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Assessing winter cover crop nutrient uptake efficiency using a water quality simulation model

I.-Y. Yeo[1], S. Lee[1], A. M. Sadeghi[2], P. C. Beeson[3], W. D. Hively[4], G. W. McCarty[2], and M. W. Lang[5]

[1]Department of Geographical Sciences, University of Maryland,
College Park, MD 20742, USA
[2]USDA-ARS, Hydrology and Remote Sensing Laboratory, Beltsville, MD 20705, USA
[3]Dream it Do it Western New York, Jamestown, NY 14701, USA
[4]USGS, Eastern Geographic Science Center, Reston, VA 20192, USA
[5]USDA Forest Service, Northern Research Station, Beltsville, MD 20705, USA

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Correspondence to: I.-Y. Yeo (iyeo@umd.edu) and A. M. Sadeghi (ali.sadeghi@ars.usda.gov)

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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 winter 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 and satellite-based estimates of winter cover crop species performance to simulate hydrological processes and nutrient cycling over the period of 1991–2000. Multiple scenarios were developed to obtain baseline information on nitrate loading without winter cover crops planted and to investigate how nitrate loading could change with different winter cover crop planting scenarios, including different species, planting times, and implementation areas. The results indicate that winter cover crops had a negligible impact on water budget, but significantly reduced nitrate leaching to groundwater and delivery to the waterways. Without winter cover crops, annual nitrate loading was approximately 14 $\mathrm{kg\,ha^{-1}}$, but it decreased to 4.6–10.1 $\mathrm{kg\,ha^{-1}}$ with winter cover crops resulting in a reduction rate of 27–67 % at the watershed scale. Rye was most effective, with a potential to reduce nitrate leaching by up to 93 % with early planting at the field scale. Early planting of winter cover crops ($\sim$ 30 days of additional growing days) was crucial, as it lowered nitrate export by an additional $\sim$ 2 $\mathrm{kg\,ha^{-1}}$ when compared to late planting scenarios. The effectiveness of cover cropping increased with increasing extent of winter 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 implement of winter cover crop programs, in part by helping to target critical pollution source areas for winter cover crop implementation.

1 Introduction

The Chesapeake Bay (CB) is the largest and most productive estuary in the US, supporting more than 3600 species of plants and animals (CEC, 2000). It is an international as well as national asset. Its importance 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. Its high watershed area to water surface (estuary) ratio (14 : 1) amplifies the influence of human modifications. Excessive nutrient and sediment runoff has led to eutrophication (Kemp et al., 2005; Cerco et al., 2007). High 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 stream flow, 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 (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 CB. 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 100 % cropland at a rate of 18 kg N ha^{-1} per year, 7 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 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). Therefore, federal and state governments have established cost-share programs to promote winter cover cropping practices (MDA, 2012). However, the overall efficiency of winter 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 significant residence time of leached N in groundwater and the difficulty of monitoring over long time periods (McCarty et al., 2008). Only a few field studies have demonstrated cover crop nitrate reduction efficiencies at the field scale (Shipley et al., 1991; Staver and Brinsfield, 2000) or at the landscape scale (Hively et al., 2009). 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 low land 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), 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 yr) of winter cover crops on water budget and nitrate loadings under multiple winter cover crop implementation scenarios (e.g., species, timing and area planted). The nutrient uptake and nitrate reduction efficiencies of winter cover crops are primarily dependent upon winter cover crop biomass. Therefore, it is crucial to simulate plant growth accurately. For this reason 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. The GB is a third order Coastal Plain stream, located within the non-tidal zone of the Choptank River Basin in the CBW (Fig. 1). Its drainage area is approximately 50 km^2 and its land use is dominated by agriculture (~ 72 %) and forest (~ 27 %) (Fig. 2). Agricultural lands are evenly split between corn and soybean cropping. The study site is relatively flat with elevations ranging from 1 to 26 m. Most of the soils are moderately well-drained (Hydrologic Soil Group (HSG) B) or moderately poorly-drained (HSG C). Soil types 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 % of the study area. Figure 2 presents information on land use, hydrologic soil types, and topography of the study site. The study site is characterized by a temperate, humid climate with an average annual precipitation of 120 cm yr^{-1} (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 US Environmental Protection Agency (US EPA) under Section 303(d) of the Clean Water Act. It was because of 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, significant efforts have been made to monitor water quality in the Choptank 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 US 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).

