Note: The page (pg) and line (ln) numbers referenced by the reviewers are based on the manuscript before the revision. The page and line numbers used in the authors' responses are based on the newly revised manuscript. 'pg' and 'ln' denote page and line numbers, respectively.

Reviewer #1 (Dan Jaynes)

General comments:

1.0. (1.0.1) *I'm unsure what they used for land cover – presumably it was based on 2008 NASS data, but* ***(1.0.2)*** *how the crops were rotated in the different years was not specified.* ***(1.0.3)*** *No information is given as to how SWAT simulated forest and non rowcrop land in the watershed. The water quality analysis for the cover crop treatments were run for the period of 1990 – 2000 apparently using a 2-yr corn-soybean rotation, but again details are lacking or contradictory as* ***(1.0.4)*** *the authors also imply that simulations were conducted for fields that were used to grow more corn than soybean.*

(1.0.1) *I'm unsure what they used for land cover – presumably it was based on 2008 NASS data*

➔ Land cover information was derived from multiple land use maps, including NLCD, NASS, and land use map digitized from 1998 aerial photography by USDA-ARS at Beltsville. We added a new discussion on land use information. See pg 10, ln 175-181.

(1.0.2) *how the crops were rotated in the different years was not specified*

➔ Detailed information was added. The crop rotation was done based on the 2-year corn-soybean or soybean-corn rotations, and its spatial placement was determined by alternating the locations of corn and soybean fields each year. While there were some variations in the spatial distribution and cropland allocation of the major crops every year, even distribution of croplands between soybean and corn and this simplified spatial placement of the 2 year crop rotations were supported by the previous land use dataset. See pg 10-11, ln 181-189.

(1.0.3) *No information is given as to how SWAT simulated forest and non rowcrop land in the watershed*

⇨ We added discussion in pg 8, ln 127-130 and pg 9, ln 150-153, to clarify that our simulation included other non-row crop lands and forests. This was done according to the default setup and the standard procedure of the SWAT simulation model (which assigns the CN value by the land use/condition and soil type).

(1.0.4) *the authors also imply that simulations were conducted for fields that were used to grow more corn than soybean*

➔ This is not correct. The simulation was done for the entire watershed. As described in pg 7, ln 99-100, pg 10-11, ln 175-189, crop lands were evenly distributed between soybean and corns, and managed with the 2-year rotations of soybean-corn or corn-soybean. As the results were averaged from the 9 years of simulation outputs (over the period 1992 – 2000, after taking out the 2 yr warm up period of 1990-1991), the fields initially set to grow corns for the 1 yr of simulation (the year of 1992) would be rotated to crop corns for 5 times and soybeans for 4 times. On the other hand, those fields initially assigned to grow soybean in 1992 would be rotated to grow soybeans for 5 times and corns for 4 times during the simulation period.

Specific comments

1.1. *L239. You state that the cover crop was "harvested" in April, but in Table 4 you state that the cover crop was chemically killed. Which practice did you simulate? Or did you simulate harvesting the cover crop in the SWAT model as a surrogate for chemical killing because SWAT does not allow for chemical killing?*

⇨ As you pointed out, chemical killing is not possible in SWAT. We used "Kill" operation in SWAT. To clarify this point, we changed the expression "harvest" to "kill".

1.2. *L254. I am confused by these last few sentences. If I understand, the 100% early planting was in fact 50% early in corn and 50% late on soybean. If true it is misleading to keep calling this the early planting scenario. But you also state that 100% early planting simulations were run just for corn fields and the results found only at the field level not the watershed, which again confuses me as I thought this was a watershed scale simulation study. A clearer explanation of what was done and what is being compared is critically needed.*

⇨ As discussed in the section 2.2 and our response to the question 1.0.4, simulation was done for the entire watershed. Given the actual practices and cover crop enrollment statistics in the study site (as described in section 2.2.4) , early planting could not be applied to the entire croplands, but only to corn fields. As early planting scenarios represent more active conservation management practices, we applied early planting date to where it was possible (i.e., corn fields), while treating remaining fields with late planting. This point was clarified in the text (pg 15, ln 283-292). This explains why early planting scenarios were "*in fact 50% early in corn and 50% late on soybean*".

As early planting can be only applied to cornfields, the watershed-scale simulation results from these scenarios actually reflect the mixed effect of 50 % early planting on corn and 50 % late planting on soybean. To analyze actual effects of early planting in comparison to late planting and no cover crop scenarios, we further extracted the simulation results at the HRUs (obtained from the watershed scale simulation runs) only assigned to grow corns, and compared differences in nitrate export at the field scale, as presented in Figure 8. We clarified this point and revised the text in pg 15, ln 289-292. Note that Figure 3 outlines the overall modeling procedure and summarizes what was being done and what was being compared. We added a new caption under Figure 3 to explain this. We also specify the spatial unit of analysis for Figure 6-8 to clarify what was being compared.

1.3. *L274. Looking at the figure, I'd think that it was September 1994 that was an outlier not August as stated here.*

⇨ Thanks for the notice. We corrected September" to "August".

1.4. *L285. It is difficult to compare modeling successes between studies because such things as number of HRU's and timeframe being modeled are probably not the same. Thus, I wonder if the reported "improvements" are real and meaningful.*

⇨ As the reviewer pointed out, it is not easy to compare modeling successes between studies, as there are differences in simulation models, timeframe of simulation, and spatial representations of modeling units (e.g., the number of HRUs). Note most of the previous studies we citied here were conducted in the upper region of the Choptank River Basin with the same or similar models (all of them were based on the CN method) and monitoring data. All of these models had very similar input data (e.g., land use, soil, and slope). See the table below to find the summary of the previous studies. Timeframe of previous two studies (except Sexton et al., 2010) overlapped with our study and the simulation results were evaluated against the same monitoring dataset that we used. The recent study with a different simulation period (2005-2007) by Sexton et al. (2010) was done with SWAT model with very similar land use management schedules. Many co-authors of this paper, Sadeghi, McCarty, and Hively were involved with two other studies as lead or co-authors. Compared to these studies, we used the most updated SWAT module which was known to significantly improve nitrate prediction in groundwater, and more accurate high resolution LiDAR to better represent a drainage network and low lying coastal environment. As a result, our simulation had more HRUs and a better representation of flow passage. These two points were identified as the limitation of previous studies for poor model fit, and reported as important factors to improve the accuracy of the watershed models by other researchers as cited in the manuscript.

Compared to previous studies, our model showed much better prediction for streamflow. The improvement for nitrate was even clearer, particularly when we compared observed nitrate against simulated nitrate values. Some of previous studies reported unacceptable performance rating on nitrate prediction, while our model produced above satisfactory or good rating. For example, the work by Sadeghi et al. (2007) used SWAT and AnnAGNPS to simulate streamflow and nitrate for the same watershed (German Branch Watershed) for the same simulation period. The model performances on stream flow prediction from this study were rated as poor, with NSE < 0.5 and $R^2<0.5$ (considered as unsatisfactory) according to Moriasi et al. (2007). Our model showed NSE > 0.65 (good or very good) and $R^2 > 0.72$ for stream flow. Based on our extensive experience and involvement with previous studies in the Choptank Watershed area, we believed the improvement was substantial and meaningful. We were also able to obtain some of input data from previous studies or detailed simulation outputs to make such comparison.

Table 1: Summary of previous studies in Choptank Watershed

	Time Frame for Cal. & Val	Number of HRU	Model
Our study (Yeo et al., 2013)	1992 ~ 1995	402	SWAT
Lee et al., 2000	1990 ~ 1995	N/A	GWLF
Sadeghi et al., (2007)	1990 ~ 1995	118	SWAT
Sexton et al. (2010)	2005 ~ 2007	233	SWAT

1.5. *L291. You state this also earlier, but I think this statement needs a reference. Although, intuitively it is logical to think that cover crop effectiveness should be linearly correlated with cover crop biomass production, I am unaware of any study documenting this and know that research we have conducted with rye does not substantiate it. Thus, a ref or two is required.*

⇨ We added a reference (Malhi et al. 2006), as suggested.

1.6. *L292. Again I interpret the period from 1991 -2000 as a 10 yr period not 9 yr as stated later.*

⇨ The simulation period is 11 years from 1990 to 2000 including the first two years of the warm-up period. Thus, the simulation period from 1992 to 2000 is the actual study period (9yr). The confusion in time frame was clarified throughout the text. In addition, as the growth period of winter cover crops included Oct. to Mar, its effects were assessed based on the 8 years of simulation outputs from Oct. 1992 to Mar. 2000. It was clarified in Fig 8, by adding the caption.

1.7. *L320. I think the minimum is from the comparison of RE with BE not RL as done here.*

⇨ "1.8 $kgha^{-1}$ (when compared RE to RL)" was corrected to "1.3$kgha^{-1}$ (when compared RE to BE)" in pg 18 ln 364-365, as pointed out.

1.8. *L352. I don't understand why there is a slope break at 60%. Do you have an explanation for this? Is it real or a modeling aberration? Does this have something to do with your using only corn fields when looking at more than 50% adoption of early cover crop planting?*

⇨ We do not believe a slope break at 60 % happened because of our using only cornfields to adopt early cover crop planting. Note late cover crop scenarios also showed a slope break at 60 %. Figure 7 shows "relative" percent improvement on nitrate loading reduction (i.e., (as shown from Nitrate Reduction Rate (%) in y axis) with increasing cover crop coverage. In general, it indicates that the relative nitrate reduction rate does not increase linearly with increasing coverage of cover crop implementation, but its efficiency rate could decrease, particularly when cover cropping coverage exceeds more than 50 % of the total croplands. While this result seem to be reasonable, further studies, such as field based studies, would need to prove this finding. We addressed this in the text.

1.9. *L365. Replace "3.0 – 18.8 kg/ha" with "3.0 – 33 kg/ha" to agree with the results for WL shown in Fig 8.*

⇨ "3.0 – 18.8 kg/ha" was corrected to "3.0 – 32.0 kg/ha" in pg 21 ln 415.

1.10. *L369. Change "28 % - 87%" to "25% - 80%" to agree with results shown in Fig 8.*

⇨ "28 % - 87%" was corrected to "25 % – 80 %" in pg 18 ln 419.

1.11. *L387. Again does "harvesting" mean chemical killing?*

⇨ Yes, as addressed in 1.6.

1.12. *L390. This statement about fields more frequently used for corn really confuses me. My understanding and what is shown in Table 4 is that 50% of the agland in the watershed is assumed corn and 50% is assumed soybean and that all agland is assumed to be in a 2 yr corn-soybean rotation. Than how did you generate data for a field that is used more frequently to grow corn?*

⇨ As discussed in 1.0.4, this happened because of the simulation being run for 9 years (1992-200) with the 2 yr rotation schedule. As a result, there were fields used to plant corns more (i.e., 5 times corn, 4 times soybean) or soybeans more (i.e., 5 times soybean and 4 times corn) during the 9 yr simulation period. However, this effect was to be canceled out at the watershed-scale simulation, as two croplands were evenly distributed for each simulation period. What we reported here was nitrate export at the field scale - we extracted simulation results at the HRU scale, and compared its nutrient loading considering frequency of the specific HRUs to be assigned to two different crop types.

Technical comments

1.13. *L189. You give an 11 yr range (1990 – 2000) but state it is a 10 yr range – I find this confusing.*

⇨ This has been corrected as discussed in (Q) 1.6.

