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The Impact of Irrigation on Surface Nitrate Export from Agricultural Fields in the Southeastern United States

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Abstract: Agricultural runoff ranks second only to atmospheric deposition as a source of nitrogen pollution to streams in the southeastern United States. Climate-smart practices such as irrigation have the potential to reduce these impacts and provide resilience in the face of climate change. The purpose of this study is to evaluate the impact of irrigation amounts and fertilizer application strategies on surface nitrate export to surrounding streams. Data from an existing experiment on corn nitrogen fertilization in the Southeastern US was utilized and a crop simulation model was employed to simulate the water and nitrogen dynamics within the soil with particular emphases on nutrient uptake and residual nutrients left in the soil after harvest under varying fertilization scenarios. A hydrologic and nutrient export model was developed to run in conjunction with the crop model to simulate lateral export from the fields. The results of this study indicate that climate and nutrient management are the dominant factors in determining surface nutrient transport under both rain fed and irrigated conditions, confirming previous studies. The overall results show that irrigation, on average, reduced nutrient export from the surface, especially in dry years. The effect is even greater if the nutrients are applied later in the year while irrigation is on-going. While this present study provides an initial look at the potential impacts of irrigation on nutrient export in humid areas, the available on-farm observational data is limited in its content. However, the results obtained support existing literature and provide further evidence on the impact of irrigation as a climate resilient practice and will help direct future studies in the region.

Keywords: nutrient transport; irrigation management; runoff; agricultural runoff; climate resilience; water quality



Academic Editor: Claude Hammecker

Received: 26 December 2024

Revised: 20 January 2025

Accepted: 11 February 2025

Published: 13 February 2025

Citation: Ellenburg, W.L.; Cruise, J.F.; Ortiz, B.V.; Suhs, R. The Impact of Irrigation on Surface Nitrate Export from Agricultural Fields in the Southeastern United States. *Land* **2025**, *14*, 392. <https://doi.org/10.3390/land14020392>

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1. Introduction

Excessive nutrient levels in surface water bodies lead to high biological productivity, which can then result in low dissolved oxygen in the stream or lake when the organisms die off. One of the biggest contributors to nutrient runoff in streams and lakes is the fertilizer applied to cultivated farmland. According to the US Geological Survey [1], agricultural runoff ranks second only to atmospheric deposition as a source of nitrogen pollution of streams in the southeastern United States. In agriculturally dominated areas, it is the main contributor [2]. These sources, together with livestock operations, are the primary causes of eutrophication of the surface waters in the eastern US [3].

Irrigation is increasingly recognized as a climate-smart agricultural (CSA) practice that enhances productivity and resilience in the face of climate change. The integration of irrigation into agricultural systems allows farmers to mitigate the adverse effects of climate variability, such as droughts and irregular rainfall patterns [4,5]. Though, in the southeast US, irrigation is less common overall [6,7], irrigation is increasing in the region, particularly in Alabama, where irrigation has increased more than twofold over the past decade [8,9]. The impacts of irrigation on nutrient export and in-stream water quality depend on a range of factors, mainly climate and soil [1,2]. In addition, the amount and timing of the inputs is also critical [10,11]. Previous studies have shown that irrigation has the potential to increase or decrease the nitrogen loads in streams, depending on the major transport mechanism [12–21]. On the one hand, since irrigation maintains the soil moisture state at a higher level, when rainfall does occur, it is expected that runoff would be higher than if there was no irrigation. On the other hand, it is assumed that irrigated crops are more efficient than rain-fed crops in uptaking nutrients from the soil since they sequester more biomass. Thus, it would seem during the growing season that irrigation would increase runoff but possibly reduce nutrient concentrations. In fact, recent droughts have been associated with an increase in the nitrogen left in the soil [22–24]. Controlled irrigation has been suggested as a means of nutrient management in irrigated agriculture [19,21]; however, this issue has normally been investigated through a few detailed small-scale field experiments and has not been extensively modeled.

The interaction between irrigation and nutrient dynamics is complex, as irrigation can facilitate both the nutrient uptake by crops and nutrient leaching into groundwater or surface runoff, depending on site-specific factors such as soil type and rainfall intensity. While irrigation may reduce the nitrogen concentrations in runoff by promoting nutrient uptake during the growing season, the improper timing or over-application of fertilizers can negate these benefits. This underscores the importance of integrating precise irrigation scheduling with nutrient management practices to minimize the risk of nutrient export to surrounding water bodies [10,11].

