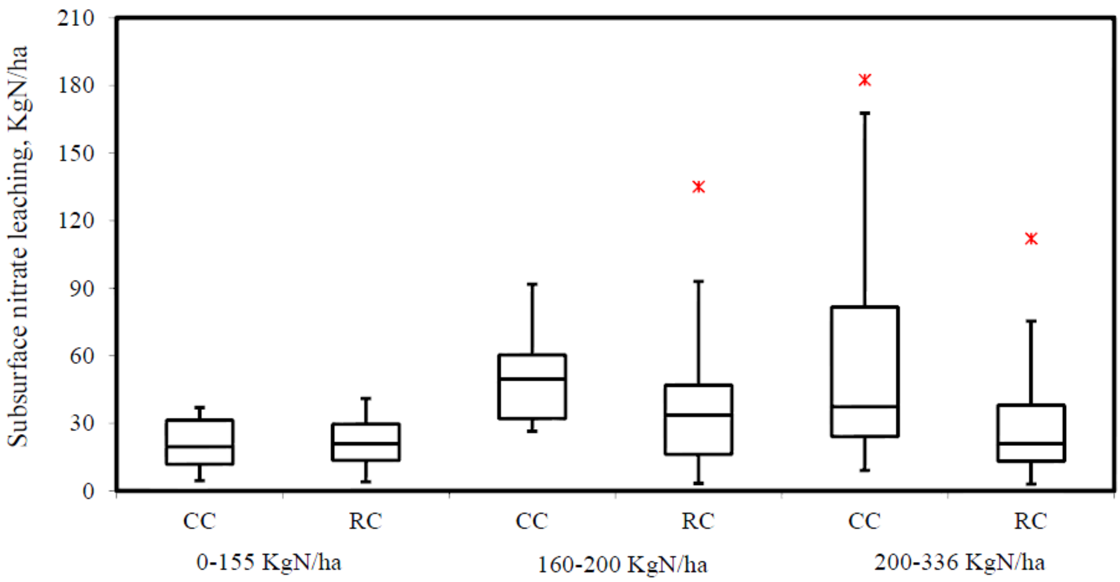

Figure 9. Nitrate leaching from silty loamy soil in continuous corn (CC) and rotated corn (RC) (six and eleven journal articles were used for analysis). CC: continuous corn, RC: Corn in rotation.

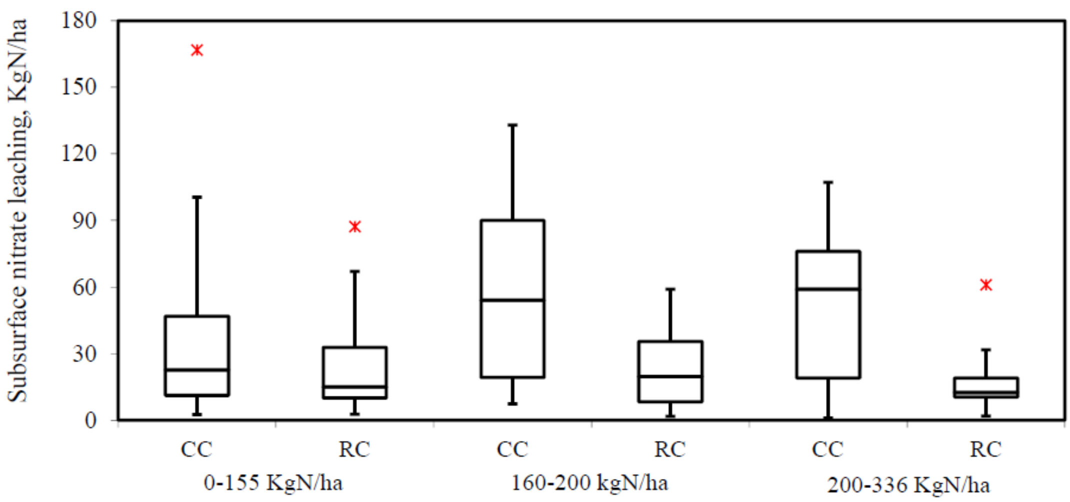

Figure 10. Nitrate leaching from fine loamy soil in continuous corn (CC) and corn in rotation (RC) (fifteen and twelve journal articles were used for analysis).