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 winter cover crop scenarios over the period of 1991–2000. Changes in nitrate loads and water budgets under multiple scenarios were compared with baseline conditions (no winter cover crops). The overall modeling approach is presented in Fig. 3. Since winter cover crop N reduction efficiency is controlled by winter cover crop biomass, we developed a new method to calibrate plant growth parameters that control leaf area development to produce simulation outputs close to observed values.

2.2.1 Description of SWAT model

SWAT is a continuous physically based semi-distributed watershed process model. Its 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 fully available online (Neitsch et al., 2011). The key physical processes in SWAT relevant to this research are briefly discussed in following.

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 andhydrologic response units (HRU). A HRU is the smallest spatial unit used for field-scale processes within the model. It 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. A modification of the Soil Conservation Service (SCS) curve number (CN) method was used to simulate surface runoff in this study. 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 on 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. The geospatial dataset needed to simulate SWAT 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 (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. The land use map was prepared using the cropland data layers produced by USDA National Agriculture Statistics Service (NASS) (Boryan et al., 2012). Soil information was obtained from the Soil Survey Geographical Database (SSURGO) available from the USDA Natural Resources Conservation Service (NRCS).

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 1991–1995 was obtained from Jordan et al. (1997). Annual estimates of N loads by sub-watershed areas within GB watershed were provided by Primrose et al. (1997).

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) in the study region during the time of water quality monitoring, and the guidelines and winter cover crop implementation practices recently developed by the Maryland Department of Agriculture (MDA) Cover Crop Programs.

2.2.3 Calibration and validation of SWAT model

Although SWAT simulations were done on a daily basis, the calibration and validation were done using the monthly water quality record available from the monitoring station located at the study watershed outlet. The calibration was manually done following the standard procedure outlined in the 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 2 yr 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 stream flows and then the nitrate values to match the simulated monthly data to the observed monthly data. To assess longer-term effects, the model simulations were performed over 10 yr (1990 to 2000) setting the 1st year as a warm up period. We used ArcSWAT2009 with the 582 version of the executable file in the ArcGIS 9.3.1 interface.

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:

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

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

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

where O_i are observed and S_i are simulated data, $\overline{O}$ 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).

Plant growth parameters were calibrated to more realistically simulate winter 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 by various planting dates in the region. This information was analyzed to obtain winter cover crop biomass estimation by 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 winter cover crop monitoring period (2005–2006). The crop growth module of SWAT was run with average daily climate data over 1991–2000 using the default parameter values to provide estimates of biomass and leaf area index (LAI) by growing degree days. 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 leaf area development curve in SWAT model.

2.2.4 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, and ran simulations between 1991 and 2000. 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 have constructed multiple scenarios relevant to current winter cover crop practices with three major winter cover crop species (i.e., barley (*Hordeum vulgare* L.), rye (*Secale cereale* L.), and wheat (*Triticum aestivum* L.)), and two planting deadlines (early/late). Additional winter cover crop scenarios were also developed to assess their effectiveness by varying extent of winter cover crop implementation. For example, we gradually increased winter cover crop implementation area for different planting species from 20 to 100 % of total croplands, to determine potential N reduction with increasing winter cover crop area.