In many agricultural areas in the southeast, the primary transport mechanism is saturated overland flow due to the poor-draining soils and precipitation patterns [1]. To the best of our knowledge, the impact of irrigation on nutrient export in regions where overland flow is primary has not been investigated. The purpose of this study was to investigate the impact of irrigation on surface nitrate export to surrounding streams. This is an important area of concern, as irrigation can be key adaptation strategy to ensure climate resilience [4]. Data from an existing experiment on corn nitrogen fertilization were utilized, and a crop simulation model was employed to simulate the water and nitrogen dynamics within the soil, with particular emphases on nutrient uptake across differing irrigation amounts and fertilizer application strategies. The goal of this study was to evaluate the influence of irrigation on reducing nitrate surface runoff in humid agricultural systems, with a focus on silty clay soils and varying fertilizer application strategies. This evaluation included a direct comparison of rain-fed and irrigated conditions to understand how irrigation alters nutrient export and utilization. Though the available on-farm observational data were limited in evaluating nutrient export directly, we further supported the conclusions with studies across the literature that investigated nutrient use efficiency (NUE). While NUE does not necessarily account for all nitrogen losses from a system, it serves as a valuable proxy for estimating potential nitrogen export. The intent of this study was to provide a baseline proof of concept and a comprehensive literature review to help direct and inform future studies in sustainable irrigation and nutrient management.

2. Materials and Methods

2.1. Experimental Design

Teh baseline data for this study were collected from a corn nitrogen fertilization study conducted at the Tennessee Valley Research Center located in Belle Mina, Alabama (34°41' N, 86°53' W), during 2010 and 2011. The center is operated by the Auburn University Agricultural Extension Service and includes an on-site weather station capable of collecting all relevant meteorological data. In general, the soil is classified as silty clay loam with moderate drainage characteristics. Though lacking some of the information that might be useful to more completely simulate the nitrogen budget, it does provide some field verification and points to a framework for future field studies. The experimental design for the fertilizer experiment was a randomized complete block (RCB) with four replications. DeKalb 67–87 corn hybrid was assigned to the main plots, and 16 randomly distributed nitrogen treatments were randomized among subplots within each main plot (Table 1).

Table 1. Experimental fertilizer treatment descriptions. The first applications were conducted on 2 April 2010 and 7 April 2011. The second applications were conducted on 14 May 2010 and 11 May 2011.

Treatment Number	Nitrogen (kg ha ^{−1})	Increase	Treatment Number	Nitrogen (kg ha ^{−1})	Increase
1	112–0	Pre-plant	9	67.2–156.8	Side-dress
2	56–56	Split	10	280–0	Pre-plant
3	33.6–78.4	Side-dress	11	140–140	Split
4	168–0	Pre-plant	12	89.6–190.4	Side-dress
5	84–84	Split	13	0–0	Control
6	56–112	Side-dress	14	56–0	Pre-plant
7	224–0	Pre-plant	15	28–28	Split
8	112–112	Split	16	0–56	Side-dress

The test site was irrigated with a linear spray irrigation system. The irrigation application rate remained constant throughout this study, although the timing and amount varied (Figure 1). The surface slope of the field was about 3%, and the fields were not tiled so that collection of direct runoff was not practical. This study was conducted primarily to examine the impacts of various fertilizer treatments and irrigation depths on crop yields. Some limited plant nitrogen data were taken, and yields were carefully measured so that some biophysical calibration of the model was possible. The plant collection and use were conducted in accordance with all the relevant guidelines. Detailed results of the experiment can be found in Ortiz et al. 2011 [25].

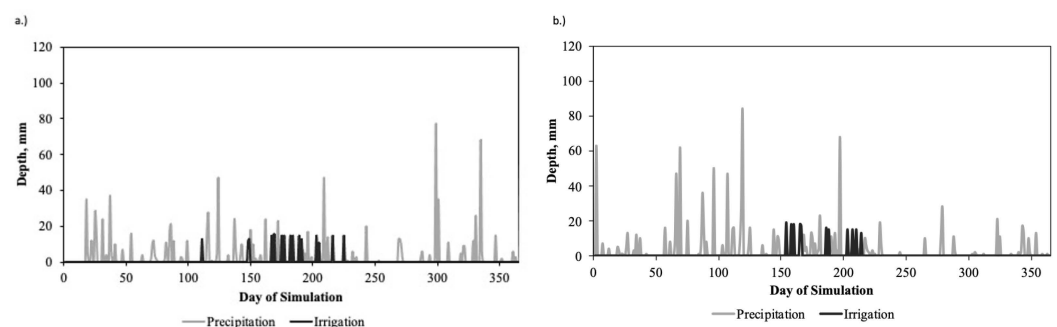


Figure 1. Precipitation records and irrigation applications for years (a) 2010 and (b) 2011.