1.14. *L260 Don't capitalize "Validation".*

⇨ Corrected as suggested.

1.15. *L345. Add "6" after "Figure".*

⇨ Corrected as suggested.

1.16. *Table 1. Define DEM.*

⇨ Corrected as suggested.

1.17. ***(1.17.1)*** *Table 2. I don't understand how you have a range for the calibrated values of LAIMX1 and LAIMX2?* ***(1.17.2)*** *You also need to include in caption describing what is meant by the "Reference" column.* ***(1.17.3)*** *It is unclear to me if the parameters in Table 2 are being calibrated for each land cover, soil type, HRU, or some combination. Please give more information in the M&M as to how you calibrated a watershed model with 6 land covers, 4 soil types and over 400 HRU's.*

(1.17.1) *Table 2. I don't understand how you have a range for the calibrated values of LAIMX1 and LAIMX2?*

➔ As the reviewer pointed out, there was no specific calibration range set for LAIMX1 and LAIMX2. There was no previous work that we could use as a reference value. What we provided earlier in that column was the ranges of "calibrated value" set for three different crop species. To clarify this, we provided specific calibrated values for three species separately and removed the range from the table.

(1.17.2) *You also need to include in caption describing what is meant by the "Reference" column.*

⇨ This means previous studies or existing literature. We clarified this in caption.

(1.17.3) *It is unclear to me if the parameters in Table 2 are being calibrated for each land cover, soil type, HRU, or some combination. Please give more information in the M&M as to how you calibrated a watershed model with 6 land covers, 4 soil types and over 400 HRU's.*

⇨ While spatial calibration/validation procedure developed for each land cover, soil, HRUs as described by Arnold et al. (2012) and suggested by the reviewer could improve the model accuracy, the suggested procedure could not be implemented for this study due to the limited data. Instead, our calibration was done using the standardized method outlined in the SWAT user's manual (Winchell et al., 2011), using the observations (time series records of stream flow and nitrate) acquired at the watershed outlet. This was discussed in the section 2.3.3 (pg 11-12, ln 206-208 & 212-215).

1.18. *Table 4. What is the meaning of the * and ** used in this table?*

⇨ The description of the symbols was added to the Table 4.

1.19. *Table 5. The units for PBIAS (%) should be shown in table. RSR, NSE, and P-bias need to be defined in table caption*.

⇨ % has been added. The performance statistics including *RSR, NSE, and P-bias* are fully described in the text, pg 12, ln 219-228.

1.20. *Fig. 1. Label the location of the German Branch watershed*.

⇨ The name of in Fig. 1 was changed to "The geographical location of the study area (German Branch watershed).

1.21. *Fig. 2.* ***(1.21.1)*** *Figure caption should identify this as the German Branch watershed. Also* ***(1.21.2)*** *the caption states that there is no soil type A in the watershed while in the paper you state it composes less than 1%. Which is true?* ***(1.21.3)*** *For what year is the land cover shown for? Is it 2008 as inferred from Table 1?* ***(1.21.4)*** *During the SWAT simulations were the row crops alternated between corn and soybean as inferred by table 4, but never explicitly stated in your M&M?*

(1.21.1) *Figure caption should identify this as the German Branch watershed*

⇨ The name of Fig. 2 was changed from "study site" to "the German Branch watershed"

(1.21.2) *Also the caption states that there is no soil type A in the watershed while in the paper you state it composes less than 1%. Which is true?*

⇨ The caption "There is no soil type A in the study site." was deleted, as there was less than 1 % of soil type A, as pointed out by the reviewer.

(1.21.3) *For what year is the land cover shown for? Is it 2008 as inferred from Table 1?*

⇨ The land use map was derived based on 1998 aerial photograph, NLCD, and NASS. We used 2008 NASS to spatially locate the major croplands. However, our comprehensive analysis of previous land use maps showed very little change. The question has been fully discussed in **(1.0.1)**.

(1.21.4) *During the SWAT simulations were the row crops alternated between corn and soybean as inferred by table 4, but never explicitly stated in your M&M?*

⇨ The calibration was done with the baseline scenario, which included the 2 year rotations of soybean-corn and corn-soybean. This was specified in pg 11, ln 206 ("The calibration was manually done under the baseline scenario"), as suggested.

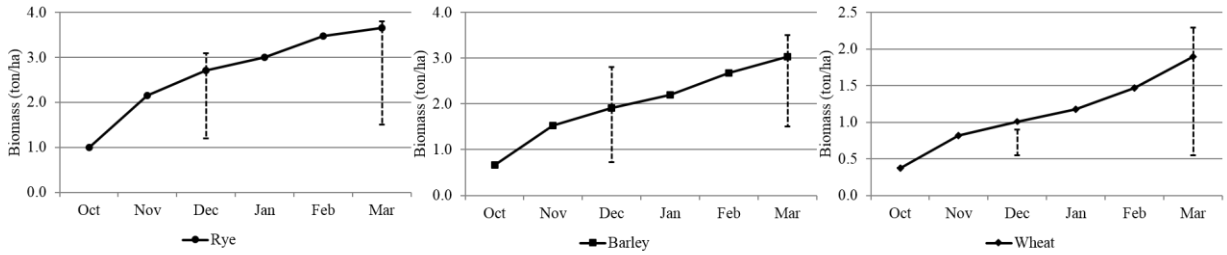
1.22. *Fig. 3. This figure adds little to the paper and should be deleted*.

⇨ We decided to keep this figure, as it shows the overall modeling procedure and clarifies what has been simulated and compared in this paper. We added a caption to clarify this.

1.23. *Fig. 4. Are nitrate load units kg N or kg NO3? I assume nitrate as N, but you are unclear. If figure starts on Jan 1992 than the outlier for flow is in Aug not Sept. 1994.*

- ⇨ It means kg NO3.
- ⇨ The month with the outlier has been corrected as suggested (answered in **1.3)**.

1.24. *Fig. 5. Can you re-draw figure so I can see the ranges for the Hively et al data for each crop? Rather than just showing the 9-yr average predicted biomass production, why not show the range in production over the simulation period as well?*



⇨ The figure above shows the range of each crop biomass, with the above biomass reported by Hively et al. in Dec. and Mar. We updated Fig 5 with this new one as suggested.

1.25. *Fig. 6.* ***(1.25.1)*** *Again is this NO3-N or NO3 as stated?* ***(1.25.2)*** *Define treatment abbreviations in caption.* ***(1.25.3)*** *The losses shown here are greater than measured for the watershed shown in fig. 4.* ***(1.25.4)*** *How were the forested lands and other crops handled in SWAT during the calibration process shown in Fig. 4?* ***(1.25.5)*** *Are these results for 100% adoption of cover crops on corn and soybean fields?*

(1.25.1) *Again is this NO3-N or NO3 as stated?*

⇨ It means NO3.

(1.25.2) *Define treatment abbreviations in caption.*

⇨ The abbreviations were already defined in Table 3.

(1.25.3) *The losses shown here are greater than measured for the watershed shown in fig. 4.*

⇨ The losses shown here are greater as fig 6 reports the 9-year average annual loading (computed from sum of monthly loading from each year), while Fig 4 shows the monthly loading.

(1.25.4) *How were the forested lands and other crops handled in SWAT during the calibration process shown in Fig. 4?*

⇨ All parameters were calibrated regardless of the land use type. The question has been answered in **1.17.3**.

(1.25.5) *Are these results for 100% adoption of cover crops on corn and soybean fields?*

⇨ Correct.

1.26. *Fig. 7. Define treatment abbreviations in caption. Are these results just for corn fields? Or for corn and soybean fields together?*

⇨ The abbreviations were already defined in Table 3.

⇨ The results are based on nitrate loadings at the watershed scale. Nitrates from all watershed area, such as crop and soybean fields, forest, and pasture lands, were considered.

1.27. *Fig 8. These nitrate loads are much greater than shown in Fig 6 or Fig 4. How can the winter losses be greater than the whole year losses?*

⇨ It is because Fig 8 shows nitrate from cornfields (where fertilizers were applied), while Fig 6 and 4 show nitrate from the entire watershed area (including all land use types, such as non-crop lands). Therefore, nitrate loading per ha from major croplands was much higher than the watershed average.

 # Reviewer 2 (Anonymous)

General comments:

2.0) *What are the criteria for assigning crops in rotation to the modeling unit (HRU)?*

I am anticipating that the authors assigned corn-soybean and soybean-corn rotations to corn and soybean pixels of 2008 land cover data, respectively. However, I am not sure about this as there is no information provided in the methods section about how the rotations were assigned to the modeling units. The spatial location of each crop in the rotation would have enormous impact on total nitrate loading because of the variability in the underlying soil characteristics and climate conditions across the space. Therefore the placement of rotations is critical in determining reliable estimates of total nitrate loading in different scenarios.

⇨ The delineation of HRUs was determined by their unique combination of land use, soil, and slope information. Based on this, those HRUs primarily used for row-crop lands are identified. The comprehensive land use analysis with existing land use information indicated little changes in land use allocation over time. We chose to use 2008 NASS map as the base map to spatially assign the locations of cornfields and soybean fields. The spatial placement of the 2-year rotations was simplified by swapping the locations of these two crop fields (HRUs). This simplified rotation pattern seems to be reasonable (when assessed by the recent NASS dataset). We do not expect that the spatial location of each crop in the rotation would have significant effect on total nitrate loading, as (1) soil characteristics and climate condition do not vary significantly for this small watershed area and (2) these two crop lands were roughly evenly distributed. We elaborated this point in the text (pg 10-11, ln 175-189) and explained them as discussed in 1.0.

2.1) *What are the different management practices used in the study?*

Again, important pieces of information are missing in the methods section. These include 1) whether irrigation was applied or not under rotation systems 2) what type of tillage (conventional or no-till) was practiced under rotations. These two operations significantly influence the total runoff to the streams. In addition, I did not find what management practices (e.g. tillage, fertilizer application, pesticide use) are assumed for the cultivation of cover crops.

⇨ The management practices in this study did not include irrigation and utilized no till and detailed information on management practices (including tillage, fertilizer, etc) is presented in Table 5. This was also specified in pg 11, ln 192-194.

2.2) *The interesting finding in this modeling study is that winter cover crops have a negligible impact on water budget with relative to the baseline scenario.* **(2.2.1)** *I am wondering whether there are field studies supporting this finding.* **(2.2.2)** *There should be a discussion on what factors allowed this practice to store the soil water equally to the baseline scenario in which land is fallowed during winter. Conventionally, croplands are fallowed in the winter season to store the soil water so that there will be enough available soil water for the next growing season.*

(2.2.1) *I am wondering whether there are field studies supporting this finding.*

⇨ Previous field based studies (also other combined field/modeling work) report similar findings on the hydrological effects of winter cover crop. We included additional references (Kaspar et al., 2007; Qi and Helmers 2010; Islam et al., 2006; Dabney 1998; Islam et al., 2006) in the revised paper in section 3.2.