Table 4 summarizes agricultural practices and scheduling used for different scenarios. There was no difference between baseline and winter cover crop scenarios during the growing season. The croplands were managed with the typical 2 yr 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, winter cover crop scenarios assumed placement of winter cover crops. The winter cover crops were planted after harvesting of summer crops either in the beginning of October (early planting) or November (late planting), but harvested in the beginning of the growing season (early April in most years). The specific dates (3 October and 1 November) of winter cover crop planting were set according to MDA guidelines and the reporting statistics, with slight adjustment to avoid those days with precipitation prior to winter cover planting over the simulation period. Note the harvesting date of summer crop under the baseline was set for 15 October, to make the model results from the baseline more comparable to those early and late winter cover crop scenarios by setting the harvesting date in between them. Early planting was only allowed for corn, assuming soybean requires longer growing days. MDA's county level statistics over 2006–2011 showed winter cover crops were generally planted late following soybean (in general, after mid-October), while two thirds of winter cover crop implementation occurred prior to mid-October after corn. This could be due to late harvesting to allow for second rotation soybean crops. As a result, those scenarios with early planting include 50 % of winter cover cropping with early planting on corn fields and remaining 50 % with late planting on soybean fields, as both crop types have roughly an equal share of total agricultural land. Since 100 % winter cover cropping with early planting could not be applied over the entire watershed area, the nitrate removal effects by different planting dates were evaluated at the field level based on simulation outputs from corn fields only.

3 Results and discussion

3.1 SWAT calibration and validation

The simulated results of monthly stream flows 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 stream flow 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 the nitrate, but the pattern of simulated nitrate was very 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 streamflows and nitrate was in 1994. Unlike simulation output, a high peak in stream flow and consequently in nitrate loading was observed in September. 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 stream flow record from an adjacent watershed, with very similar characteristics and size, did not produce high peak values for streamflow during the same period. This 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).

Accurate simulation of winter cover crop growth and biomass at various stages of production is crucial to accurately estimating its potential 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 1991–2000. However, we are confident in our biomass simulation, as the 9 yr averaged winter cover crop biomass estimates were comparable to the range of winter cover crop biomass reported by 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.

Without calibration, crop growth was simulated at a much faster growth rate and the growth trend over winter months did not match field data. With default values, SWAT predicted much higher winter biomass than those reported by Hively et al. (2009). The modeled growth rate of rye was significantly 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 winter cover crop biomass were at the upper end of the reported values, as the simulation output included both above and below-ground biomass.

3.2 Multiple scenarios analysis

While the hydrologic effect of winter cover crops was found to be somewhat negligible, the conservation practice had a profound effect on nitrate loads. Figure 6 presents 9 yr average streamflow, actual evapotranspiration, and nitrate loads, under baseline and multiple winter cover crop scenarios. Winter cover cropping slightly reduced stream flow from 8.5 to 7.8 $m^3 s^{-1}$ (RE, Rye Early) – 8.4 $m^3 s^{-1}$ (WL, Wheat Late), and increased evapotranspiration from 667 to 673 mm (WL) – 710 mm (RE), in comparison to the baseline scenario. Rye caused most changes to the hydrologic budget followed by barley and winter wheat. Early planting scenarios produced slightly lower stream flow but 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 winter cover crop scenarios ranged from 4.6 $kg ha^{-1}$ (RE) to 10.1 $kg ha^{-1}$ (WL). The difference in nitrate loadings under different winter cover crop scenarios ranged from 1.8 $kg ha^{-1}$ (when compared RE to RL, Rye Late) to 5.5 $kg ha^{-1}$ (when compared RE to WL). If the comparison of the removal efficiency was made per planting species, early winter cover cropping (3 October) lowered annual nitrate loads by 1.8 (rye and winter wheat) – 2.7 (barley) $kg ha^{-1}$, compared to late winter cover cropping (1 November). When compared with the baseline scenario (13.9 $kg ha^{-1}$), the winter cover crop scenarios reduced nitrate loads by 27 % (WL) to 67 % (RE) at the watershed scale. This 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 winter cover crop biomass during winter season. Therefore, earlier planting could increase the amount of nitrogen uptake by winter 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 ($\mathrm{kg\,N\,ha^{-1}}$) 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 winter 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. It exhibits better nutrient uptake capacity than wheat (Malhi et al., 2006; Clark, 2007). Our simulation results were consistent with previous studies. As shown from Fig. 5, rye grows much 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 (Fig. 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 (Fig. 6). Figure 6 illustrates that late planted rye was nearly as effective as early planted barley, and more effective than early planted winter wheat.