4.5. Effect of Tillage on Nitrate Loss

Tillage facilitates aeration by increasing the availability of O_2 to soil microorganisms leading to increased aerobic microbial activity and soil nitrogen mineralization [59]. Also, it depends when tillage occurred because, depending upon the climatic conditions, tillage can cause nitrate mineralization too early and increases loss before crops can utilize the available nitrate. Therefore, there are mixed experiences of tillage effect on nitrate loss. Most studies have concluded that nitrate management is more crucial than tillage. For example, Randall and Iragavarapu [50] concluded that conventional tillage slightly increased nitrate losses and reported that loss more depends on the growing season precipitation than tillage. Randall and Mulla [42] also concluded that nitrate management practices are more crucial for loss than the tillage system.

In this analysis, various types of tillage were clustered into a single category of tillage for the comparison of tillage vs. no-tillage. A tillage system demonstrated slightly higher nitrate loss than no-tillage system use, see Figure 11, in a continuous corn field. In contrast, the no-tillage system demonstrated higher nitrate loss than the tillage system, see Figure 11, in rotated corn fields. Various studies in the past indicate the significant influence of fertilizer application [60,61] and management practices [42] rather than the tillage system in the level of nitrate loss.

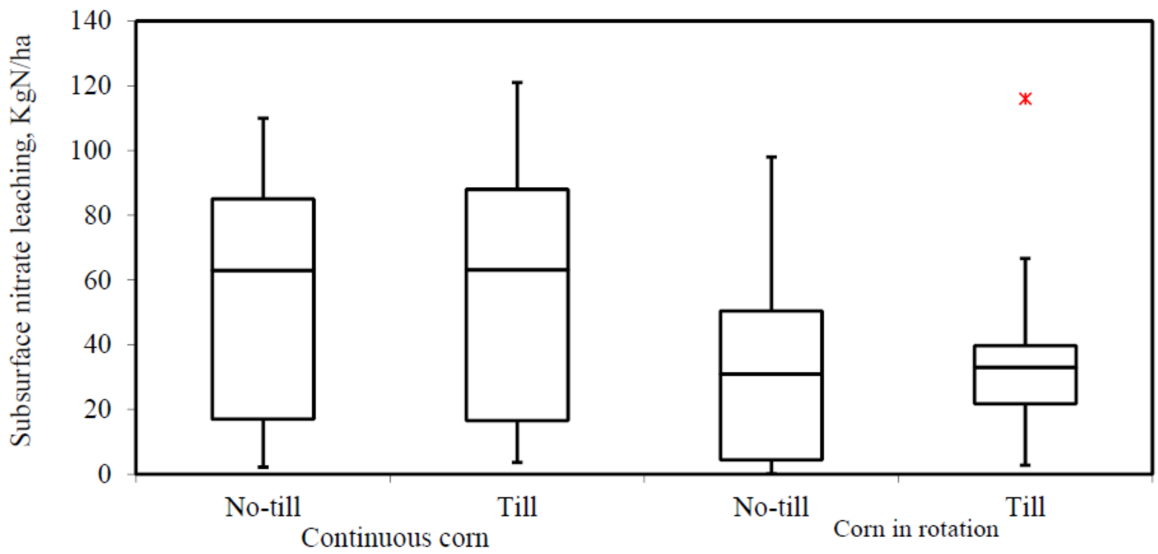

Figure 11. Comparison of tillage effect on nitrate leaching through continuous and corn in rotation (six and eight journal articles were considered for this analysis).

4.6. *Effect of Tile and Controlled Drainage*

There are several experimental [3,62] and simulated studies [43] to demonstrate the decrease in nitrate loss with increased tile drain spacing. In general, nitrate loss is inversely proportional to the spacing of tiles [61–63]. For large tile drain spacing, soil moisture availability leads to more anaerobic conditions and increased denitrification [64]. Tile drainage spacing depends upon various factors including annual precipitation, the hydraulic properties of a soil, drainage required and the depth of installation [6].