(2.2.2) *There should be a discussion on what factors allowed this practice to store the soil water equally to the baseline scenario in which land is fallowed during winter.*

⇨ The following discussion was added in the text (pg 18, ln 348-357). "As reported from previous studies (Kaspar et al., 2007; Qi and Helmers 2010; Islam et al., 2006), the inclusion of winter cover crop reduced streamflows only slightly (< 10 %). Similarly, our study found streamflow reductions of less than 8 % ..... While the effects of winter vegetation on evapotranspiration were relatively low, any water loss due to evapotranspiration could be offset as cover cropping usually increases soil saturation by increasing water infiltration capacity (Dabney 1998; Islam et al., 2006). Because the study site typically exhibits maximum streamflow during winter with rising groundwater levels (Fisher et al., 2012), the relative difference in streamflows due to winter cover crops remained small."

2.3) *P. 14238, Ln. 18-19: Information should be provided here on how you assigned cover crops to the croplands when you increased the implementation area. Are they just randomly assigned? As mentioned above, placement is a very important factor. When we assign cover crops close to streams, nitrate loading could be different than when we assign cover crops far from streams.*

⇨ We expanded this section to describe how we assigned the coverage of cover crops (pg 14 and ln 258-264). They are not randomly assigned, but done following the ranked order of nitrate export potential at the field scale, with an increment of 20 %.

2.4) *What is the spatial resolution of HRUs?*

⇨ The German Branch watershed was subdivided into 29 sub-basins based on tributary drainage area. Within each sub-basin, the superimposing of similar land uses, soil, and slope created 402 hydrologic response units (HRUs). Threshold area values of $\geq$20 %, $\geq$10 %, and $\geq$ 20 % were used to include land use, soils and slope types in the HRU delineation process. The sizes of HRUs vary in the range of [0.2 -118.6] ha, with average of 11.8 ha and standard deviation of 13.0 ha. We added this discussion in the revised text in 2.2.2 (pg 11, ln 197-200).

ASSESSING WINTER COVER CROP NUTRIENT UPTAKE EFFICIENCY USING A WATER QUALITY SIMULATION MODEL

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Abstract

Winter cover crops are an effective conservation management practice with potential to improve water quality. Throughout the Chesapeake Bay Watershed (CBW), which is located in the Mid-Atlantic US, winter cover crop use has been emphasized and federal and state cost-share programs are available to farmers to subsidize the cost of cover crop establishment. The objective of this study was to assess the long-term effect of planting winter cover crops at the watershed scale and to identify critical source areas of high nitrate export. A physically-based watershed simulation model, Soil and Water Assessment Tool (SWAT), was calibrated and validated using water quality monitoring data to simulate hydrological processes and agricultural nutrient cycling over the period of 1990-2000. To accurately simulate winter cover crop biomass in relation to growing conditions, a novel approach was developed to further calibrate plant growth parameters that control the leaf area development curve using multi-temporal satellite-based measurements of species-specific winter cover crop performance. Multiple SWAT scenarios were developed to obtain baseline information on nitrate loading without winter cover crops and to investigate how nitrate loading could change under different winter cover crop planting scenarios, including different species, planting dates, and implementation areas. The simulation results indicate that winter cover crops have a negligible impact on water budget but significantly reduce nitrate leaching to groundwater and delivery to the waterways. Without winter cover crops, annual nitrate loading from agricultural lands was approximately 14 kg/ha, but decreased to 4.6 – 10.1 kg/ha with cover crops resulting in a reduction rate of 27-67 % at the watershed scale. Rye was the most effective species, with a potential to reduce nitrate leaching by up to 93 % with early planting at the field scale. Early planting of cover crops (~ 30 days of additional growing days) was crucial, as it lowered nitrate export by an additional ~ 2 kg/ha

when compared to late planting scenarios. The effectiveness of cover cropping increased with increasing extent of cover crop implementation. Agricultural fields with well-drained soils and those that were more frequently used to grow corn had a higher potential for nitrate leaching and export to the waterways. This study supports the effective implementation of cover crop programs, in part by helping to target critical pollution source areas for cover crop implementation.

1. Introduction

The Chesapeake Bay (CB) is the largest and most productive estuary in the US, supporting more than 3,600 species of plants and animals (CEC, 2000). It is an international as well as a national asset. The importance of CB has been recognized by its designation as a Ramsar site of international importance (Gardner and Davidson, 2011). However, the Bay's ecosystems have been greatly degraded. The Chesapeake Bay Watershed (CBW) extends over 165,759 km^2 and covers parts of New York, Pennsylvania, Maryland, Delaware, West Virginia, Virginia and the District of Columbia. Nearly 16 million people reside in the CBW, and its population is increasing rapidly, leading to accelerated land use and land cover change. The high ratio of watershed area to estuary water surface (14:1) amplifies the influence of human modifications, and excessive nutrient and sediment runoff has led to eutrophication (Kemp et al., 2005; Cerco et al., 2007). High nitrogen (N) input to the Bay is the foremost water quality concern (Boesch et al., 2001). In the CBW, groundwater contributes more than half of total annual streamflow, and groundwater nitrate loads account for approximately half of the total annual N load of streams entering the Bay (Phillips et al., 1999). Nitrate leached to the groundwater has substantial residence time on the order of 5-40 years (McCarty et al., 2008; Meals et al., 2009).

It is particularly important to implement best management practices (BMPs) on agricultural lands in the Coastal Plain in order to improve water quality in the Chesapeake Bay. Nitrogen exports from agricultural lands are significantly higher than that for other land uses in the Coastal Plain of the CBW (Jordan et al., 1997; Fisher et al., 2010; Reckhow et al., 2011). Fisher et al. (2010) discussed that N export increases by a factor of ~10 as agriculture increases from 40 % to 90 % of land use within Coastal Plain watersheds. Jordan et al. (1997) showed that

N was exported from cropland at a rate of 18 kg N/ha per year, seven times higher than the rate from other land uses in the Coastal Plain. High nitrate exports from Coastal Plain watersheds have intensified CB water quality problems, due in part to short hydraulic distances (Reckhow et al., 2011).

The implementation of winter cover crops as a best management practice on agricultural lands has been recognized as one of the most important conservation practices being used in the CBW (Chesapeake Bay Commission 2000). Winter cover crops can sequester residual N after the harvest of summer crops, reducing nitrate leaching to groundwater and delivery to waterways by surface runoff (Hively et al., 2009), and can also reduce the loss of sediment and phosphorus from agricultural lands. Therefore, federal and state governments have established cost-share programs to promote winter cover cropping practices (MDA, 2012). However, the overall efficiency of cover crops for reducing nitrate loadings has not been fully evaluated. The influence of BMPs, such as winter cover crops, on nitrate flux to streams has not been measured *in situ* at scales larger than field, because of the substantial residence time of leached N in groundwater and the difficulty of monitoring over long time periods (McCarty et al., 2008). A few field studies have demonstrated cover crop nitrate reduction efficiencies at the field scale (e.g., Shipley et al., 1991; Staver and Brinsfield, 2000). Hively et al. (2009) used satellite remote sensing images and field sampling data to estimate winter cover crop biomass production and N uptake efficiency at the landscape scale. However, the catchment-scale benefits of winter cover crop have not been fully understood. As the nutrient uptake and nitrate reduction efficiencies of winter cover crops are primarily dependent upon cover crop biomass (Malhi et al., 2006; Hively et al., 2009), it is crucial to simulate plant growth accurately. The accurate simulation of the plant growth would require field-based information and an improved calibration method to carefully account for the climate, soil characteristics, and site-specific nutrient management. Furthermore, the effectiveness of nutrient management practices, such as winter cover crops, has not been fully explored for coastal agricultural watersheds in the study region due to the challenge of accurately simulating hydrologic and nutrient cycling in lowland areas with high groundwater–surface water interaction (Lee et al., 2000; Sadeghi et al., 2007; Sexton et al., 2010; Lam et al., 2012).

This study utilized a physically based watershed model, Soil and Water Assessment Tool (SWAT) (Arnold and Fohrer, 2005), to simulate hydrological processes and nitrogen cycling for an agricultural watershed in the Coastal Plain of the CBW. We examined the long-term impact (~10 years) of winter cover crops on water budget and nitrate loadings under multiple cover crop implementation scenarios (e.g., species, timing and area planted). To accurately simulate the growth of winter cover crops and their nutrient uptake and nitrate reduction efficiencies, we have developed a novel approach to calibrate model parameters that control winter cover crop biomass, resulting in model estimates that closely approximate observed values. This study provided important information for decision making to effectively implement winter cover crop programs and to target critical pollution source areas for future BMP implementation.

2. Data and Method

2.1. Description of the study site

This study was undertaken in the German Branch (GB) watershed, located within the CBW. The GB is a third order Coastal Plain stream, located within the non-tidal zone of the Choptank River Basin (Figure 1). Its drainage area is approximately 50 km^2 and its land use is dominated by agriculture (~72 %) and forest (~27 %) (Figure 2). Agricultural lands are evenly split between corn and soybean cropping. The study site is relatively flat with elevations ranging from 1 m to 26 m above sea level. Most of the soils are moderately well-drained (Hydrologic Soil Group (HSG) B) or moderately poorly-drained (HSG C). Soil groups B and C cover 52 % and 35 % of the study area, respectively. Well-drained (HSG A) and poorly-drained (HSG D) soils account for less than 1 % and 14 %, respectively, of the study area. Figure 2 presents information on land use, hydrologic soil types, and topography of the study site. The area is characterized by a temperate, humid climate with an average annual precipitation of 120 cm/yr (Ator et al., 2005). Precipitation is evenly distributed throughout the year, and approximately 50 % of annual precipitation recharges groundwater or enters streams via surface flow, while the remaining precipitation is lost to the atmosphere via evapotranspiration (Ator et al., 2005).

The Choptank River watershed has been identified as an "impaired" water body by the U.S. Environmental Protection Agency (US EPA) under Section 303(d) of the Clean Water Act due to excessive nutrients and sediments, and nutrient runoff from agricultural land has been identified as the main contributor of water pollution (McCarty et al., 2008). Since 1980, substantial efforts have been made to monitor water quality in the Choptank River watershed to establish baseline information on nutrient loadings from agricultural watersheds. Water quality in the GB watershed was intensively monitored between 1990 and 1995 as part of the Targeted Watershed Project, a multi-agency state initiative (Jordan et al., 1997; Primrose et al., 1997). In 2004, the Choptank River watershed was selected to become part of the U.S. Department of Agriculture (USDA) Conservation Effects Assessment Project (CEAP), which evaluates the effectiveness of various agricultural conservation practices designed to maintain water quality for the mid-Atlantic region of the US (McCarty et al., 2008).

[Insert Figure 1. Geographical location of the study area (German Branch watershed)]

[Insert Figure 2. Characteristics of the study site (German Branch watershed)]

2.2. SWAT model: model description, data, calibration, and validation.

SWAT was used to simulate the effects of winter cover crops on nitrate uptake with multiple cover crop scenarios over the period of 1990-2000. The model simulation was run for the entire watershed (including forested, row croplands, and non-row croplands), and changes in both water budgets and nitrate loads to receiving waters under multiple scenarios were compared with baseline conditions (no cover crops) at the field and/or watershed scales. The overall modeling approach is presented in Figure 3. Since cover crop N reduction efficiency is controlled by winter cover crop biomass (Malhi et al., 2006), we developed a new method to calibrate plant growth parameters that control leaf area development to produce simulation outputs close to observed values (discussed in Section 2.2.4).