Nitrate removal efficiency was greatly affected by different levels of winter cover cropping implementation as shown from Fig. 7. As expected, removal efficiency increased with increasing coverage of winter cover crop implementation, though the slope of removal efficiency slightly decreased at 60 % of extent. It was noticeable that 60 % winter cover crop coverage with an early planting date would reduce more nitrate than 100 %

winter cover crop coverage with late planting, emphasizing the importance of early winter cover crop planting as shown by other studies (Ritter et al., 1998; Hively et al., 2009).

The effects of winter cover cropping were further assessed by quantifying the amount of nitrate transported from agricultural fields by different delivery pathways to streams or 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 Fig. 8) over the winter fallow period (October to March) without winter cover crops was estimated as 43 kg ha^{-1}. With winter cover crops, nitrate leaching decreased to 3.0–18.8 kg ha^{-1}, 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 groundwater (referred as "DPs", direct pathways in Fig. 8) was greatly reduced from 2.9 to 10.7 kg ha^{-1} with winter cover crop scenarios, a reduction rate of 28–87 %. 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.

Geospatial analysis to identify high nitrate loading areas

The 9 yr 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 (283 HRUs out of 402 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 9 yr 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, harvesting of winter cover crop and fertilizer application in April, and winter 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. 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 Fig. 8). We hypothesize that areas with moderately well drained soils allowed high nitrate leaching due to their high infiltration capacity (Fig. 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.

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 they 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 winter 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 winter 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 winter cover crops. Unfortunately at the present there is very limited data on winter cover crop growth and biomass estimation at the field or landscape scale. However, this data limitation should 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 winter 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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Table 1. List of data used in this study.

Data	Source	Description	Year
DEM	MD-DNR	LiDAR-based 2 m resolution	2006
Land use	USDA-NASS	Land use map based on cropland data layer	2008
Soils	USDA-NRCS	Soil Survey Geographic database	2012
Climate	NCDC	Daily precipitation and temperature	1990 ~ 2010
Stream flow	Jordan et al. (1997)	Monthly stream flow	1990 ~ 1995
Water Quality	Jordan et al. (1997)	Monthly nitrate	1990 ~ 1995

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 ∼ 0.12	Hively et al. (2009)
LAIMX2	LAI	Fraction of the maximum leaf area index corresponding to the second point	–	0.14 ∼ 0.35	Hively et al. (2009)

Table 3. List of winter cover crop scenarios.

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

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

	Baseline scenario	
Year	Corn-Soybean rotation	Soybean-Corn rotation
First Year	12 Apr – poultry manure; 4942 kg ha^{-1} (4413 lb ac^{-1}) 27 Apr – poultry manure; 2471 kg ha^{-1} (2206 lb ac^{-1}) 30 Apr – Corn plant: no-till 15 Jun – sidedress 30 % UAN; 112 kg ha^{-1} (100 lb ac^{-1}) 15 Oct – Corn harvest	20 May – Soybean plant: no-till 15 Oct – Soybean harvest
Second Year	20 May – Soybean plant: no-till 15 Oct – Soybean harvest	12 Apr – poultry manure; 4942 kg ha^{-1} (4413 lb ac^{-1}) 27 Apr – poultry manure; 2471 kg ha^{-1} (2206 lb ac^{-1}) 30 Apr – Corn plant: no-till 15 Jun – sidedress 30 % UAN; 112 kg ha^{-1} (100 lb ac^{-1}) 15 Oct – Corn harvest
	Winter cover crop scenario	
Year	Corn-Soybean rotation	Soybean-Corn rotation
First Year	12 Apr – poultry manure; 4942 kg ha^{-1} (4413 lb ac^{-1}) 27 Apr – poultry manure; 2471 kg ha^{-1} (2206 lb ac^{-1}) 30 Apr – Corn plant: no-till 15 Jun – sidedress 30 % UAN; 112 kg ha^{-1} (100 lb ac^{-1}) 1 and 30 Oct – Corn harvesting 3 Oct and 1 Nov – Winter cover crops planting[a]	20 May – Soybean plant: no-till 30 Oct – Soybean harvesting 1 Nov – Winter cover crop planting[b]
Second Year	1 Apr – chemically kill winter cover crops 20 May – Soybean plant: no-till 30 Oct – Soybean harvesting 1 Nov – Winter cover crop planting[a]	1 Apr – chemically kill winter cover crops 12 Apr – poultry manure; 4942 kg ha^{-1} (4413 lb ac^{-1}) 27 Apr – poultry manure; 2471 kg ha^{-1} (2206 lb ac^{-1}) 30 Apr – Corn plant: no-till 15 Jun – sidedress 30 % UAN; 112 kg ha^{-1} (100 lb ac^{-1}) 1 and 30 Oct – Corn harvesting 3 Oct and 1 Nov – Winter cover crop planting[a]

