Study on nitrogen load reduction efficiency of agricultural conservation management in a small agricultural watershed

Xiaoli Liu, Qiuwen Chen and Zhaoxia Zeng

ABSTRACT

Different crops can generate different non-point source (NPS) loads because of their spatial topography heterogeneity and variable fertilization application rates. The objective of this study was to assess nitrogen NPS load reduction efficiency by spatially adjusting crop plantings as an agricultural conservation management (ACM) measure in a typical small agricultural watershed in the black soil region in northeast China. The assessment was undertaken using the Soil and Water Assessment Tool (SWAT). Results showed that lowland crops produce higher nitrogen NPS loads than those in highlands. It was also found that corn gave a comparatively larger NPS load than soybeans due to its larger fertilization demand. The ACM assessed was the conversion of lowland corn crops into soybean crops and highland soybean crops into corn crops. The verified SWAT model was used to evaluate the impact of the ACM action on nitrogen loads. The results revealed that the ACM could reduce NO_3-N and total nitrogen loads by 9.5 and 10.7%, respectively, without changing the area of crops. Spatially optimized regulation of crop planting according to fertilizer demand and geological landscapes can effectively decrease NPS nitrogen exports from agricultural watersheds.

Key words | agricultural conservation management, agricultural watershed, nitrogen non-point source load

Xiaoli Liu
Qiuwen Chen (corresponding author)
RCEES,
Chinese Academy of Sciences,
Beijing 100085,
China
E-mail: *qchen@rcees.ac.cn*

Xiaoli Liu
College of Resources & Environment,
Hunan Agricultural University,
410128,
China

Qiuwen Chen
CEER,
Nanjing Hydraulics Research Institute,
Nanjing 210023,
China

Zhaoxia Zeng
Institute of Subtropical Agriculture,
Chinese Academy of Sciences,
410125,
China

INTRODUCTION

Non-point source (NPS) pollution export from agricultural lands is considered to be a major contributor to water quality degradation (Darnault & Ghannadi 2009; Liu *et al.* 2013). One effective control method is to implement agricultural conservation management (ACM) practices, which have often been called best management practices (BMPs) (Lam *et al.* 2011). ACM practices are structural, vegetative or cultural methods by which NPS pollutant exports are reduced to meet water quality criteria (Novotny 2003). While monitoring and modeling have been used mainly to estimate the NPS reduction efficiency of ACM, it has been found that modeling is comparatively more beneficial in assessing short- and long-term impacts of watershed-level ACM through scenario analysis (Ullrich & Volk 2009).

In this study, the Soil and Water Assessment Tool (SWAT) was applied to evaluate the environmental benefits of ACM in a typical small agricultural watershed in the black-soil region in northeast China. Many recent studies have employed SWAT to simulate NPS pollution at agricultural sub-watershed and watershed scales (Liu *et al.* 2013). The SWAT model has an established module for modeling the effects on water quantity and quality of different agricultural practices, including land use, changes in fertilizer and pesticide application, tillage operations, crop rotation, ponds, dams and riparian buffer strips (Arabi *et al.* 2006; Bracmort *et al.* 2006, Ullrich & Volk 2009; Boskidis *et al.* 2012).

It can be assumed that different crops can generate different NPS pollutant exports because of their spatial location and variable fertilizer demands. The geographical information system (GIS) interface of the model (AvSWAT; Di Luzio *et al.* 2002; Arabi *et al.* 2006) enables users to identify critical source areas, and facilitates the assessment of the spatial distribution of NPS pollution under different crops and fertilizer application rates (Arabi *et al.* 2006; Zhang & Zhang 2011). Thus, the SWAT model provided a viable platform to assess the effectiveness of ACM practices at watershed scales in improving the quality of receiving waters.

doi: 10.2166/wst.2014.076

As reported (Zeng *et al.* 2010), crop growth and yield formation can be affected by the field topography and soil properties, which can vary within small agricultural watersheds. The interaction of the typography and rainfall can cause differences in spatial and temporal topographical micro-climates, and particular attention should be paid to the sub-watershed scale of NPS pollutant exports (Zhou *et al.* 2012).