We compiled data from two journal articles by Kladivko et al. [3] and Simunic et al. [62] to analyze how nitrate loss varies with tile drainage space. Since tile drainage is generally installed in poorly drained soil landscapes to increase drainage and increase the crop yield, it is essential to properly optimize the drain space for the highest yield with minimum nitrate loss. In this study, the decrease in nitrate loss corresponding to the increase in drain space from 5 m to 10 m, 10 to 20 m, and 20 to 30 m, see Figure 12, was analyzed to evaluate the sensitivity of nitrate loss with the increased tile drain space in the continuous corn field. Median nitrate loss was reduced by almost 20% if the spacing is increased by 10 m for the continuous corn field, see Figure 12. The decrease in nitrate loss is relatively more if spacing is increased by 5 m indicating more reduction can be expected for smaller increases in drain space, see Figure 12. However, similar analysis was conducted in rotated corn fields but no significant difference was observed, see Figure 13. Nitrate loss through the subsurface can be reduced with a proper design of drain space and drain depth, though it still increases the nitrate loss through runoff [17].

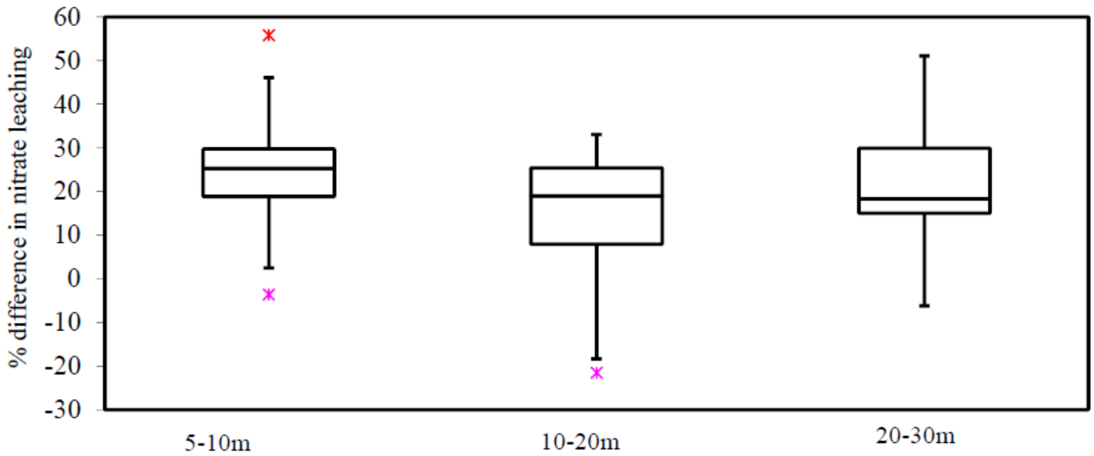

Figure 12. Figure showing more nitrate leaching with narrow increase in tile drain space in continuous corn (two journal articles were considered for analysis).