Table 5. Model performance measures for stream flow and nitrate.

Variable	Period	RSR	NSE	P-bias
Flow	Calibration	0.495[c]	0.744[b]	7.0[c]
	Validation	0.517[b]	0.718[b]	−2.9[c]
Nitrate	Calibration	0.550[b]	0.684[b]	−3.4[c]
	Validation	0.688[a]	0.503[a]	−15.6[c]

Performance rating: [a] satisfactory, [b] good, [c] very good. The performance rating criteria are adapted from Moriasi et al. (2008).

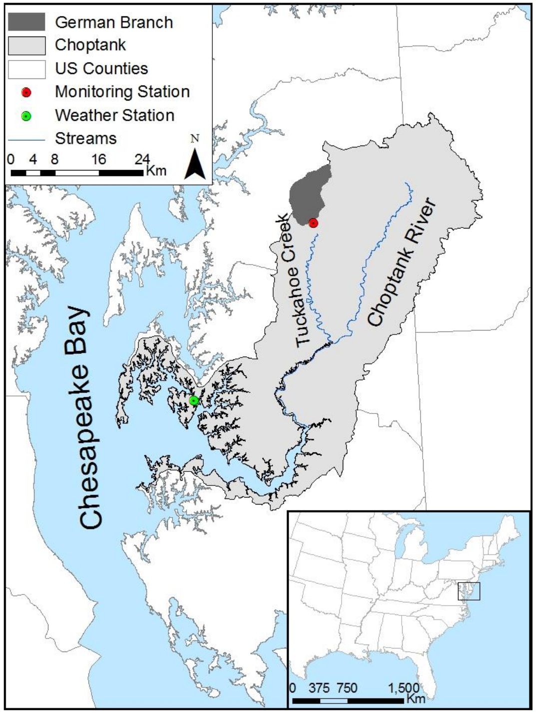

Fig. 1. Geographical location of the study area.

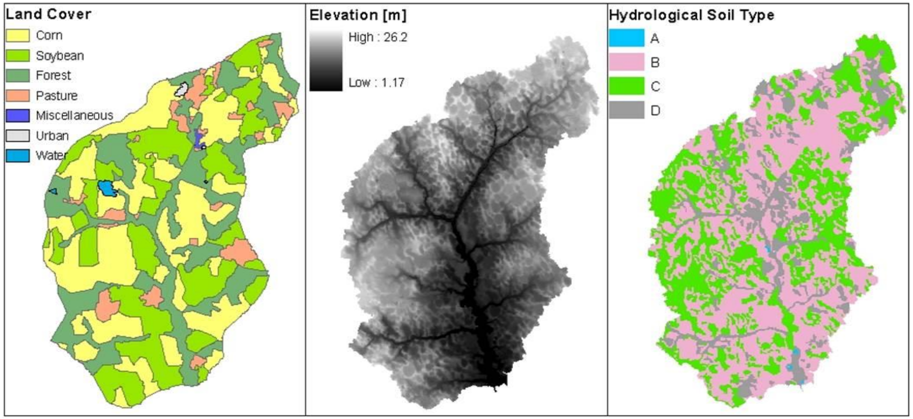

Fig. 2. Characteristics of the study site: land cover, elevation, and hydrologic soil group. Note: (1) Miscellaneous land cover indicates agricultural lands used for minor crops, vegetables, and fruits; (2) Hydrologic soil group (HSG) is characterized as follows: Type A – well drained soils with 7.6–11.4 mm h^{-1} (0.3–0.45 inch h^{-1}) water infiltration rate; Type B – moderately well drained soils with 3.8–7.6 mm h^{-1} (0.15–0.30 inch h^{-1}) water infiltration rate; Type C – moderately poorly drained soils with 1.3–3.8 mm h^{-1} (0.05–0.15 inch h^{-1}) water infiltration rate; Type D – poorly drained soils with 0–1.3 mm h^{-1} (0–0.05 inch h^{-1}) water infiltration rate. There is no soil type A in the study site.