2.2. Modeling Setup

To simulate nitrate export under rain-fed and irrigated conditions, a combined agricultural and water quality modeling system was developed. The primary modeling component was the crop simulation model (Decision Support System for Agro-technology Transfer, DSSAT [26,27]). The DSSAT simulates crop growth and yield in response to management, climate, and soil conditions. This cropping system model allows for the detailed the soil–water–plant extraction process to be simulated. The DSSAT has been previously coupled with a soil hydrology model (DRAINMOD) to evaluate management strategies and their impact on N loss [18,20]. Previous studies have primarily focused on subsurface drainage. For this study, a kinematic-wave-based hydrologic model was constructed and connected to a nitrate transport equation to estimate losses due to surface pathways. The integrated modeling system employed moisture and mobile nitrate volumes from the DSSAT as the input to the kinematic wave and nitrate transport model.

On a daily time step, with the subplots as the modeling area, the CSM-CERES-Maize model (within the DSSAT) was used to simulate the development and growth of maize from planting until maturity using physiological processes that are defined by the crop's response to soil and atmospheric conditions as well as management practices (fertilizer and irrigation) and specific genotypes. The soil profile used in this study was disseminated within the DSSAT for the Belle Mina Research Center and developed using the methodology of [28] by converting soil survey matrix data (particle size distribution, Table 2a) to DSSAT parameters, as described in [29] (Table 2b).

Table 2. Soil properties: physical, chemical, hydraulic, and root growth characteristics.

(a) Physical and Chemical Properties.							
Depth (cm)	Master Horizon	Clay (%)	Silt (%)	Sand (%)	pH (In Water)	Cation Exchange Capacity (cmol/kg)	Total Nitrogen (%)
5	Ap	31.1	56.2	12.7	6.7	0.2	0.43
20	Bt 1	36.7	50.2	13.1	7.4	0.2	0.14
46	Bt 2	48.9	43.1	8.3	7.3	0.3	0.09
104	Bt 3	54.1	38.4	7.5	7.1	0.3	0.08
132	Bt 4	56.5	34.6	8.9	5.1	0.3	0.08
152	Bt 5	56.2	33.8	10	5.1	0.3	0.08
(b) Hydraulic and Root Growth Properties.							
Depth (cm)	Master Horizon	Lower Limit	Drained Upper Limit	Saturation	Bulk Density (g/cm ³)	Saturated Hydraulic Conductivity	Root Growth
5	Ap	0.172	0.346	0.485	1.29	0.15	1
20	Bt 1	0.204	0.373	0.492	1.27	0.15	1
46	Bt 2	0.284	0.444	0.514	1.21	0.09	0.54
104	Bt 3	0.319	0.472	0.517	1.2	0.06	0.001
132	Bt 4	0.334	0.483	0.521	1.19	0.06	0.001
152	Bt 5	0.332	0.48	0.517	1.2	0.06	0.001

Soil water drainage is dictated by a water mass balance methodology as a function of the lower limit of plant water availability, the drained upper limit, and the field saturation [30]. In an effort to better capture fallow-season nitrogen dynamics, the DSSAT-CENUTURY module [31] was initialized and used to simulated the soil organic matter [32–35].

The “tipping bucket” approach was employed in vertical drainage based on the available water capacity of the soil layers, where excess water in a layer drains downward once field capacity is exceeded, simulating gravity-driven movement. Moisture moves

vertically through the soil profile either through drainage or through plant uptake for biomass sequestration or ET [30]. Many studies have validated the CSM-CERES-Maize model in various soil types and a range of climates [26,36,37]. The DSSAT does not simulate any lateral transport of water or pollutants off of the field. Excess water (such as surface runoff) is computed and simply assumed to be lost to the system [30].

Excess water was carried off the field using a kinematic wave model. The kinematic wave is the standard approximation in most runoff models. It has been shown to be accurate (errors in the order of 1–10%) when properly applied [38]. The conditions in the present study fit well within the recommended constraints for kinematic wave modeling: bottom slope > 0.002 ; 0-depth gradient or normal downstream control, and kinematic number greater than 7.5 [38,39]. Ref. [38] achieved errors of less than 1% for the numerical solution of large kinematic numbers; however, errors increased for the analytical solution as noted here.

The fraction of nitrate that is mobile and potentially removed from each layer by moving water can then be determined using the methodology of the Soil and Water Assessment Tool (SWAT) [40]:

$$conc_{NO3, mobile} = \frac{NO3_{ly}(1 - e^{-w_{mobile}/(1-\theta_e)SAT_{ly}})}{w_{mobile}} \quad (1)$$

where $conc_{NO3, mobile}$ ($\text{kg Nmm}^{-1} \text{H}_2\text{O}$) is the concentration of nitrate transported, $NO3_{ly}$ (kg Nha^{-1}) is the amount of nitrate in the soil layer available for movement (from the DSSAT), w_{mobile} ($\text{mm H}_2\text{O}$) is the amount of mobile water in the layer, θ_e is the fraction of the porosity from which anions are excluded, and SAT_{ly} ($\text{mm H}_2\text{O}$) is the saturated water content, or porosity in this study, of the soil layer. The amount of mobile water in each layer can be determined from the hydrologic equations above. For surface runoff, the amount of nitrate in the top 5 cm of soil is “flushed”. The SWAT model has been in use for many years, and the nutrient transport module has been thoroughly tested and verified [41–43].