[Insert Figure 3. Diagram of the overall modeling approach]

2.2.1. ***Description of SWAT Model***

SWAT is a continuous, physically-based semi-distributed watershed process model. SWAT simulation runs on a daily time step. SWAT includes and enhances modeling capabilities of a number of different models previously developed by the USDA Agricultural Research Service (ARS) and the US EPA. Arnold and Fohrer (2005) discuss the capabilities of SWAT in detail. Technical documents on physical processes implemented in SWAT, input requirements, and explanation of output variables are available online (Neitsch et al., 2011). The key physical processes in SWAT relevant to this research are briefly discussed below.

The main components of SWAT include weather, hydrology, sedimentation, soil temperature, crop growth, nutrients, pesticide, pathogens, and land management (Neitsch et al., 2011). In SWAT, a watershed is subdivided into smaller spatial modeling units, subwatersheds and HRU. A HRU is the smallest spatial unit used for field-scale processes within the model. HRU is characterized by homogeneous land cover, soil type, and slope. The overall hydrologic balance as well as nutrient cycling is simulated for each HRU, summed to the subwatershed level, and then routed through stream channels to the watershed outlet. In the SWAT model, a modification of the Soil Conservation Service (SCS) curve number (CN) method was used to simulate surface runoff for all land cover types including row crops, forests, and non-row croplands. The CN method determines runoff based on land use, the soil's permeability, and antecedent soil water conditions. The transformation and transport of nitrogen are simulated as a function of nutrient cycles within a HRU, comprising several organic and inorganic pools. Simulated loss of N can occur by surface runoff in solution and by eroded sediment and crop uptake. It can also take place in percolation below the root zone, in lateral subsurface flow, and by volatilization to the atmosphere.

2.2.2. Data and input preparation

Table 1 presents the list of data and other relevant information used in this study. Daily climate records on precipitation and temperature were obtained from the National Oceanic Atmospheric Administration (NOAA) National Climate Data Center (NCDC) (Royal Oak, Station ID: USC00187806). Daily solar radiation, relative humidity, wind speed, and missing precipitation and temperature information were derived using SWAT's built-in weather generator (Neitsch et al., 2011). Monthly streamflow and water quality information over the period of

1990 - 1995 was obtained from Jordan et al. (1997). Annual estimates of nitrate loads by sub-watershed areas within GB watershed were provided by Primrose et al. (1997).

The geospatial dataset needed to run SWAT simulations includes digital elevation models (DEM), hydrologic soil types, and land cover/land use. A LiDAR-based 2-m DEM, processed to add artificial drainage ditches by the USDA-ARS at Beltsville, Maryland, (Lang et al., 2012) was used to extract topographic information. The DEM was used to delineate the drainage area, subdivide the study area into smaller modeling units, and define the stream network. Soil information was obtained from the Soil Survey Geographical Database (SSURGO) available from the USDA Natural Resources Conservation Service (NRCS).

A map of land use was prepared based on the comprehensive analysis of existing land use maps, including the U.S. Geological Survey's National Land Cover Database of 1992 and 2001, and 2006, the USDA National Agriculture Statistics Service (NASS) National Cropland Data Layer (NCDL) of 2002, 2008, 2009, and 2010 (Boryan et al., 2012), and a high-resolution land use map developed from 1998 National Aerial Photography Program (NAPP) digital orthophoto quad imagery (Sexton et al., 2012). These maps indicated a consistent pattern of land use distribution over the last two decades with little change. The spatial distribution of major croplands (e.g., soybean and corns) (Fig 2) was determined using 2008 NCDL. As the two-year rotations of corn-soybean or soybean-corn were common practice and agricultural lands were used evenly for both crops, the placement of the crop rotations was simplified to alternate the locations of corn and soybean croplands every year using the 2008 NCDL as a base map. While the placement of crop rotations between various years would vary, it was not possible to obtain the spatial distribution of major croplands for each simulation year. In addition time series cropland patterns observed from recent NCDL maps seem to support this generalized crop rotation pattern of interchanging the locations of corn and soybean fields.

Detailed agronomic management information was collected in the field, as well as through literature reviews and interviews with farmers and extension agents. Modeled agricultural practices and management reflects actual practices (i.e., no winter cover crop practice, utilizing conservation tillage without irrigation) in the study region during the time of water quality monitoring (Sadeghi, et al., 2007), and the guidelines for winter cover crop implementation practices were developed by the Maryland Department of Agriculture (MDA) cover crop program.

The GB watershed was subdivided into 29 sub-basins based on tributary drainage areas. Within each sub-basin, the superimposing of similar land uses and soil type generated a total of 402 HRUs with 283 classified as agricultural HRUs. The average size of HRUs ranged from 0.2 – 118.6 ha, with an average size of 11.8 ha and a standard deviation of 13.0 ha.

[Insert Table 1. The list of data used in this study]

2.2.3. Calibration and validation of SWAT model

Although SWAT simulations were calculated on a daily basis, the calibration and validation were performed using the monthly water quality record available from the monitoring station located at the study watershed outlet. The calibration was performed manually under the baseline scenario with the two-year crop rotations, following the standard procedure outlined in the SWAT user's manual (Winchell et al., 2011). The key parameters and their allowable ranges were identified using the sensitivity analysis performed by Sexton et al. (2010) and previous studies (Table 2). The simulations included a two-year warm up period (1990-1991) to establish the initial conditions. Model calibration was done using the next two years of water quality records (1992-1993), and the remaining records were used for validation (1994-1995). We first adjusted the parameters related to the streamflows and then for nitrate. An attempt was made to match the simulated monthly model outputs to the observed monthly data obtained at the watershed outlet. To assess longer-term effects, the model simulations were performed over the period of 1992 - 2000. We used ArcSWAT2009 with the 582 version of the executable file in the ArcGIS 9.3.1 interface.

[Insert Table 2. List of calibrated parameters]

Accuracy of the model calibration was assessed with three statistical model performance measures: the Nash-Sutcliffe efficiency coefficient (NSE), root mean squared error (RMSE)-standard deviation ratio (RSR), and percent bias (PBIAS) (Moriasi et al., 2007). They are defined as follows:

$$NSE = 1 - \left[\frac{\sum_{i=1}^{n}(O_i - S_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2}\right] \tag{1}$$

$$RSR = \frac{RMSE}{STDEV_{obs}} = \left[\frac{\sqrt{\sum_{i=1}^{n}(O_i - S_i)^2}}{\sqrt{\sum_{i=1}^{n}(O_i - \bar{O})^2}}\right] \tag{2}$$

$$PBIAS = \left[\frac{\sum_{i=1}^{n}(O_i - S_i) \times 100}{\sum_{i=1}^{n} O_i}\right] \tag{3}$$

where O_i are observed and S_i are simulated data, $\bar{O}$ is observed mean values, and n equals the number of observations. The values of those statistical measures were compared to the model evaluation criteria set for various water quality parameters (Moriasi et al., 2007).

2.2.4. Calibration of plant growth parameters

Cover crop plant growth parameters were calibrated to more realistically simulate cover crop growth during winter. Specifically, we modified the parameters that control the leaf area development curve using biomass estimates provided by Hively et al. (2009). Their study reported satellite-based biomass estimates for three commonly used winter cover crops categorized by various planting dates over the period of 2005-2006 in the Choptank River region. This information was analyzed to associate winter cover crop biomass estimates with heat units. Heat units were computed based on the potential heat unit (PHU) theory as implemented in SWAT, with the daily climate record over the cover crop monitoring period (2005-2006). The crop growth module of SWAT was then run with average daily climate data over 1990-2000 using the default parameter values to provide estimates of biomass and leaf area index (LAI) by growing degree days. It was assumed that there was no change in climate condition between the cover crop monitoring period and the SWAT simulation period. Using this information, we then were able to relate LAI values to the reported biomass estimates and heat units. These LAI values and the corresponding heat units were then normalized by the maximum LAI and total potential heat units required for plant maturity, and the relationship between these two normalized values (fractional LAI and heat units) was fitted using a simple regression model. This fitted model was extrapolated to identify two LAI parameter values (Table 2) required to adjust the leaf area development curve in the SWAT model.

2.2.5. Assessing the effectiveness of winter cover crops with multiple scenarios

We assessed the potential effects of winter cover crops on nitrate removal at the field and watershed scales under multiple implementation scenarios. Details of these scenarios are presented in Table 3. The MDA Cover Crop program offers varying cost share according to winter cover crop planting species and cut off planting dates. Following the program guidelines and county level statistics of winter cover crop implementation (MDA, 2012), we constructed multiple scenarios relevant to regional cover crop practices with three major cover crop species [i.e., barley (*Hordeum vulgare* L.), rye (*Secale cereale* L.), and wheat (*Triticum aestivum* L.)], and two planting date categories (early/late). Additional cover crop scenarios were developed to assess their effectiveness by varying extent of cover crop implementation. The average nitrate export was assessed at the field scale based on the simulation output over the period of 1992-2000 under the baseline scenario (i.e., no cover crop). Then, all agricultural HRUs were sorted by nitrate loading and equally subdivided into five groups. Each group was then introduced incrementally for cover crop implementation, in order from the highest to the lowest nitrate loading.

Table 4 summarizes agricultural practices and scheduling used for different scenarios. There was no difference between baseline and cover crop scenarios during the growing season. The croplands were managed with the typical two-year corn-soybean or soybean-corn rotation, and fertilizer was only applied to corn cropping in the beginning of the growth season, due to its high demand for nutrients to support growth and yield. Instead of winter fallow, cover crop scenarios assumed placement of winter cover crops. The cover crops were planted after harvesting of summer crops either in the beginning of October (early planting) or November (late planting), and were chemically killed at the beginning of the following growing season (early April). The specific dates (Oct. 3 and Nov. 1) of cover crop planting were set according to MDA guidelines, with slight adjustment over the course of the simulation period to avoid days with substantial precipitation falling immediately prior to winter cover planting. Note that the harvest date of summer crops under the baseline was set for October 15 to make the model results from the baseline more comparable to the early and late cover crop scenarios by setting the harvesting date in between them. Actual practices and historical statistics indicate that early planting was generally allowed for corn only, as soybean requires later harvest in the Choptank River region. MDA's county level statistics over 2006-2011 showed that winter cover crops were generally planted later following soybean (in general, after mid-October), while two thirds of cover crop implementation occurred prior to mid-October after corn. This difference could be due to late harvesting to allow for double planted soybean crops. In this study, early planting scenarios were considered to be more active conservative agricultural practices than late planting scenarios. Therefore, early planting scenarios were set to apply 100 % of early planting date to where it could be applicable (i.e., corn fields), while the remaining fields (i.e., soybean fields) were assumed to be treated with 100 % of late plantings. As a result, these scenarios include 50 % of cover cropping with early planting on cornfields and remaining 50 % with late planting on soybean fields, as both crop types have roughly an equal share of total croplands. Due to this mixed effect, the nitrate removal efficiency by different planting dates could not be fully assessed at the watershed scale, but evaluated at the field scale by comparing differences in nitrate export obtained from those HRUs assigned to grow corn.