Black soil, which is mainly distributed in the northeast of China, is the most fertile soil type in the country; however, nitrate pollution of groundwater is becoming a serious issue in the black soil region (Zhao *et al.* 2008). The main objective of this study was to evaluate the nitrogen NPS load reductions through spatially optimized adjustment of the crop planting structure in a typical small agricultural watershed in the black soil region of northeast China.

MATERIALS AND METHODS

SWAT model description

The SWAT is a physically based, conceptual, continuous river basin model with spatially distributed parameters, which can operate at a daily time step and was designed to predict the impacts of various management practices on hydrological processes at the watershed scale (Arnold *et al.* 1998; Arnold & Fohrer 2005). The model is one of the most suitable models for predicting the impacts of land management on water, sediment, and agricultural nutrient NPS loads in complex watersheds with varying soils, land use, topography and agricultural operations (Arnold & Fohrer 2005; Behera & Panda 2006). The model integrates all relevant eco-hydrological processes including water flow, nutrient transport and turnover, vegetation growth, land use and management at the watershed scale. Furthermore, a watershed can be divided into sub-watersheds based on the number of tributaries (or user requirements). Sub-watersheds are further disaggregated into hydrological response units (HRUs). A HRU is a particular combination of land use, soil type and slope range. Surface runoff, nutrient loads, sediment yield, and management practices are simulated for each HRU and then routed to obtain the total water, sediment and nutrient yields (Neitsch *et al.* 2001). Surface runoff from daily rainfall is estimated using the Soil Conservation Service runoff curve number method, and sediment yield is calculated using the Modified Universal Soil Loss Equation (Williams & Berndt 1977; Nossent & Bauwens 2012). Interested readers are referred to Arnold *et al.* (1998) and Arnold & Fohrer (2005) for a detailed description of the components and theories of the SWAT model.

ACM scenario presentation

The SWAT model has been widely and successfully used in agricultural NPS pollution mitigation studies for different optimized agricultural management practices in China (Zeng *et al.* 2010, Liu *et al.* 2013). As the name suggests, NPS pollution is difficult to characterize and control due to its spatio-temporal heterogeneity and complexity. ACM practices have been proposed as effective ways to reduce nutrient loads, which can be a major contributor of pollutants to aquatic systems (Easton *et al.* 2008; Rao *et al.* 2009; Zeng *et al.* 2010, Liu *et al.* 2013). The factors that influence NPS pollutant exports include land use, conservation tillage, fertilizer management, vegetative buffer strips, etc. It is time-consuming and unnecessary to simulate all factors, but it is important to identify the primary critical factors. This research only focused on the land-use components of the SWAT model. It was assumed that croplands situated in different landscapes within a watershed would give variable NPS exports with different crop coverage and different chemical fertilizer demands. In this study, the interest was in the spatial adjustment of crop planting as an ACM practice to reduce nitrogen NPS exports from a typical small agricultural watershed in the black soil region, northeast China.

Model performance evaluation

The performance of the SWAT model was evaluated using statistical methods to determine the quality of the model predictions when compared to the observed values. The coefficient of determination (R^2, Equation (1)) and Nash–Sutcliffe coefficient of efficiency (E_{NS}, Equation (2)) (Nash & Sutcliffe 1970) were used to evaluate the goodness of fit of the model calibration

$$R^2 = \frac{\left[\sum_{i=1}^{n}\left(Q_{\mathrm{o}}^{i} - \bar{Q}_{\mathrm{o}}\right)\left(Q_{\mathrm{s}}^{i} - \bar{Q}_{\mathrm{s}}\right)\right]^2}{\sum_{i=1}^{n}\left(Q_{\mathrm{o}}^{i} - \bar{Q}_{\mathrm{o}}\right)^2 \sum_{i=1}^{n}\left(Q_{\mathrm{s}}^{i} - \bar{Q}_{\mathrm{s}}\right)^2} \tag{1}$$