2.3. Model Calibration and Verification

The base model calibration was performed on the cultivar-specific parameters in the crop model based on the observed 2010 yields. Of the six cultivar parameters in the model, only the coefficients of the reproductive growth parameters G2 (potential kernel number) and G3 (kernel growth rate) were determinative for yield, and they were adjusted from a base medium-to-full season default maize hybrid cultivar using yield data from 2009. In the DSSAT-CERES-Maize model, the G2 and G3 parameters are directly related to yield outcomes, making them the most suitable for calibration when observed yield data are the primary calibration metric [44].

The model was evaluated in two parts, first against observed yield and then in context of nutrient balance and runoff. Yield data from 2010 were used to evaluate the calibrated DSSAT model. As stated previously, the fields utilized in this example were not tiled, so no direct runoff data were available for comparison. However, there were data available to allow for placing the results in context. In addition to observed yield, samples of stalk nitrogen levels and soil nitrate were taken and were used to evaluate the effectiveness of the model to simulate plant N uptake and provide further confidence in model accuracy related to the moisture and nitrogen flux from the fields.

At the R-1/silking stage (a critical stage in corn growth when silks emerge from the husk and become receptive to pollen), a one-meter row of plants was harvested for testing of the total nitrogen in the biomass. A total of 30 samples were acquired. Corn stalks were collected following protocols from the Alabama Cooperative Extension System (ACES) guidelines and analyzed at the Auburn University Plant Diagnostic Lab. The model was

ten days late in becoming N-limited so an earlier stalk N trial was not determinative and thus was not used.

Soil samples taken in June 2011 were used to validate residual soil nitrate to the greatest extent possible. Standard soil sampling procedures were followed to minimize disturbances [45], and the samples were sent to the ACES Soil Lab for nitrate testing. The sampling depth was limited to 15–20 cm due to high soil resistance. This was unavoidable under the field conditions; however, these depths are still in the range of those in the National Resource Conservation Service guidelines [46]. The average nitrate concentrations were computed for each sample and compared to the averages for the same depths in the model. A total of 30 soil samples were taken, representing 13 different treatments on two different dates (23 March 2011 and 16 June 2011).

3. Results

3.1. Model Calibration and Validation

The calibration of the DSSAT CERES-CSM base medium-to-full season default maize hybrid cultivar resulted in the adjustment of the G2 and G3 parameters from 890.0 to 879.8 and from 8.50 to 7.20, respectively. The DSSAT calibration and verification results are shown in Figure 2. Panels (a) and (b) show the modeled vs. observed yield (grain weight) for each fertilizer treatment for the years 2010 (calibration) and 2011 (verification), respectively. Panel (c) shows the model-predicted vs. observed plant N concentrations at the silking stage during the 2011 season.

It can be seen from Figure 2a that the model was unable to capture the full variance in the observed yields and was positively biased. However, taking into account the assumption of unequal variances, a *t*-test of the observed mean yields and the simulated yields suggested that the difference in the means was not significant with a *p*-value of 0.105. The means for the observed and simulated grain weights were 9216.35 kg/ha and 9917.61 kg/ha, respectively. Further investigation revealed a significant difference in the variance among the observed replications with a *p*-value of 0.007. However, the average variance in the replications of the first four treatments was less than half that of the other twelve (1,120,337 vs. 2,684,222 kg/ha) and accounted for only 11% of the total variance among the replications. Thus it appears that in order to simulate the yields of the twelve treatments with higher variance among the replications, the model was forced to overpredict the four treatments with less variance. An ANOVA test of the overall variances of the data showed that the variances of the observations and simulated yields were not significantly different with a *p*-value of 0.208.

Figure 2b shows the validation of the calibrated model for the year 2010. The r^2 value of the scatter plot was 0.9518, with a standard error of 13.76. The variances of the observed and the simulated yields were 125,345.9 kg/ha and 230,628.93 kg/ha, respectively. The higher variance among the treatments of the observed yields suggested that, in this case, the fertilizer treatments had a greater impact on the yields than was the case in the 2010 (drier) season. With the assumption of unequal variances, a *t*-test of the observed mean yields and the simulated yields suggested that the difference in the means was not significant, with a *p*-value of 0.460. The means of the observed and simulated yields were 8375.47 kg/ha and 8277.99 kg/ha, respectively.

The figures show that the model simulated plant growth well during both years in nearly all of the experimental cases. Panel (c) also demonstrates that the model did well in simulating stalk nitrogen levels at silking, with an r^2 value of 0.81. Though unable to capture the full variance (*p*-value < 0.05), the simulated mean was only 8% below the observed mean (2.10 and 1.93, respectively). Based on these results, it appears that the DSSAT model did well in simulating the nitrogen uptake by the corn plants at this stage.