Insert Table 3. List of cover crop scenarios

Insert Table 4. Agricultural practices and management scheduling for the baseline and cover crop scenarios

3. Results and Discussion

3.1. SWAT calibration and validation

The simulated results of monthly streamflows and nitrate were compared with the observed data for both the calibration and validation periods. Table 2 provides the list of the adjusted parameter values after model calibration. Figure 4 shows good agreement between measured and simulated monthly discharge of streamflow and nitrate. Table 5 presents a summary of model performance measures and their accuracy ratings based on the statistical evaluation guidelines reported by Moriasi et al. (2007). Overall, the model performance rating for streamflow and nitrate loads exceeded the “satisfactory” rating in both the calibration and validation periods. Model simulation results for streamflow were more congruent with the observed values than for nitrate, but the pattern of simulated nitrate was similar to the trend of simulated streamflow. Also, simulation results for the calibration period were in better agreement with the observed values, compared to the validation period. The largest discrepancy between simulated and measured streamflow and nitrate was in 1994. Unlike simulation output, a high peak in streamflow and consequently in nitrate loading was observed in August. This relatively high flow and nitrate were somewhat unusual, as the weather record for this site did not show any dramatic change in precipitation during this period. In addition, the streamflow record from an adjacent watershed, with similar characteristics and size, did not produce high peak values for streamflow during the same period. This difference could perhaps be explained due to unexpected agricultural practices, localized thunderstorms that did not occur at the weather station and nearby watershed, or human/measurement errors, although the exact cause of such error could not be determined. The SWAT simulation provided considerably improved results compared to previous studies conducted in the study area (Lee et al., 2000; Sadeghi et al.

2007; Sexton et al., 2010). These improvements may be due to the recent update of the SWAT model to more accurately predict nitrate in groundwater (USDA-ARS, 2012) and use of more accurate higher spatial resolution DEMs (Chaplot 2005; Chaubey et al., 2005).

Insert Figure 4. Observed and simulated streamflows and nitrate loads during the monitoring period over 1992-1995.

Insert Table 1. Model performance measures for streamflow and nitrate

Accurate simulation of winter cover crop growth and biomass at various stages of production is crucial to accurately estimating the potential of winter cover crop to uptake residual N and reduce nitrate loading. The winter cover crop program was implemented in 2005 at this site, and therefore, no data were available to validate predicted winter cover crop biomass over the period of 1992-2000. However, we are confident in our biomass simulation, as the simulated nine-year averaged winter cover crop biomass estimates were comparable to the range of cover crop biomass reported by Hively et al. (2009). It is to be noted that without calibration, cover crop growth was simulated at a much faster growth rate, and the growth trend over winter months did not match field data as reported in Hively et al. (2009). This study calculated above ground winter cover crop biomass with a range of planting dates, based on field survey and satellite images acquired over the period of 2005-2006. The modeled growth rate of rye was substantially lower in the early growth stage, producing much less biomass than observed values. Figure 5 shows the agreement between measured and simulated biomass estimates after calibration. Note that the simulated estimates of cover crop biomass were at the upper end of the reported values, as the simulation output included both above and below-ground biomass.

Insert Figure 5. Estimation of winter cover crop biomass during the winter fallow period

3.2. Multiple scenarios analysis

Winter cover crops had little impact on catchment hydrology but a profound effect on nitrate exports. Figure 6 presents nine-year average annual mean streamflow, annual evapotranspiration, and annual nitrate loads, under baseline and multiple cover crop scenarios. As reported from previous studies (Kaspar et al., 2007; Qi and Helmers 2010; Islam et al., 2006), the inclusion of winter cover crop reduced streamflows only slightly (< 10 %). Similarly, our study found streamflow reductions of less than 8 %. Winter cover cropping reduced streamflow from 8.5 m^3/s to 7.8 m^3/s (RE, Rye Early) - 8.4 m^3/s (WL, Wheat Late), and increased evapotranspiration from 667 mm to 673 mm (WL) -710 mm (RE), in comparison to the baseline scenario. While the effects of winter vegetation on evapotranspiration were relatively low, any water loss due to evapotranspiration could be offset as cover cropping usually increases soil saturation by increasing water infiltration capacity (Dabney 1998; Islam et al., 2006). Because the study site typically exhibits maximum streamflow during winter with rising groundwater levels (Fisher et al., 2012), the relative difference in streamflows due to winter cover crops remained small. Rye cover crops caused the most changes to the hydrologic budget followed by barley and winter wheat cover crops. Early planting scenarios produced slightly lower streamflow and higher evapotranspiration, compared to those with the later planting date.

Unlike its small hydrologic effect, winter cover cropping greatly reduced nitrate loads and there were large differences in nitrate loads by planting species and dates. Annual nitrate loads with cover crop scenarios ranged from 4.6 kg/ha (RE) to 10.1 kg/ha (WL). The difference in nitrate loadings under different cover crop scenarios ranged from 1.3 kg/ha (when RE was compared to BE, Barley Early) to 5.5 kg/ha (when RE was compared to WL). If the comparison of the removal efficiency was made within species, early cover cropping (Oct. 3) lowered annual nitrate loads by 1.8 (rye and winter wheat) to 2.7 (barley) kg/ha, compared to late cover cropping (Nov. 1). When compared with the baseline scenario (13.9 kg/ha), the cover crop scenarios reduced nitrate loads by 27 % (WL) to 67 % (RE) at the watershed scale. This finding compared well with the results of previous studies that reported the importance of early planting date (Ritter et al., 1998; Feyereisen et al., 2006; Hively et al., 2009). Shorter day-lengths and lower temperatures could also limit the growth of cover crop biomass during winter season. Therefore, earlier planting could increase the amount of nitrogen uptake by cover crops because of longer growing seasons and warmer conditions (Baggs et al., 2000). Similar research in Minnesota also demonstrated that winter cover crops planted 45 days earlier reduced 6.5 (kg N/ha) more nitrogen than late planting (Feyereisen et al., 2006). Our simulation results are slightly lower than these published values, due to fewer growing days (~ 30 days). The earlier planting occurred ~30 days prior to the late planting.

The simulation results indicate that rye is the most effective cover crop at reducing nitrate loads. Rye is well adapted for use as a winter cover crop due to its rapid growth and winter hardiness, and these characteristics enabled rye to consume larger amount of excessive nitrogen than other crops (Shipley et al., 1992; Clark, 2007; Hively et al., 2009). Barley is a cool-season crop and develops a strong root system during the winter season. Barley exhibits better nutrient uptake capacity than wheat (Malhi et al., 2006; Clark, 2007). Our simulation results were consistent with previous studies. As shown from Figure 5, rye grows faster than other winter cover crops particularly in the early growth stage, taking up higher levels of nitrate. Compared to the baseline scenario, rye removed more than 67 % of nitrate with early planting, and 54 % with late plating (Figure 6). Barley had a nitrate reduction rate of 57 % and winter wheat 41 %

with early planting, but this removal efficiency drops to 38 % for barley and 27 % for winter wheat with late planting (Figure 6). Figure 6 illustrates that late planted rye was nearly as effective as early planted barley and more effective than early planted winter wheat.

Insert Figure 6. 9-year average streamflow, actual evapotranspiration (ET), and nitrate loads at watershed scale under multiple cover crop scenarios.

Simulated nitrate removal efficiency was greatly affected by different levels of cover cropping implementation as shown from Figure 7. As expected, removal efficiency increased with increasing coverage of cover crop implementation, though the slope of removal efficiency slightly decreased at 60 % of extent. This finding seems to indicate that nitrate reduction rate does not increase linearly with increasing coverage, but its relative efficiency could decrease after the coverage of cover crop implementation exceeds 50 % of the croplands. While this finding seems to be reasonable, further field-based studies are needed to verify this finding. It was noted that 60 % cover crop coverage with an early planting date would reduce more nitrate than 100 % cover crop coverage with late planting, emphasizing the importance of early cover crop planting as indicated by other studies (Ritter et al., 1998; Hively et al., 2009).

Insert Figure 7. Nitrate reduction rates by varying degree of cover crop implementation at the field scale.

The effects of cover cropping were further assessed by quantifying the amount of nitrate transported from agricultural fields by different delivery pathways to waterways (surface runoff, lateral flow, and shallow groundwater) and nitrate leached to deep groundwater. Figure 8 presents nitrate loads per unit area leaving agricultural fields during the winter fallow period (October to March). The effectiveness of winter cover cropping to reduce nitrate leaching is particularly noticeable, as reported by earlier studies (McCraacken et al., 1994; Brandi-Dohrn et al., 1997; Francis et al., 1998; Bergstrom and Jokela, 2001; Rinnofner et a1., 2008). At the field scale, the seasonal average of nitrate leaching (shown as “L” in Figure 8) over the winter fallow period (October to March) without cover crops was estimated as 43 kg/ha. With winter cover crops, nitrate leaching decreased to 3.0 – 32.0 kg/ha, depending on planting species and timing, resulting in a reduction rate of 26 -93 %, compared to baseline values. In addition, the amount of nitrate transported from fields to waterways by surface runoff, lateral flow, or shallow groundwater (referred as “DPs”, direct pathways in Figure 8) was greatly reduced from 2.9 to 10.7 kg/ha with cover crop scenarios, a reduction rate of 25 % - 80 %. Similar to the watershed scale analysis, rye with an early planting date produced the most effective result at the field scale with the highest reduction rate both through direct pathways and leaching.

Insert Figure 8. 8-year average nitrate leaching and delivery to waterways during winter fallow (October to March).

3.2.1. **Geospatial analysis to identify high nitrate loading areas**

The nine-year annual and monthly nitrate loads from agricultural fields (HRU) simulated under the baseline scenario were analyzed to pinpoint those areas with a high potential for nitrate loadings and better understand the characteristics and variability of these high loading zones. We classified all agricultural HRUs into five classes according to different levels of nitrate export potential. Nitrate export potential was computed by summing up nitrate transported by direct pathways and leaching to groundwater. We observed consistent spatial patterns in nitrate loadings at the inter-annual and monthly time scale. Figure 9 illustrates the geographical distribution of nutrient loadings from all agricultural HRUs based on the nine-year annual and monthly average simulation results from selected months. Those selected months were chosen considering seasonal characteristics of climate and hydrology as well as the timing of agricultural practices and scheduling that may produce differences in nitrate loadings (e.g., high precipitation and groundwater flow in March/April, killing winter cover crop and fertilizer application in April, and cover crop application in November).

The location of high nitrate loading areas was generally associated with moderately well drained soils and agricultural fields more frequently used for corn over the simulation period. Nitrate leaching dominated the total nitrate loads from the fields (i.e., potential for nitrate export), as it outweighed nitrate transport by direct pathways (as shown in Figure 8). We hypothesize that areas with moderately well-drained soils allowed high nitrate leaching due to their high infiltration capacity (Figure 2). Because of the high nitrogen demand for corn growth and yield, corn cropping requires a considerable amount of fertilizer application during the early growth stage, while soybean does not require any fertilizer application (Table 4). Consequently, nitrate export from agricultural fields more frequently used for corn over the simulation period was significantly greater than those used for soybean, as reported by Kaspar et al. (2012). Therefore, it would be important to prioritize winter cover cropping application for those areas with well drained soils used for corn production.