$$E_{\mathrm{NS}} = 1 - \frac{\sum_{i=1}^{n}\left(Q_{\mathrm{o}}^{i} - Q_{\mathrm{s}}^{i}\right)^2}{\sum_{i=1}^{n}\left(Q_{\mathrm{o}}^{i} - \bar{Q}_{\mathrm{o}}\right)^2} \tag{2}$$

where n is the number of observations, Q_{o}^{i} and Q_{s}^{i} are observed and simulated values, $\bar{Q}_{\mathrm{o}}$ and $\bar{Q}_{\mathrm{s}}$ are the arithmetic means of observed and simulated values. The R^2 measured how accurately the SWAT model captured the variation of the observed values, and R^2 above 0.5 is often considered to have acceptable performance (Green & van Griensven 2008). The closer the E_{NS} value is to 1.0, the better is the model performance when comparing simulation results to observed values. $E_{NS} \geq 0.75$ is considered to be an excellent estimation and E_{NS} between 0.75 and 0.36 is regarded to be satisfactory (Motovilov *et al.* 1999). The difference between E_{NS} and R^2 is that E_{NS} can interpret model performance in replicating individually observed values, while R^2 cannot.

Study site and model input data

The study site is a 12.9 km^2 enclosed agricultural watershed located in Hailun City, Heilongjiang Province, northeast China. It is about 4.0 km from the Hailun Agroecology Station (47°26′N, 126°38′E, altitude 240 m). The terrain is dominated by gentle hills (Figure 1). Our previous study (Zeng *et al.* 2010) in the same area showed that highlands in small agricultural watersheds have more terrain scenery and a gentler slope than slope-lands and lowlands, and slope-lands have the largest slope among the three landscapes.

The SWAT version 2005 (embedded within ArcGIS software named ArcSWAT) was used in this study. The required model input data include digital topography, climate, land management and coverage, and soil properties.

Soil classes of the three typical landscapes (Figure 1) were sampled and measured in the laboratory to obtain the necessary soil physico-chemical parameters for the SWAT model. The watershed was divided into 20 sub-catchments by manually adding outlets according to different actual crop coverage and landscape characteristics (Figure 1) to identify the spatial distribution of NPS pollution exports. Seventeen, 15, and 11 soil samples of 0–80 cm depth at 20 cm increment were collected and analyzed from highland, slope-land and lowland, respectively (Figure 1) to obtain all necessary parameters such as soil physical and chemical properties of different landscapes.

On-site daily measured precipitation was input into the SWAT model. Other meteorological data sets such as solar radiation, minimum and maximum temperatures, relative humidity and wind speed were obtained from the Hailun Agroecology Meteorological Station.

Land-use and field management measures including fertilization and weed tillage practices were recorded and input into the SWAT model. The N fertilizer (urea) was applied at 75 kg/ha, in early May each year (input on 10 May 2006 and 10 May 2007). Additional N (urea) fertilizer was applied at a 15 cm soil depth with a handle hill-drop machine in corn lands at a density of 75 kg/ha, in late June (input on 22 June 2006 and 22 June 2007). Two chisel-tillage practices