The soil N comparison was inconclusive, as the timing of the sampling (March and June) missed the most dynamic fluctuations in the surface layers. However, the overall means between the simulated and observed soil nitrate levels in the samples matched fairly well (3.94 vs. 5.29 mg L⁻¹, respectively) with a model variance of 46.98 versus the observed variance of 62.62. A two-sample *t*-test assuming unequal variances failed to reject the equality of the means ($p = 0.48$).

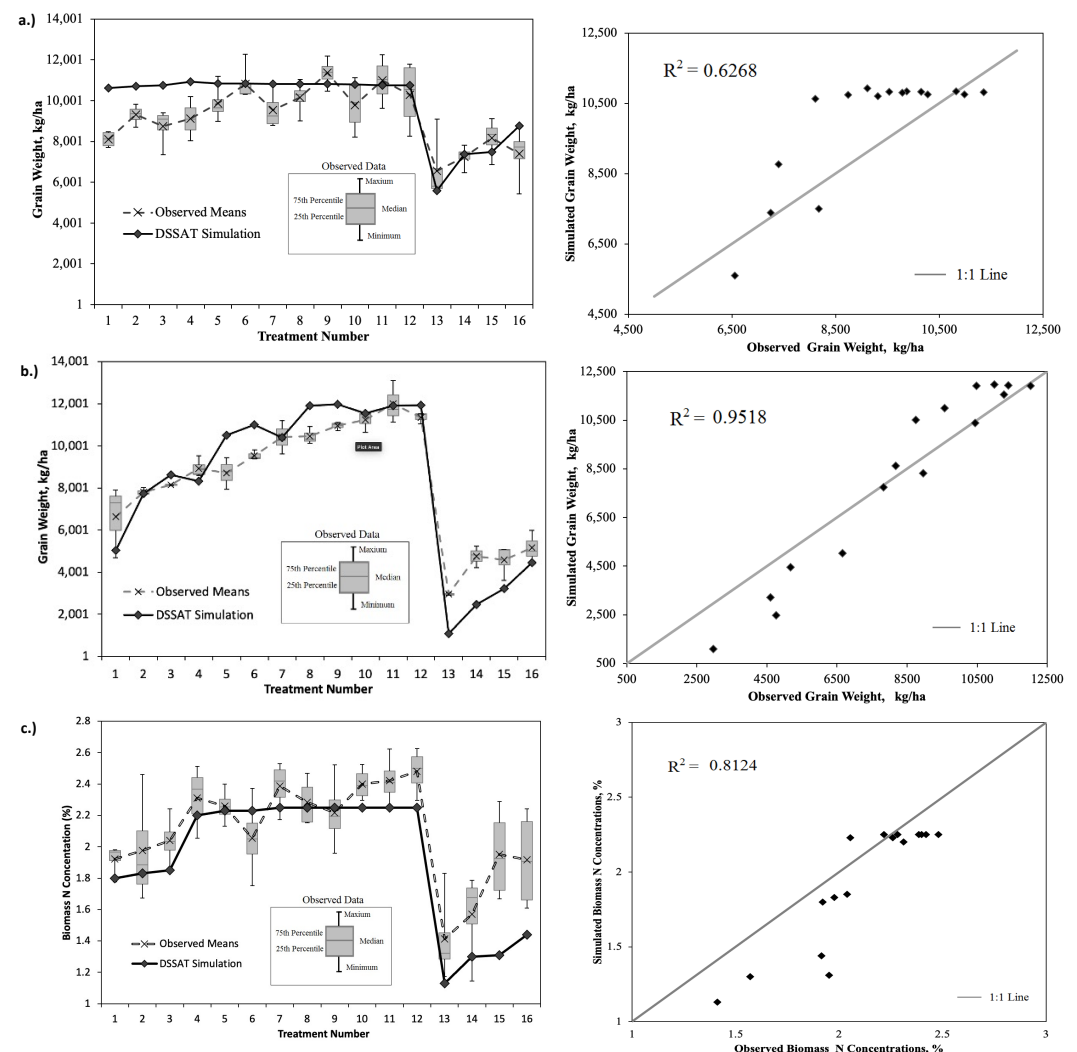


Figure 2. Comparison of simulated and measured yields and their scatter plot comparison for (a) 2009 model calibration and (b) 2010 model evaluation, and (c) the comparison of 2010 simulated and measured N stalk concentrations and their scatter plot comparison for model validation during the silking period of growth.