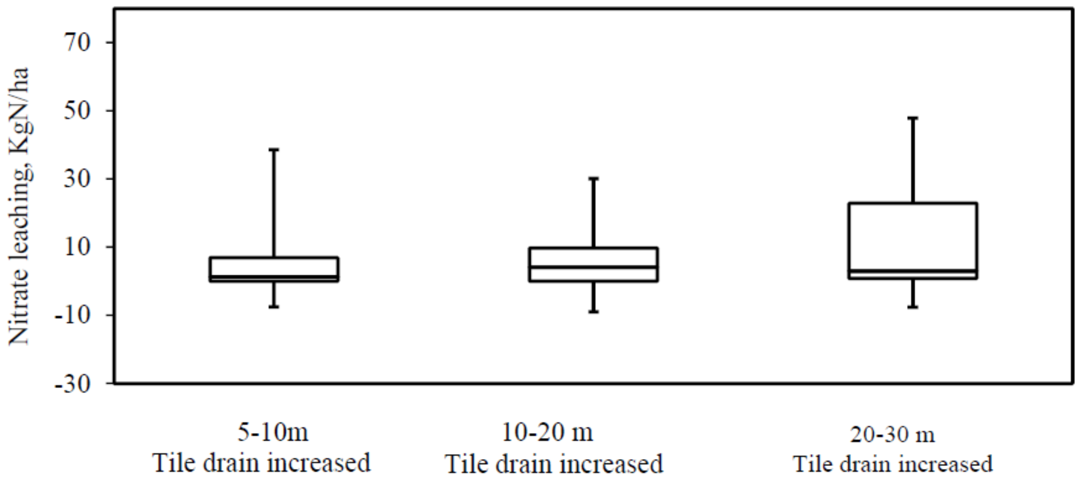

Figure 13. Figure showing mean nitrate leaching are not sensitive to the increased tile drain space in rotated corn (two journal articles were considered for analysis).

Control drainage systems (CDS's) are also one of the factors that reduce nitrate loss either by reducing the volume of drainage water leaving a field or by increasing the opportunity for denitrification due to the high-water table. Nitrate loss through surface runoff may increase due to CDS's, though it is not significant compared to the loss incurred through subsurface loss [17].

4.7. Effect of Irrigation

Since water is the limiting factor for nitrate loss [65], the mobility of nitrate increases as the water content of soil increases. Hence, precipitation will have effect on nitrate loss in two ways. First, slight precipitation from the non-growing season might contribute to loss from the root zone of irrigated crops. Second, heavy precipitation especially after irrigation may lead to excess nitrate loss [66]. Similarly, high loss can be encountered in crop season due to excess soil moisture from irrigation which might be reinforced due to excessive precipitation.

We compiled the peer reviewed journal articles discussing irrigation effect on nitrate loss. The studies related with irrigation effect were conducted in two types of soil categories; sandy loam soil and silty loam soil. The data represents identical soil types that had a similar range of precipitation and fertilization rate. However, the mean nitrate loss through the irrigated corn was significantly higher in the continuous corn field, see Figure 14. Since these experiments were not conducted over the same location, factors such as prior year precipitation, water surplus and prior year fertilization rate could also be the controlling factors. Also, soils may have a different degree of variability of soil nitrate content in different sites even though the comparisons were made over the same categories of soil. Research shows that nitrate loss can be reduced by changing full irrigated continuous corn to partially irrigated corn [55].

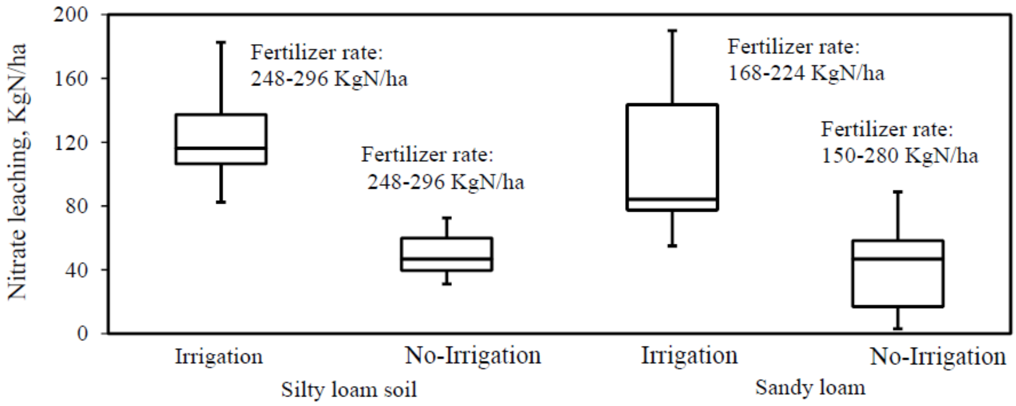

Figure 14. Irrigation effect on nitrate leaching in two different soil types through continuous corn field (two articles in silty loam soil and two articles in sandy loam soil were used for analysis).