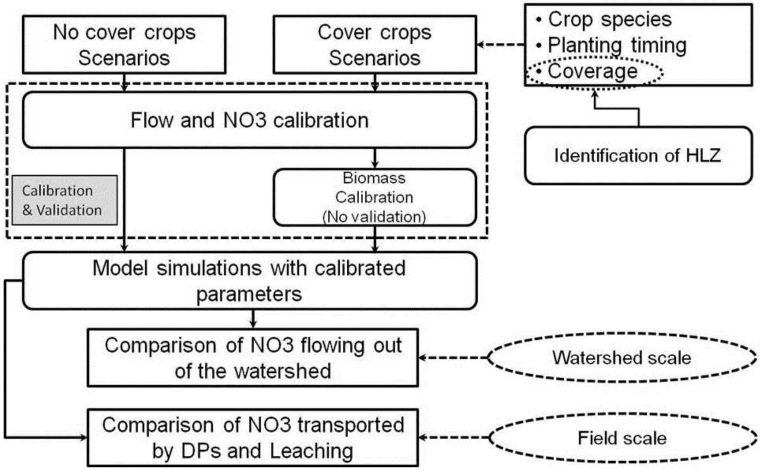

Fig. 3. Schematic diagram of modeling procedure. Note: HLZ (High Loading Zones) refers to those agricultural fields (HRUs) with high nitrate export potential.

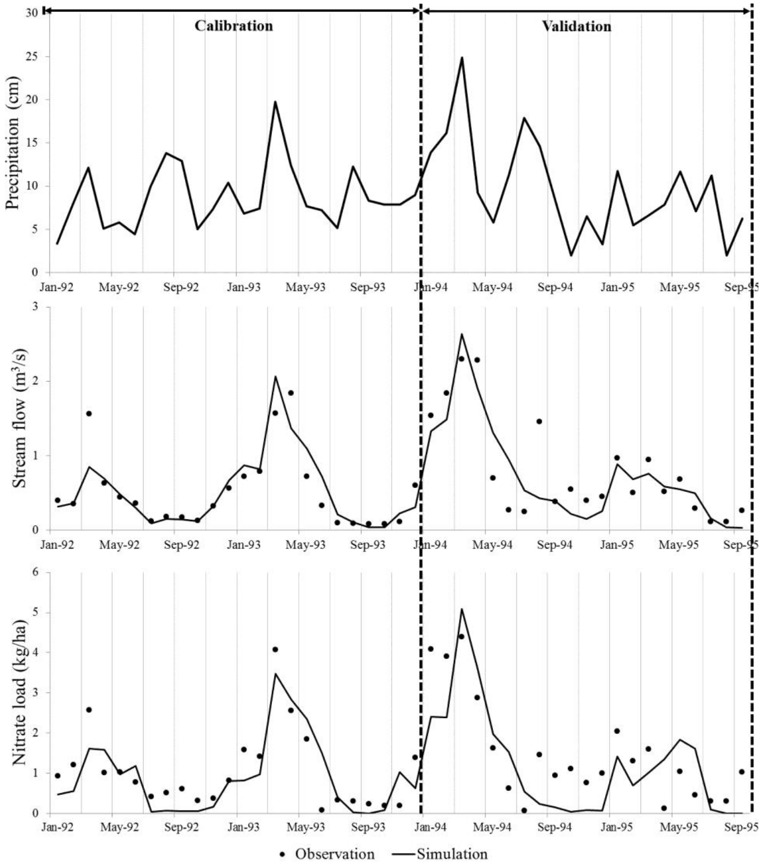

Fig. 4. Observed and simulated stream flows and nitrate loads during the monitoring period (1992–1995).