3.2. Nutrient Export

The hybrid crop and hydrologic model was run to simulate each of the experimental treatments described below in both rain-fed and irrigated scenarios. Of the two years simulated, 2011 received 20 cm more rainfall than 2010 during the growing season. Thus, the 2010 crop was irrigated a total of 213 mm (8.4 in), while 2011 received 179 mm (7 in) of irrigation. It is important to note that the amount and uniformity of irrigation, as well as the amount and timing of fertilization, are very important interacting factors that influence both crop yield and nitrate export [47]. As such, the following results are dependent upon both the irrigation and fertilization schedules presented above.

The simulated surface runoff for 2010 were 94.2 mm and 98 mm for rain-fed and irrigated respectively, and 152.8 and 161.3 mm for 2011. Of course, the runoff results are unaffected by fertilizer applications and are practically the same for all experiments. The results show that in totality, the irrigated field does produce slightly more surface runoff than does the rain-fed field, however, the difference is less than 10 mm in all treatments for both years.

Table 3 demonstrates that the nitrate export from the surface was different. The table shows a comparison between the surface nitrate export for all treatments under irrigated and rain-fed conditions. Note that treatment 13 was the control (no fertilizer) case. The results show that during the dry year (2010), the rain-fed field consistently exported more nitrate off the field than under irrigated conditions when the same amount of fertilizer was applied in both cases. In the wetter year (2011), only the larger treatments (>200 kg/ha) resulted in a noticeable difference in export. Overall, the differences between the rain-fed and irrigated export means were significant during 2010, except for the eight small applications (treatments 1–4 and 13–16) with a p -value of 0.02. Conversely, during the wetter 2011, although most treatments did show a greater export under rain-fed conditions, they were not statistically significant (p value = 0.44).

Table 3. Results for total surface-transported nitrate (kg/ha) for each treatment, irrigated and rain-fed conditions, for 2010 and 2011. Total exports are annotated for treatments 4–9 to aid in the discussion in the text.

Treatment Number	2010		2011		Total Exported	
	Irrigated	Rain-Fed	Irrigated	Rain-Fed	Irrigated	Rain-Fed
1	33.8	33.45	42.01	41.73	75.81	75.18
2	23.32	23.93	23.55	23.26	46.87	47.19
3	19.61	20.69	16.44	16.79	36.05	37.48
4	47.02	59.83	60.51	60.21	107.53	120.04
5	31.51	45.37	32.79	33.36	98.5	78.73
6	26.61	40.79	23.61	25.69	50.22	66.48
7	60.08	73.57	79.04	78.65	139.12	152.22
8	39.51	54.36	41.68	44.02	81.19	98.38
9	31.62	47.085	26.83	31.81	58.45	78.895
10	73.12	87.4	97.07	97.06	170.19	184.46
11	47.58	63.58	50.92	54.85	98.5	118.43
12	38.84	55.55	34.42	41.28	73.26	96.83
13	8.1	6.88	6.72	6.55	14.82	13.43
14	17.72	16.2	23.53	23.78	41.25	39.98
15	12.59	11.34	14.48	14.31	27.07	25.65
16	11.11	9.93	6.74	6.46	17.85	16.39

The detailed results for treatment 1 (112 kg ha^{-1} before planting) are shown in Figure 3. Nitrogen was applied on day 92 in 2010 and on day 97 in 2011. As shown in Figure 1, irrigation began on day 110 in 2010, while it began on day 154 in 2011. Thus, the large rainfall event on day 116 in 2010 was impacted by the irrigation, while the event on day 107 in 2011 was not. Accordingly, the results show that noticeably fewer nitrates were exported during 2010 under irrigated conditions than under the rain-fed scenario, indicating that the nitrogen had “watered in” to the deeper layers and was thus not available for surface transport. The overall results show that irrigation, on average, reduced the nutrient export from the surface. Rain-fed simulations showed the export of 8 kg ha^{-1} more nitrate on average in 2010 while a more modest 1.2 kg ha^{-1} in 2011 (wetter year). These results support the supposition that after the fertilizer was applied to the surface, irrigation tended move

the nitrogen below the surface at a faster rate than under rain-fed conditions. Thus, there was less nitrates available for transport under the irrigated scenario, even though there was more runoff in that case.

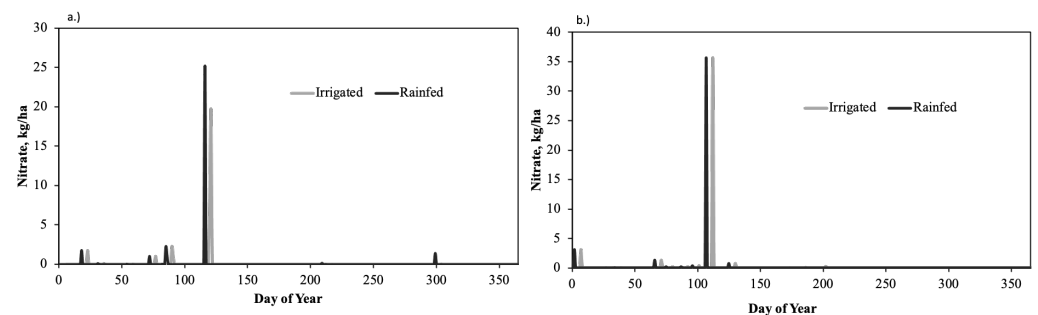


Figure 3. Simulated surface nitrate export for treatment 1 in (a) 2010 and (b) 2011.