4.8. Timing and Type of the Fertilizer Application

Since our regression equations were developed based on the annual rate of fertilizer application, the type of fertilizer and its timing of the application were missing in the analysis. The proper type of fertilizer and its time of application are always important to avoid loss. Application of nitrification inhibitors [30] is a general approach to minimize nitrate loss. Nitrapyrin (NP) is one of the most widely used nitrification inhibitors, especially for ammonium fertilizer such as anhydrous ammonium or urea to slow down the process of nitrification. In the past, various experiments were conducted mixing nitrapyrin with the nitrogen fertilizer (N + NP) in various seasons. Several recent articles [6,42] suggest that nitrogen application in the spring minimizes loss. Randall et al. (2005) [67] (reported that out of the four experiments of Fall N, Fall N + NP, Spring pre-plant N and Spring N + NP, the order of nitrate loss was higher in Fall N followed consequently with Spring N + NP, Fall N + NP and Spring N).

Similarly, the type of fertilizer and the form of nitrogen applied are equally important for loss. For example, swine manure application is more crucial for nitrate loss compared to urea ammonium nitrate (UAN) fertilizer both for the continuous corn plot and the rotated corn. This indicates that a swine manure application system should be managed properly during rainy and dry seasons [25].

The proper nitrogen management to improve N use efficiency is one of the strategies to avoid loss. Application of the pre-side dress soil nitrate test (PSNT) or the late-Spring nitrate tests (LSNT) to reduce loss are some examples of N management [59]. Split application is considered a better approach because it leads to the reduction of loss and an increase in N use efficiency due to better synchronization between crop uptake and the time of application [6]. However, there are mixed experiences to support [60,67] this concept.

5. Nitrate Loss from *Miscanthus* and Switchgrass

Various past studies suggest that perennial grass such as *Miscanthus* and switchgrass reduce nitrate loss, significantly compared to row crops [5,36,59]. There are several reasons for reducing nitrate loss: (i) these perennial grasses use relatively more water due to high evapotranspiration and reduce potential for loss; (ii) they can grow and maintain high productivity for longer periods of time without fertilizer, and even fertilizer is not recommended for the first two years to avoid weed growth; (iii) these are perennial rhizomatous plants and are highly efficient to manage soil and fertilizer N [68]; (iv) these crops recycle nutrients seasonally between the above and below ground portions of the plant and hence minimize the fertilizer requirements and corresponding loss. Therefore, *Miscanthus* and switchgrass have the potential to reduce nitrate contamination in surface and groundwater due to the characteristics of high nitrogen and water use efficiency.

Nitrate loss through surface runoff in switchgrass is relatively less compared to corn. The annual nitrate loss in switchgrass (0.98 KgN/ha) through surface runoff, excluding the establishment year, was almost 3 times lower than the nitrate loss from corn (3.22 KgN/ha) [40]. The mean annual nitrate loss through surface runoff from continuous corn fields based on various studies was 2.22 KgN/ha [1,4,19,20,22,23]. The maximum loss of 7.17 KgN/ha corresponding to 296 KgN/ha fertilizer rate, and minimum loss of 0.019 KgN/ha corresponding to 67 KgN/ha fertilizer rate was recorded. Considering the average nitrate loss is in the range of 2.22 to 3.22 KgN/ha [40], the loss from surface runoff through switchgrass fields (0.98 KgN/ha) can be assumed to be 2 to 3 times lower than the average annual nitrate loss from continuous corn.

Table 2 indicates the increasing trend of nitrate loss through subsurface runoff for *Miscanthus* as the fertilization rate was increased. It also indicates the decreasing rate of loss from the establishment year, which is partly consistent with the findings from [35], suggesting average nitrate loss from *Miscanthus* and switchgrass were not significantly different due to the different rates of fertilizer applications but were significantly different from the establishment year. With a high nitrate application rate, residual nitrate will be high and contribute to loss, see Table 2. Christian and Riche (1998) [69] reported reduced nitrate loss from the first year to third year in each treatment (0, 60 and 120 KgN/ha) in silty clay loam soil. For example, they observed very high nitrate loss in the first year which was 154, 187 and 228 KgN/ha for treatment of 0, 60,120 KgN/ha, respectively. However, they observed nitrate loss of 3, 11 and 30 kgN/ha for treatment of 0, 60,120 KgN/ha, respectively. In fact, first year nitrate loss is even higher than that of the corn field. This indicates that during the establishment phase, nitrate loss can be relatively high for silty *Miscanthus* followed by a decreased loss in the subsequent year.