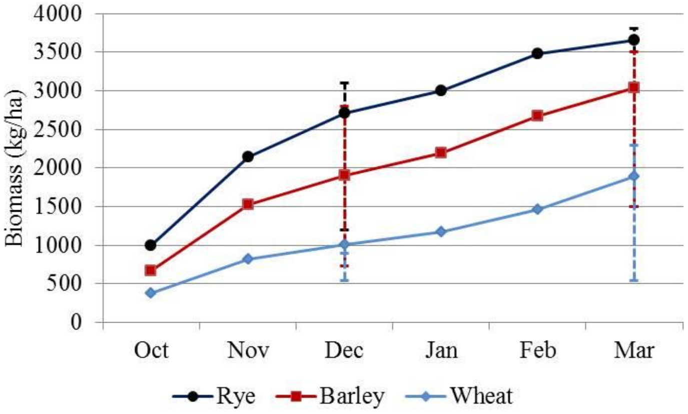

Fig. 5. Estimation of winter cover crop biomass during the winter fallow period. Note: This figure presents monthly average total biomass (both above- and below-ground biomass) over the simulation period. The vertical dotted line represents the range of above-ground biomass estimates due to different growing/planting days from Hively et al. (2008). The simulated total biomass lies at the upper end of above ground biomass estimates.

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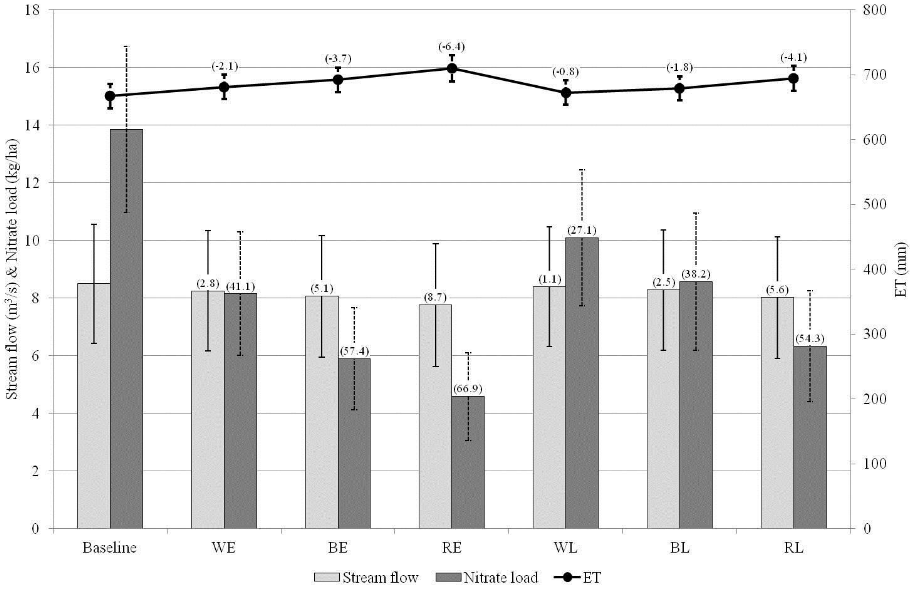

Fig. 6. 9 yr average stream flow, actual evapotranspiration (ET), and nitrate loads at watershed scale under multiple winter cover crop scenarios. Note: Error bar (vertical line) represents standard deviation. The numeric value in parentheses, (), indicates reduction rate (RR). RR is calculated by taking the relative difference in simulation outputs from the baseline and winter cover crop scenarios [RR = (Baseline – Winter cover crop Scenario)/Baseline].