Insert Figure 9. The spatial distribution of nitrate export potential from agricultural fields

4. Conclusions

This study demonstrates the effectiveness of winter cover crops for reducing nitrate loads and shows that nitrate removal efficiency varies greatly by species, timing, and extent of winter cover crop implementation. It also illustrates that nitrate exports vary based on edaphic and agronomic characteristics of the croplands upon which crops are planted. Therefore, it is important to develop management guidelines to encourage optimal planting species, timing, and locations to achieve enhanced water quality benefits. This study suggests that early planted rye is the most effective cover crop practice, with potential to reduce nitrate loading by 67 % over baseline at the watershed scale. We hypothesize that the relatively high nitrate removal efficiency of early planted rye is due to the more rapid growth rate of rye, especially in the early growth stage, compared to other species. As expected, nitrate removal efficiency increased significantly with early planting of all species and increasing cover crop implementation. The study also illustrates that locations of high nitrate export were generally associated with moderately well-drained soils and agricultural fields more frequently used for corn. Therefore, it would be important to prioritize winter cover crop application with early planted rye for those areas with well-drained soils used for corn production.

This study also provides a novel approach to calibrate winter cover crop growth parameters. Growth parameters for winter cover crops need to be carefully calibrated for shorter day-lengths and lower temperatures during the winter, to provide accurate estimation of the nutrient uptake efficiency of cover crops. Unfortunately, at present there are limited data available on winter cover crop growth and biomass estimation at the field or landscape scale. However, this data limitation is expected to be resolved in the future, as the planting of winter cover crops becomes more common and monitoring programs are enhanced through the availability of no or low cost time series remotely sensed data (e.g., Landsat). With multi-year cover crop biomass and growth data, the methodology presented in this paper could be extended to better calibrate growth parameters and validate winter cover crop biomass, improving accuracy of SWAT to estimate nitrate removal efficiency by winter cover crops.

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List of Tables

Table 1. List of data used in this study

Data	Source	Description	Year
DEM	MD-DNR	LiDAR-based 2 meter resolution	2006
Land use	USDA-NASS	Land use map based on cropland data layers	2008
	USGS	National Land Cover Database	1992, 2002, 2006
	USDA-ARS at Beltsville	Land use map developed through on-screen digitizing using National Aerial Photography Program (NAPP) digital orthophoto quad imagery (Sexton et al., 2012)	1998
Soils	USDA-NRCS	Soil Survey Geographic database	2012
Climate	NCDC	Daily precipitation and temperature	1990 ~ 2010
Streamflow	Jordan et al. (1997)	Monthly streamflow	1990 ~ 1995
Water Quality	Jordan et al. (1997)	Monthly nitrate	1990 ~ 1995
Winter Cover Crop Biomass	Hively et al. (2009)	Winter cover crop biomass estimated from field survey and satellite imageries	2005 ~ 2006

Table 2. List of calibrated parameters

Parameter	Simulation module	Description	Range	Calibrated value	Reference*
CN2	Flow	Curve number	-20 ~ +20%	-16%	Zhang et al., 2008
ESCO	Flow	Soil evaporation compensation factor	0 ~ 1	1.000	Kang et al., 2006
SURLAG	Flow	Surface runoff lag coefficient	0 ~ 10	1	Zhang et al., 2008
ALPHA_BF	Flow	Base flow recession constant	0 ~ 1	0.045	Meng et al., 2010
GW_DELAY	Flow	Delay time for aquifer recharge	0 ~ 50	26	Meng et al., 2010
CH_K2	Flow	Effective hydraulic conductivity	0 ~150	2	Zhang et al., 2008
CH_N2	Flow	Manning coefficient	0.02 ~ 0.1	0.038	Meng et al., 2010
NPERCO	Nitrogen	Nitrogen percolation coefficient	0.01 ~1	1	Meng et al., 2010
N_UPDIS	Nitrogen	Nitrogen uptake distribution parameter	5 ~ 50	50	Saleh and Du, 2004
ANION_EXCL	Nitrogen	Fraction of porosity from which anions are excluded	0.1 ~ 0.7	0.405	Meng et al., 2010
ERORGN	Nitrogen	Organic N enrichment ratio for loading with sediment	0 ~ 5	0.497	Meng et al., 2010
BIOMIX	Nitrogen	Biological mixing efficiency	0.01 ~ 1.0	0.01	Chu et al., 2004
LAIMX1	LAI	Fraction of the maximum leaf area index corresponding to the first point on the leaf area development curve	-	0.01 (Wheat) 0.02 (Barley) 0.12 (Rye)	Hively et al., 2009
LAIMX2	LAI	Fraction of the maximum leaf area index corresponding to the second point	-	0.14 (Wheat) 0.31 (Barley) 0.35 (Rye)	Hively et al., 2009

The ranges of parameters were adapted from existing literature (noted as Reference*). LAIMX1 and LAIMX2 were estimated using regression method based on biomass estimates reported in Hively et al. (2009) and the simulation outputs from the crop growth module of SWAT (see details in section 2.2.3).

Table 3. List of cover crop scenarios

Scenario	Cover crop species	Planting timing	Abbreviations
1	None	N/A	Baseline
2	Winter wheat	Early planting (Oct 3)	WE
3	Barley	Early planting (Oct 3)	BE
4	Rye	Early planting (Oct 3)	RE
5	Wheat	Late planting (Nov 1)	WL
6	Barley	Late planting (Nov 1)	BL
7	Rye	Late planting (Nov 1)	RL

Note: early planting scenarios include 50 % of early planting on corn and 50 % of late planting on soybean. Soybean requires longer growing day, and actual practices and county statistics showed that early planting was generally allowed for corn only.

Table 4. Agricultural practices and management scheduling for the baseline and cover crop scenarios

Baseline scenario		
Year	Corn-Soybean rotation	Soybean-Corn rotation
First Year	Apr. 12- poultry manure; 4942 kg/ha (4413 lb/ac)	May 20- Soybean plant: no-till
	Apr. 27- poultry manure; 2471 kg/ha (2206 lb/ac)	Oct. 15 – Soybean harvest
	April 30- Corn plant: no-till	
	Jun. 15- sidedress 30% UAN; 112 kg/ha (100 lb/ac)	
	Oct. 15- Corn harvest	
Second Year	May 20- Soybean plant: no-till	April 12- poultry manure; 4942 kg/ha (4413 lb/ac)
	Oct. 15 – Soybean harvest	April 27- poultry manure; 2471 kg/ha (2206 lb/ac)
		April 30- Corn plant: no-till
		Jun. 15- sidedress 30% UAN; 112 kg/ha (100 lb/ac)
		Oct. 15- Corn harvest
Cover crop scenario		
Year	Corn-Soybean rotation	Soybean-Corn rotation
First Year	April 12- poultry manure; 4942 kg/ha (4413 lb/ac)	May 20- Soybean plant: no-till
	April 27- poultry manure; 2471 kg/ha (2206 lb/ac)	Oct. 30 – Soybean harvesting
	April 30- Corn plant: no-till	Nov. 1 – Cover crop planting**
	Jun. 15- sidedress 30% UAN; 112 kg/ha (100 lb/ac)	
	Oct. 1 & Oct. 30- Corn harvesting	
	Oct. 3 & Nov. 1 – Cover crops planting *	
Second Year	Apr. 1 – chemically kill cover crops	Apr. 1 – chemically kill cover crops
	May 20- Soybean plant: no-till	April 12- poultry manure; 4942 kg/ha (4413 lb/ac)
	Oct. 30 – Soybean harvesting	April 27- poultry manure; 2471 kg/ha (2206 lb/ac)
	Nov. 1 – Cover crop planting *	April 30- Corn plant: no-till
		Jun. 15- sidedress 30% UAN; 112 kg/ha (100 lb/ac)
		Oct. 1 & Oct. 30- Corn harvesting
		Oct. 3 & Nov. 1 – Cover crop planting *

Table 5. Model performance measures for streamflow and nitrate

Variable	Period	RSR	NSE	P-bias (%)
Flow	Calibration	0.495***	0.744**	7.0***
	Validation	0.517**	0.718**	-2.9***
Nitrate	Calibration	0.550**	0.684**	-3.4***
	Validation	0.688*	0.503*	-15.6***

Performance rating * indicates Satisfactory, ** Good, *** Very Good. The performance rating criteria are adapted from Moriasi et al. (2008).

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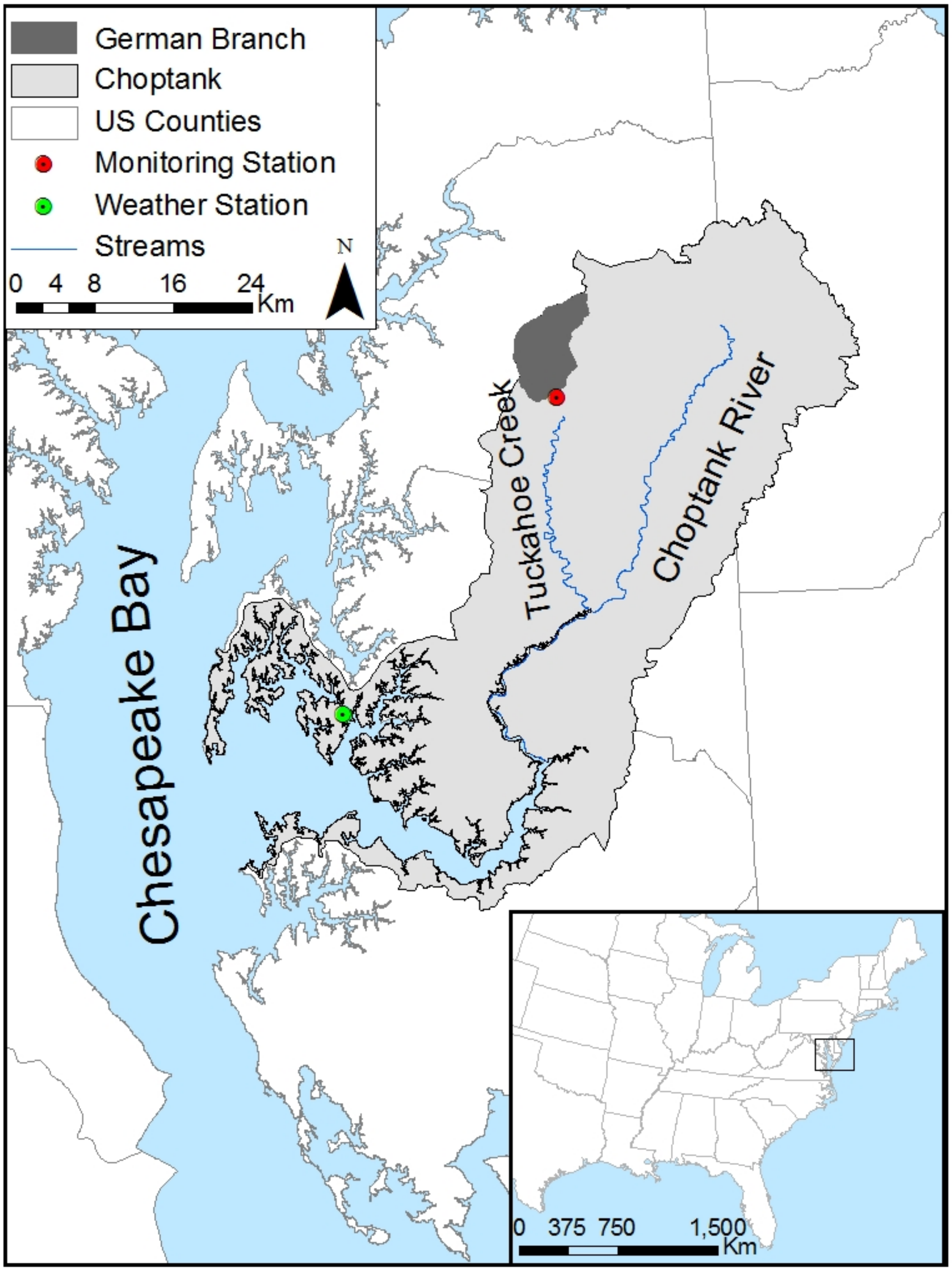