Table 2. Nitrate Leaching through *Miscanthus* fields (data taken from Behnke et al. [35] and Christian and Riche [69]).

Nitrate Leaching in kgN/ha for 0 KgN/ha Fertilizer	Nitrate Leaching in kgN/ha for 60 KgN/ha Fertilizer Application	Nitrate Leaching in kgN/ha for 120 KgN/ha Fertilizer Application
6.4	7.1	13.3
8.45	19.65	57.95
3	11	30

Table 3 suggests that the initial nitrate losses from a bioenergy crop field are comparable to a corn field in an establishment year. However, after a few years of establishment, it starts decreasing [36,37]. Though the nitrate loss from the study [37] seems to be higher (Table 3), it shows a similar trend of loss because [37] measured nitrate loss in the beginning of the establishment year, whereas McIssac et al. measured nitrate loss after 2 years of establishment. Essentially, nitrate loss from both studies looks similar, see Table 3, after a few years of establishment. The reason for the increased loss in an establishment year is likely due to the higher mineralization and nitrification level resulting from the disturbance from replanting [37] which would have been consumed by plant uptake if the plant had been fully developed. Some scientists argue that less loss from the *Miscanthus* and switchgrass is due to simply the less fertilizer requirement. However, during the soybean year of a rotated corn crop, no fertilizer is applied, nitrate loss does not significantly reduce. Therefore, it is not entirely the fertilizer that contributes to the greater loss but the perennial extensive root system that potentially retains more soil nitrogen.

Table 3. Nitrate leaching from swithcgrass and *Miscanthus* fields (data taken from McIssac et al. and Smith et al.) [36,37].

Nitrate Loss from Switchgrass Fields			
	McIssac et al.		Smith et al.
Year	Nitrate leaching in various years	Year	Nitrate leaching in various years
2006–2007	0.3	2008–2009	23.2
2007–2008	0.4	2009–2010	8
2008–2009	3.9	2010–2011	8.3
2009–2010	1.1	2011–2012	5.1
Nitrate Loss from *Miscanthus* Fields			
	McIssac et al.		Smith et al.
Year	Nitrate leaching in various years	Year	Nitrate leaching in various years
2006–2007	6.6	2008–2009	76
2007–2008	1.6	2009–2010	30.2
2008–2009	1.5	2010–2011	17.3
2009–2010	3	2011–2012	2.3

Nitrate loss through the rotated corn field averaged over a three year period is 45.5 KgN/ha [37]. However, for the same type of soil and climatic conditions, nitrate loss for the established switchgrass is almost 5 KgN/ha, and established *Miscanthus* is less than 5 KgN/ha/year, see Table 3. This rate of nitrate loss is 9 times lower than that of corn. Nitrate loss through *Miscanthus* is consistent with the findings of Beale et al. [32]. However, there are some reported cases of a very high nitrate loss [33] in *Miscanthus*. The 10-year average winter nitrate loss in silty loam soil was 22.4, 26.7 and 62.9 KgN/ha for treatment of 0, 60 and 120 KgN/ha, respectively [69]. The main reason behind this unrealistic nitrate loss, as reported by authors, was due to the residual winter bean which reduced the runoff thus permitting more subsurface loss.

Beale et al. [32] observed nitrate losses through *Miscanthus* as 5 kg/ha and several factors were reported for this low nutrient loss [32]; (i) higher crop nitrogen demand at the initial days of growing season immediately after fertilizer application; (ii) continuous growth through the period when reserved mineralized nitrogen is high (summer and early autumn); (iii) an extensive rooting network with better hold of the nutrient across the plot without any gap between plants. Moreover, Cadoux et al. [70] reported that *Miscanthus* requires less nutrient compared to other crops due to many reasons; (i) nutrient cycling between the rhizome and biomass; (ii) nutrient recycling before the harvest and (iii) the contribution of N fixation by bacteria.