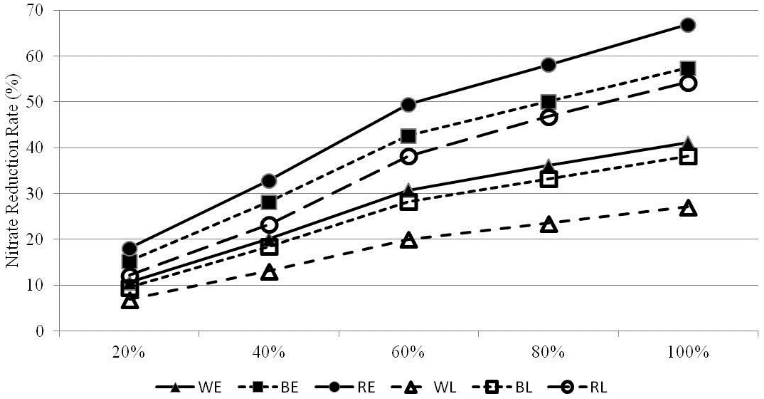

Fig. 7. Nitrate reduction rates by varying degree of winter cover crop implementation.

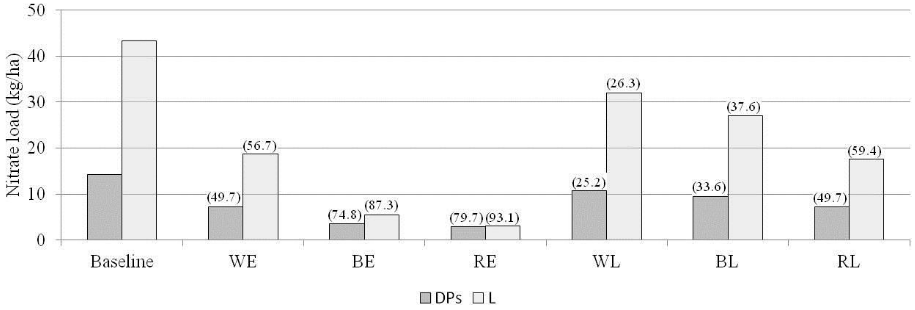

Fig. 8. 9 yr average nitrate leaching and delivery to waterways during winter fallow (October to March). Note: DPs (Direct pathways) refers to the amount of nitrate transported from agricultural fields (HRUs) to waterways by surface flow, lateral flow, and ground water; L is nitrate leaching to groundwater. The numeric value in parentheses, (), indicates reduction rate (RR).

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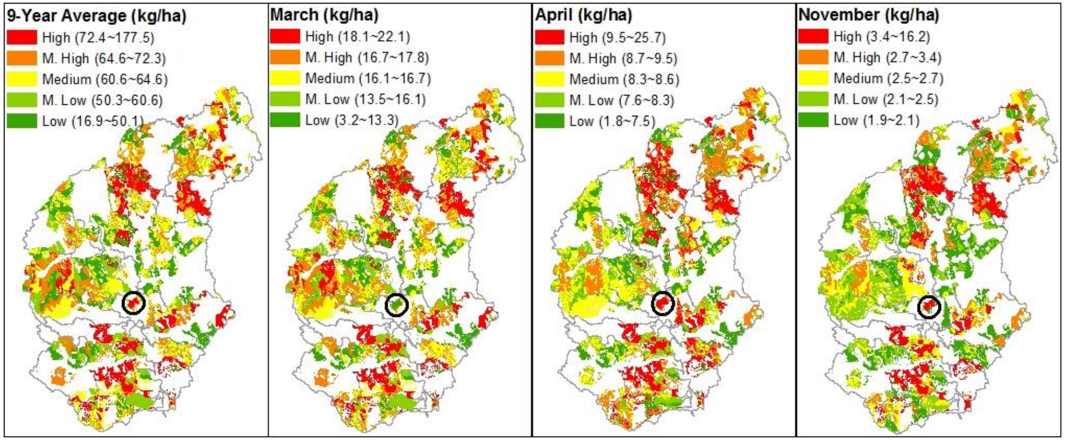

Fig. 9. The spatial distribution of nitrate export potential from agricultural fields. Note: Nitrate export potential was computed by adding the annual or monthly averaged amount of nitrate leaching to the groundwater (*L*) and leaving to the streams by surface runoff, lateral flow, and groundwater (DPs) from the 9 yr 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.