4. Discussion

Particularly in the dryer 2010 season, irrigation produced a significant mitigating effect on nitrate transport, and, even more significantly, this effect was greater for the larger-nitrogen-application experiments. In North Alabama, irrigating farmers normally apply 200–250 kg ha^{−1} or more nitrogen in order to obtain maximum yields, as recommended by the Alabama Cooperative Extension System [48]. On the other hand, farmers using rain-fed farming usually apply nitrogen in the order of 150–200 kg ha^{−1}. As such, it would be interesting to investigate scenarios that better simulate the actual practices in the area. This can be accomplished by comparing experiments under rain-fed and irrigated conditions. For example, in treatments 4, 5, and 6, 168 kg ha^{−1} was applied under different strategies, while in trials 7, 8, and 9, 224 kg ha^{−1} was applied. The first set of trials could be considered representative of rain-fed conditions, while the second set could represent irrigated conditions in this region (see annotation in Table 2).

Considering the rate of applied N, the N export from the irrigated field was always lower than from the rain-fed field when comparable treatments were observed (i.e., 4–6 vs. 7–9). However, in some treatments, the total export was less, which was significant since ~100 kg ha^{−1} more N was applied. In addition to irrigation, fertilizer management had a clear impact on the export of nutrients from the field. When more fertilizer was applied at (or before) planting, there was less opportunity for the plants to uptake the nutrients because their root systems were not developed yet. Thus, more N was available to be transported during the spring rains. However, when less N was applied initially and more was used as side dressing, there was a significantly positive effect. For example, there was an overall two-year 14% increase in nitrogen export under irrigated conditions as compared to rain-fed conditions when all nitrogen was applied at planting (treatments 4 and 7: 120 vs. 139 kg ha^{−1}). However, this decreased to 3% when 50% of the N was applied at planting and the other 50% was applied as a side dressing (treatments 5 and 8: 78.7 vs. 81.2 kg ha^{−1}). When one-third was applied up front, there was an overall decrease in export of 12% when irrigation was used (treatments 6 and 9: 66.5 vs. 58.5 kg ha^{−1}). This was in spite of the fact that 33% more N was applied under the irrigated conditions.

The impact of climate on nutrient runoff from the area is also clearly illustrated. Irrigation was more effective in mitigating nutrient export in the dry year (2010) as opposed to the wetter year (2011). In a dry year, irrigation serves to reduce the nutrient export from the fields. When all the fertilizer is applied at planting, there is very little increase in export in dry years, and the mitigation becomes more pronounced as side dressings

are increased. In this region, subsurface transport is minimal due to the poorly draining soils [49]; therefore, the N that reaches the root zone is likely to be assimilated by the plant.

These results support the hypothesis that nutrients are absorbed into the root zone with the irrigated water, to be taken up by the plants even with scarce rainfall. On the other hand, there is some increase in export under all scenarios in wet years; however, as side dressings increase, nutrient export decreases even under wet conditions. This indicates that the nitrogen is washed off the fields by rainfall (especially in spring time) before it is absorbed by the plant roots. However, again, when less fertilizer is applied early in the year, there is less loss through surface export.

The Alabama Cooperative Extension System recommends that nitrogen be applied to corn with one-quarter to one-half applied at planting and the remainder as a side dressing [48]. Yield did not appear to be significantly impacted by the application strategy, so that the 1/3–2/3 fertilizer split procedure appears to be the most environmentally responsible management practice. This practice, along with the use of irrigation, appears to maximize yields while minimizing environmental consequences.

Overall, this study found that irrigation reduced the N loss by nearly 50% as a function of the *applied nitrogen* from 45% to 25%. Udawatta et al. [50] showed that, on average, 73% of the applied N was lost as NO_3 in a rain-fed scenario in Missouri, though they showed that this could be reduced by as much as 30% when soybean/corn rotation was used. They also noted that cover crops throughout the year could reduce runoff and lower TN and NO_3 -N losses. Hoos and McMahon [1], Udawatta et al. [50] both pointed to surface export events as the primary mechanism for the difference in the export of N between rain-fed and irrigated systems, indicating the importance of irrigation in moving the nitrogen below the surface. Furthermore, because irrigated fields with increased nitrogen inputs and higher plant spacing produce much higher yields, this can also be interpreted as reduction in the net export per yield. Thus, overall, this study shows that irrigation can significantly reduce the nutrient export relative to the yield produced.