The agronomic characteristics of bioenergy crops are given in Table 4. The post-establishment fertilizer requirement for corn is significantly higher than *Miscanthus* and switchgrass. Similarly, research shows that perennial grasses demonstrate a substantial rooting network with root densities greater than 0.1 mg dry biomass per cm^3 extended to a depth of 100 cm. whereas corn root densities were extended to a depth of 10 cm [71]. From this, it can be concluded that there is significant evidence of less nitrate loss through *Miscanthus* and switchgrass compared to corn and rotated corn. However, at what degree and extent the reduction occurs is still a matter for investigation. Further studies are needed to find the true differences in nitrate loss at different spatial extents from these bioenergy crops using various field scales and watershed scale studies. Similarly, nitrate loss through short rotation crops (e.g., willow and poplar) and its comparison with the loss from other bioenergy crops will be interesting research topics for the future.

Table 4. Prevailing agronomy practices for bioenergy crops and potential nitrate leaching.

Crops	Pre-Establishment N Fertilization Practice	Post-Establishment N Fertilization Practice	Source	Plant Root Densities
Switchgrass	0 0 0	22.4 kg *t*-1 DM 50–100 kg/ha 100–140 kg/ha	Khanna et al. [72]	
Miscanthus	60 kg/ha, 103.9 kg/ha	50–80 kg/ha 88–130 kg/ha		1–2 plants/m^2 2 plants/m^2
Corn	NA	190–220	Randall et al. [50] and Hofmann et al. [63]	

6. Conclusions

In this study, we explored some of the potential factors for nitrate loss for three bioenergy crops; corn, switchgrass and *Miscanthus*. These factors not only provide guidelines for monitoring nitrate loss through bioenergy crop fields, but are also useful for scientists to develop predictive nitrate loss simulation models. The study was conducted based on a large number of field or plot scale studies and provided general insight of various factors associated with nitrate loss. Nitrate loss is a resultant effect of various combinations of factors such as tillage, soil type, timing and rate of fertilization application, irrigation, water surplus, climatic condition, antecedent moisture condition, evapotranspiration, temperature, crop yield and several other environmental factors. Therefore, the estimation of nitrate loss through a given field is a complex process which cannot be fully described by regression equations. A significant portion of this manuscript covered the analysis of several potential factors associated with nitrate loss through a corn field and rotated corn field based on the large set of data compiled through the published literature. The analyses from these various studies showed that fields planted in continuous corn fields treated with fertilizer had the maximum effect on nitrate loss into the tile system. It was found that fields with switchgrass and *Miscanthus* contributed less nitrate loss. Switchgrass and *Miscanthus* can grow with significantly less fertilizer compared to corn. Besides, *Miscanthus* and switchgrass have a perennial rooting network that helps hold against loss and high nitrogen and water use efficiency by recycling nutrients from the aboveground biomass to the roots or rhizomes. Also, these crops consume more water resulting in less soil water content available for loss. Both surface and subsurface nitrate loss in *Miscanthus* and switchgrass is much less than that through corn fields. The large scale implementation of second generation biofuel, replacing many cornfields with perennial grass in the American Midwest, will likely decrease the nitrate loss that enters the Gulf of Mexico. Since nitrates lost into the soil can affect downstream conditions in various ways, including an effect on drinking water quality and eutrophication, suitable agricultural practices should be implemented in order to maintain maximum water quality without compromising the crop yield. Since some of the agricultural land might convert into switchgrass/*Miscanthus* in the Midwest to meet the EISA target, it is essential to compare the environmental impact of those crops with their associated nitrate loss. Also, more field scale and watershed scale studies are needed in the future, especially for *Miscanthus* and swithgrass fields, to evaluate the degree and range of nitrate loss at various spatial extents.

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