Figure 1. Geographical location of the study area (German Branch watershed)

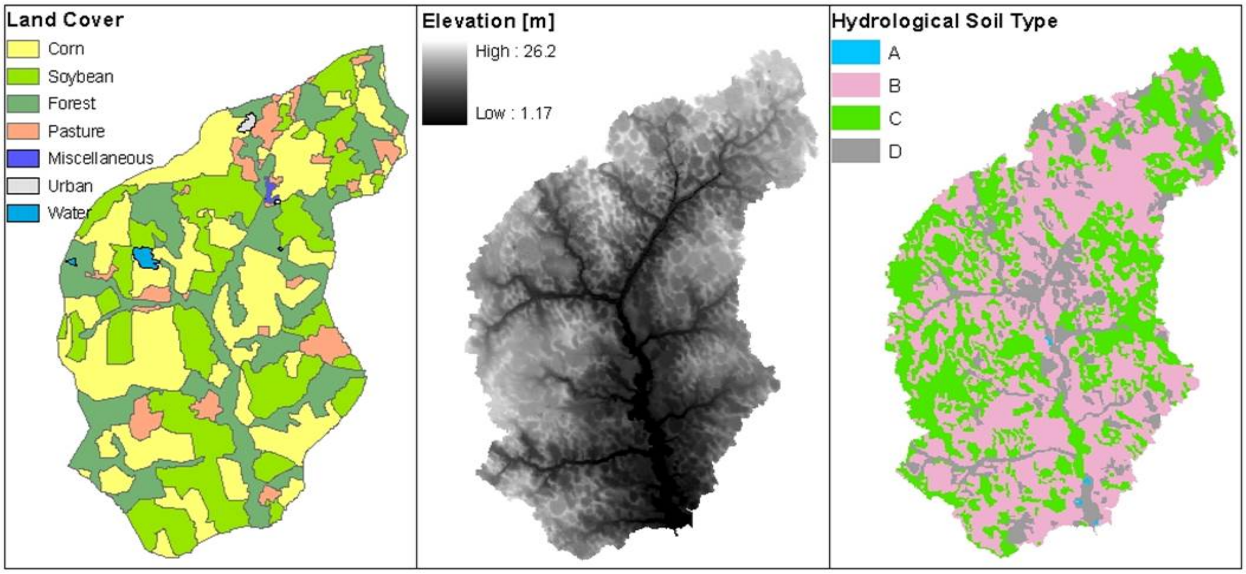

Figure 2. Characteristics of the study site (German branch watershed): land cover, elevation, and hydrologic soil group

Note: (1) Miscellaneous land cover indicates agricultural lands used for minor crops, vegetables, and fruits; (2) Hydrologic soil group (HSG) is characterized as follows: Type A- well drained soils with 7.6-11.4 mm/hr (0.3-0.45 inch/hr) water infiltration rate; Type B - moderately well drained soils with 3.8-7.6 mm/hr (0.15-0.30 inch/hr) water infiltration rate; Type C - moderately poorly drained soils with 1.3-3.8 mm/hr (0.05-0.15 in/hr) water infiltration rate; Type D - poorly drained soils with 0-1.3 mm/hr (0-0.05 inch/hr) water infiltration rate.

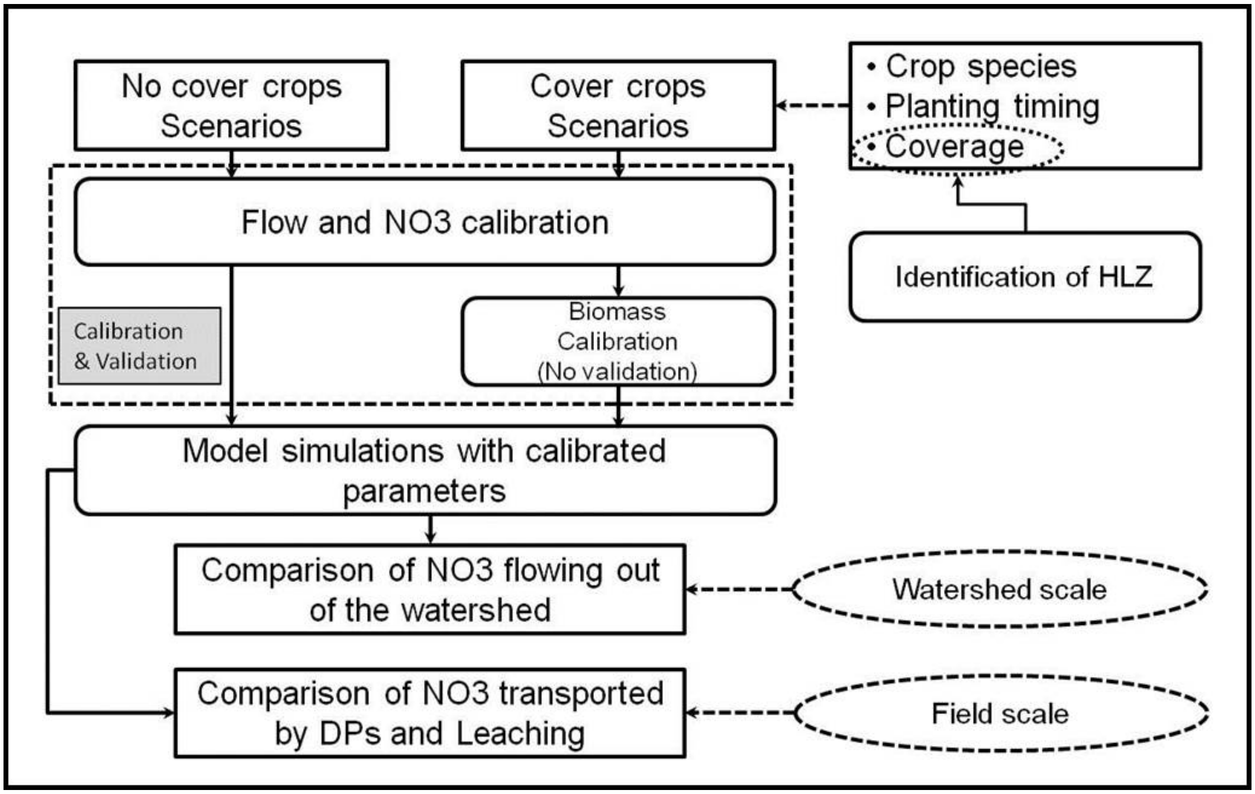

Figure 3. Schematic diagram of modeling procedure

This shows the overall modeling procedure of the presented study and summarizes what simulation results are compared at the various spatial scales. HLZ (High Loading Zones) refers to those agricultural fields (HRUs) with high nitrate export potential

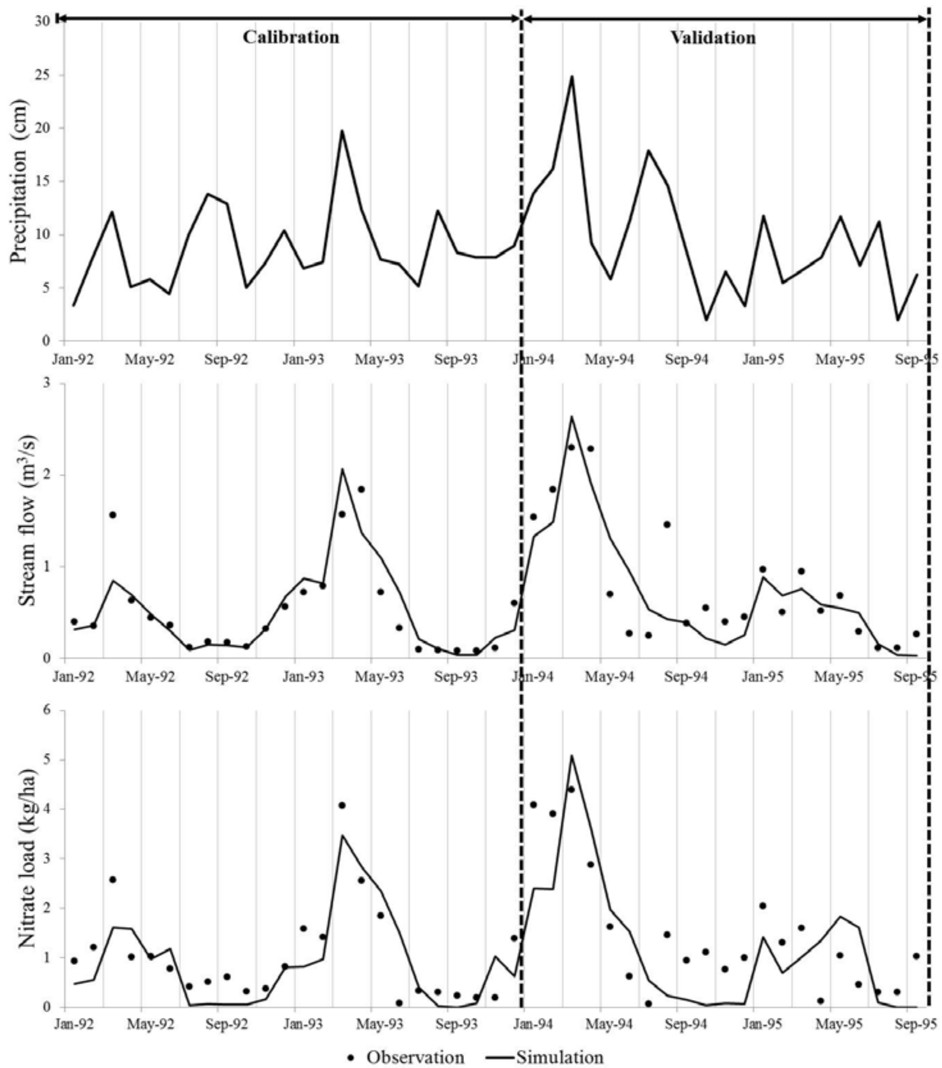

Figure 4. Observed and simulated monthly streamflows and nitrate loads during the monitoring period (1992-1995) at the watershed scale.

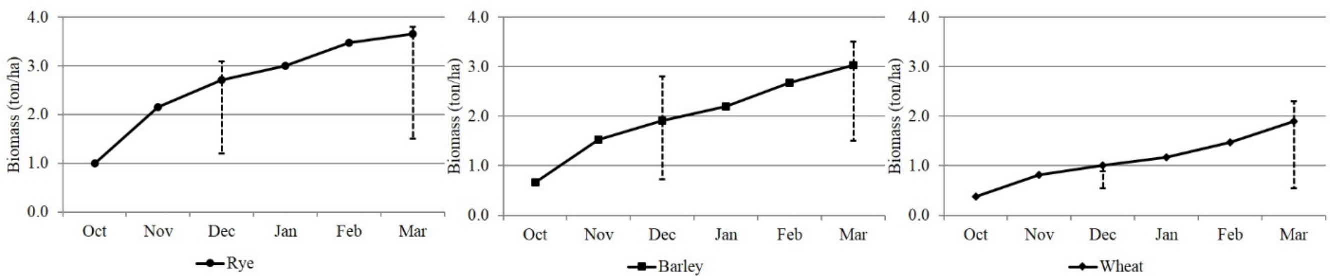

Figure 5. Estimation of winter cover crop biomass during the winter fallow period

Note: This figure presents monthly average total biomass (both above- and below-ground biomass) over the simulation period for three planting species. The vertical dotted line represents the range of above-ground biomass estimates due to different growing/planting days from Hively et al. (2008). The simulated total biomass lies at the upper end of above ground biomass estimates.