Given the limited data for full evaluation, we can further support these results from studies that evaluated similar processes. Another way of comparing the differences in potential N export between irrigated and rain-fed fields is through the nutrient use efficiency (NUE). Davies et al. [51] found that the recovery efficiency of applied N fertilizer for rain-fed corn ranged from 36% to 66% for the recommended N applications in Nebraska. Dobermann [52] showed that under optimal irrigation conditions, the NUE as a percent of applied N was 72%. Sangha et al. [53] found that for a sandy soil under rain-fed conditions, the nitrogen uptake by corn varied from around 40% to 70% of the applied N depending on the amount applied and rainfall amount. Wortmann et al. [54] found that the N uptake as a percentage of applied N in an irrigated system averaged 64% but ranged from 74% to 40%, further confirming that split applications of nitrogen closer to periods of high crop demand further improve the NUE, minimizing nitrogen losses to leaching and volatilization.

Though the NUE does not necessarily indicate that the remaining N is lost to the system, it does provide an estimate of potential export. Though ranging from nearly 30% to 60%, the convergence of evidence between the NUE and N loss studies suggest a conservative average estimate of 50% NUE for rain-fed corn and 75% NUE for irrigated corn.

In terms of the processes being modeled, the overwhelming source of nitrogen flux from the field is the plant uptake and N export. Volatilization and denitrification represent the other N sinks. Denitrification takes place primarily during the fallow season so does not directly impact plant growth. Direct observations demonstrated that the model simulated plant uptake very well. Since nitrogen is the most limiting nutrient for corn yield [55], N uptake would be the primary driver of crop yield in cases where water is not limited (such as under irrigation). Therefore, the good agreement between the observed and simulated

yields in 2009 would provide further evidence that the model simulated plant uptake well. With the nitrogen uptake component of the model well validated, and the residual soil nitrogen validation within the limits possible given the prevailing soil conditions, it appears that the model simulated the full nitrogen processes at an acceptable level. Thus, despite the limitations in available data, these results provide a foundation for making a preliminary assessment of the impact irrigation may have on nutrient export. While the results of this study alone are not fully conclusive, the support from the associated literature does provide a convergence of evidence, suggesting that irrigation does have significant potential to reduce the amount of nitrate export, when properly supplied.

5. Conclusions

The methodology in this paper presents a proof of concept for determining the impact of irrigation on the fate and surface transport of agricultural non-point-source nutrient runoff through both a modeling exercise and a review of the literature. The preliminary results show that, for the conditions that were simulated in this experiment (silty clay soils, humid climate), irrigation tends to reduce surface nitrate loss, especially in dry years. Furthermore, the evidence from nutrient uptake efficiency studies support these conclusions. The results indicate that irrigation may tend to depress nutrient export through the movement of nutrients to the root zone, where they can be more effectively utilized by the plants.

The results of this study indicate that climate and nutrient management are the dominant factors in determining surface nutrient transport under both rain-fed and irrigated conditions. Surface export occurs when the nitrogen residing on the surface is impacted by intense convective rain storms that frequently occur during the summer months in the region. Irrigation during dry periods can “water in” these nutrients to an extent and thus limits their availability for surface runoff. The effect is even greater if the nutrients are applied later in the year while irrigation is ongoing rather than at planting, where they are available to wash off prior to root development. The results show that irrigation can reduce surface runoff up to 12% when fertilizer is applied in a split or side-dressed manner over a normal sequence of wet and dry years. This results in a reduction of nearly 50% as of function of applied nitrogen.

In the southeast, the growing season precipitation is highly variable, and climate change is expected to intensify the hydrologic cycle. Though there is still considerable uncertainty, the trends in growing season precipitation show an inclination towards slightly drier conditions [56]. Irrigation can be a key climate adaptation strategy to bolster resilience [4]; thus, a further understanding of the implication of increased irrigation is needed.

Author Contributions: W.L.E. conducted the modeling study, analyzed the results, and lead the writing of the manuscript; J.F.C. assisted in the conceptual framework and with the writing of the manuscript; B.V.O. conceived and conducted the experiment; R.S. assisted in the analysis of the results. All authors reviewed this manuscript. All authors have read and agreed to the published version of this manuscript.

Funding: This research was supported under the joint NSF/USDA Project “F/USDA/NIFA Type 2—Collaborative Research—Migration of Agricultural Production Back to the Southeast”.

Data Availability Statement: The datasets generated and/or analyzed during the current study are available from a Google Drive repository, [https://drive.google.com/drive/folders/1HBNkmB_UWQ8rvZXCym4bU3APvmx8CU0i?usp=sharing (accessed on 10 February 2025)].

Acknowledgments: The assistance of Chet Norris and Charles Burmeister of the Belle Mina Agricultural Research station is gratefully acknowledged. Cameron Handyside assisted with the soil sampling.

Conflicts of Interest: The authors declare no conflicts of interest.

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