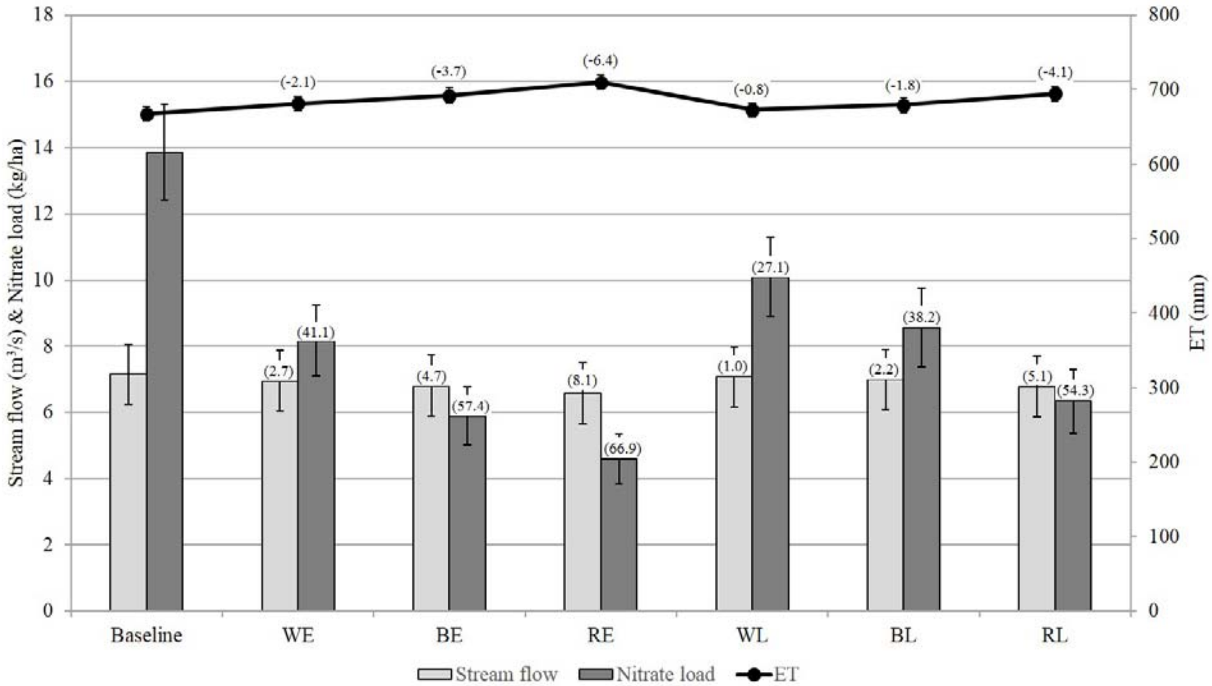

Figure 6. Nine-year average annual mean streamflow, annual actual evapotranspiration (ET), and annual nitrate loads at watershed scale under multiple cover crop scenarios

Note: Error bar (vertical line) represents standard deviation. The numeric value in parentheses, (), indicates reduction rate (RR). RR is calculated by taking the relative difference in simulation outputs from the baseline and cover crop scenarios [RR = (Baseline – Cover crop Scenario) / Baseline].

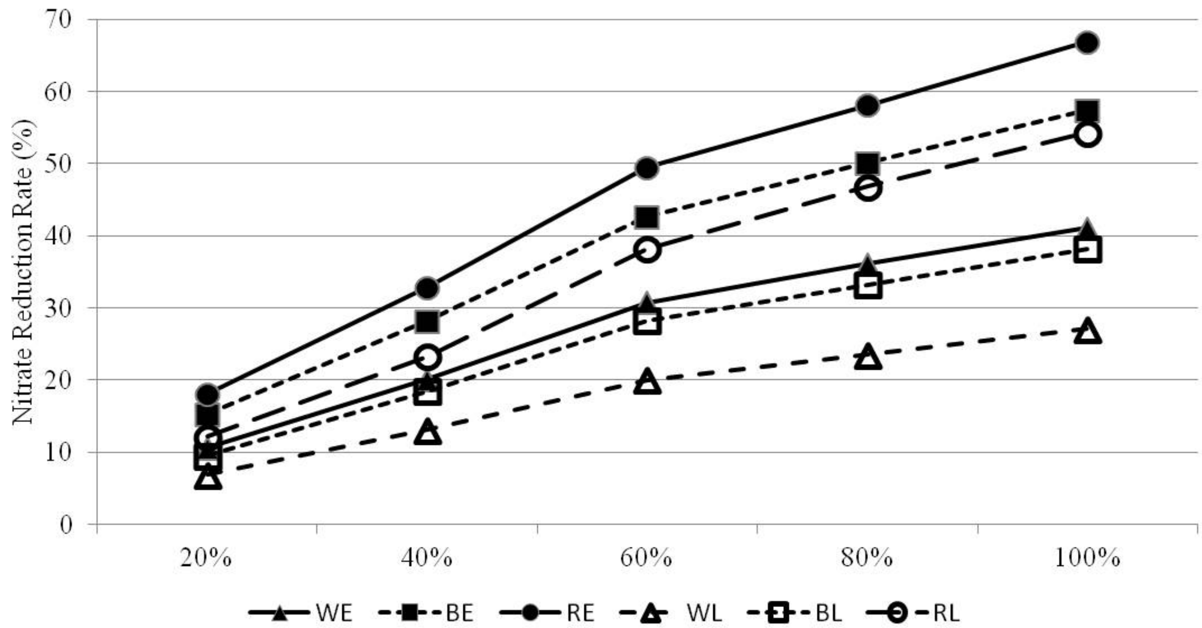

Figure 7. Nitrate reduction rates by varying degree of cover crop implementation evaluated at the watershed scale.

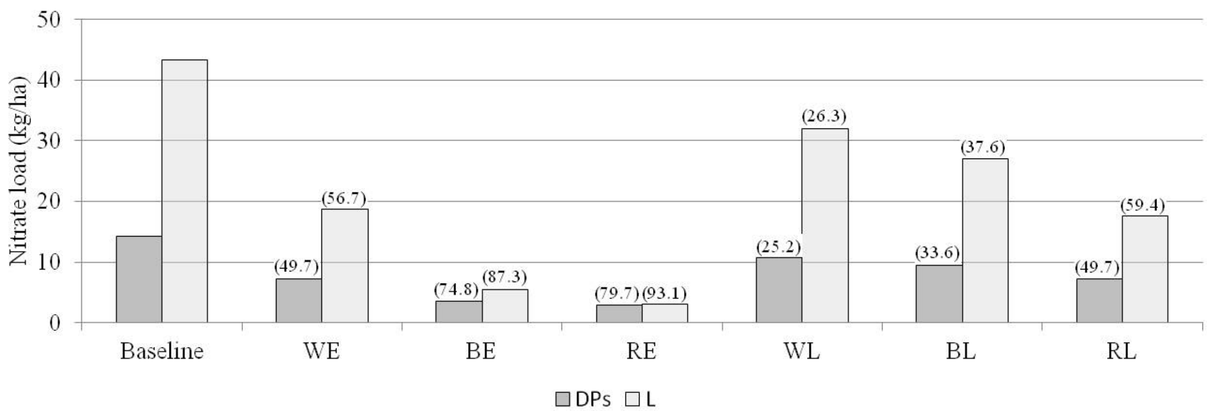

Figure 8. Eight-year average nitrate leaching and delivery to waterways during winter fallow assessed at the field scale under multiple cover crop scenarios.

Note: DPs (Direct pathways) refers to the amount of nitrate transported from agricultural fields (HRUs) to waterways by surface flow, lateral flow, and groundwater; L is nitrate leaching to groundwater. The numeric value in parentheses, (), indicates reduction rate (RR). As the growth period of winter cover crop covers from October to March, results presented in Figure 8 were based on the eight years of simulation from October 1992 to March 2000.

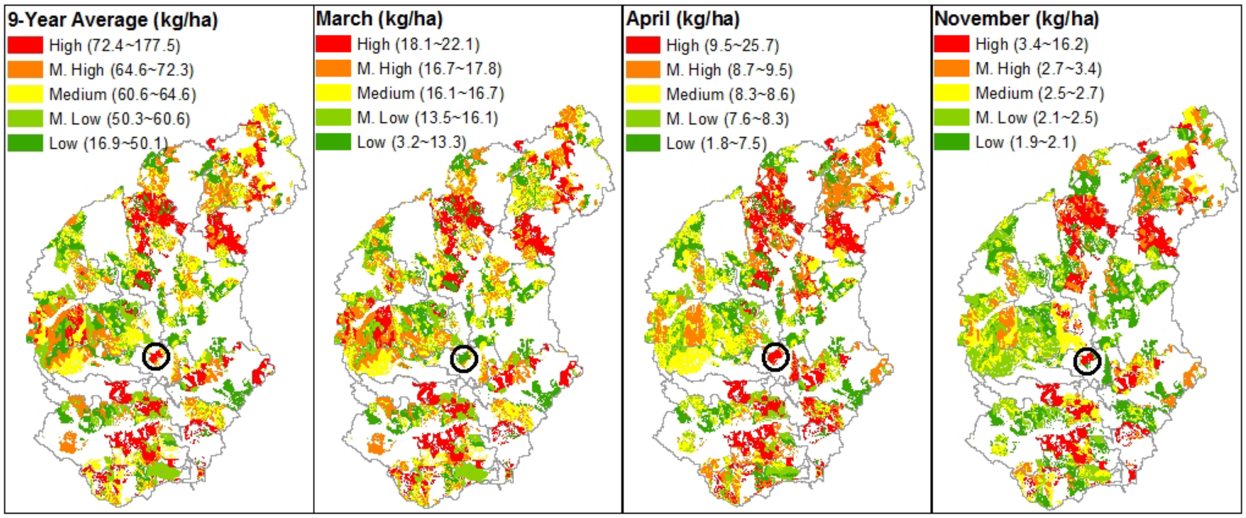

Figure 9. The spatial distribution of nitrate export potential from agricultural fields

Note: Nitrate export potential was computed by adding the annual or monthly averaged amount of nitrate leaching to the groundwater (L) and leaving to the streams by surface runoff, lateral flow, and groundwater (DPs) from the 9-year simulation results. Estimated nitrate loads from the HRUs were classified into five groups. In the legend, M. High refers to Moderately High and M. Low Moderately Low. The HRUs within the black circle indicates outliers with extremely high nitrate loadings. This area is characterized by poorly drained hydric soil ("Urban land") and consistently produces extremely high nitrate loadings throughout years and seasons.