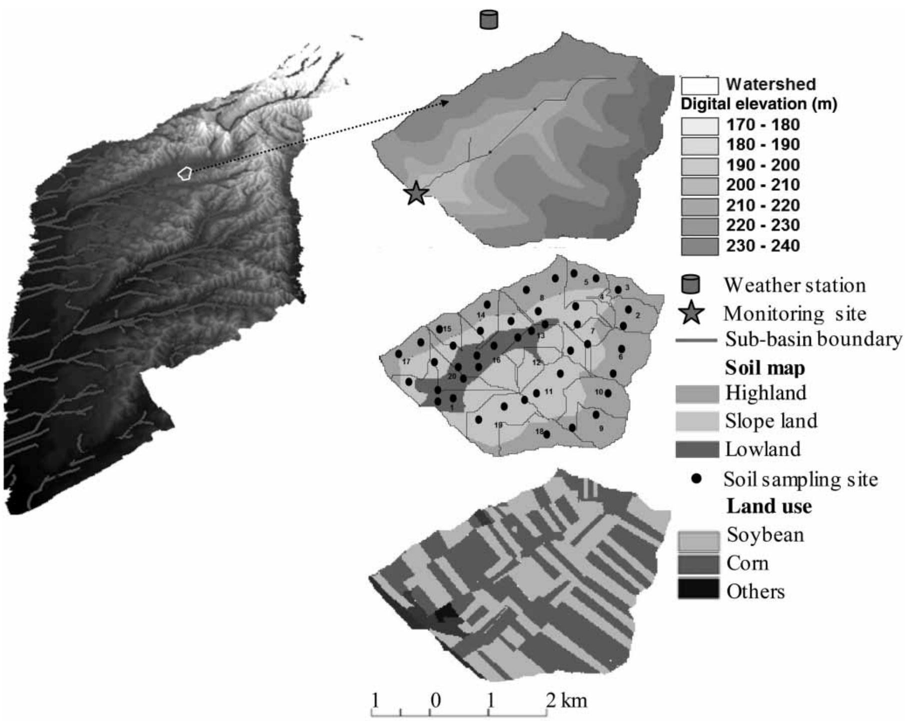

Figure 1 | Soil class, land use, and watershed subdivision of the study watershed.

were implemented on 7 June 2006, 20 June 2006, 7 June 2007 and 20 June 2007 for weeding.

Water samples were collected weekly at the outlet of the watershed (Figure 1) from May to October of 2006 and 2007. Daily water samples were taken at the outlet of the watershed during rainfall events in the periods. The water samples were stored in an ice chest after being acidified to pH < 2 by sulfuric acid *in situ*, and then transported to the laboratory in the Hailun Agroecology Station. The samples were kept below 4 °C for further analysis. The analysis work was completed within 48 hours. Sample pretreatment and determination of NO_3-N and total nitrogen (TN) were both conducted following national standard methods (NEPB 2002). NO_3-N was measured by UV spectrophotometry. The water samples were filtered with MF-Millipore nylon membrane filters (0.45 μm pore size), and absorbance of 220 and 275 nm wavelength was measured respectively, and then the NO_3-N contents were obtained referring to standard curve formulation. TN was analyzed using the alkaline potassium persulfate digestion–UV spectrophotometry method. The water samples were sealed in colorimetric tubes after alkaline potassium persulfate solution addition and were kept in a medical sterilizer at 120–124 °C for half an hour. After shaking, the absorbance of 220 and 275 nm wavelength was measured, and the TN concentration was obtained by referring to the standard curve. The weekly data and daily data were merged before use.

RESULTS

Model calibration and validation

The flow and water quality data observed from May 2006 to October 2006 were used to calibrate the model. The values of the SURLAG, EPCO, N, CN2, SOL_AWC, SOL_NO_3 and NPERCO parameters were calibrated as given in Table 1. These values were adopted for assessment purposes.

The observed and simulated stream flows from the watershed were compared in Figure 2 for the model calibration period (May 2006 to October 2006) and validation period (May 2007 to October 2007). The E_{NS} and R^2 values of 0.58 and 0.64 respectively for calibration, and 0.51 and 0.53 respectively for validation were all higher than 0.5, indicating the satisfactory performance of the SWAT model in predicting stream flow, notwithstanding that the peaks of stream flow simulated by the SWAT model were lower than the observed values (Figure 2).

In this study, TN and nitrate-nitrogen (NO_3-N) that can impact on receiving water quality were selected as key pollutants. The same indexes were used for both calibration and validation of the SWAT model; i.e. observed data from May 2006 to October 2006 were used to calibrate the model, and observed data from May 2007 to October 2007 were used to validate the model. As shown in Figure 3, a comparable level of agreement was achieved in general for TN and nitrate-nitrogen. The E_{NS} and R^2 values of TN from May 2006 to October 2006 were 0.69 and 0.78, respectively, obviously higher than the values of 0.45–0.49 and 0.49–0.51 in the other period (Figure 3). The E_{NS} values of both calibration and validation periods were between 0.75 and 0.36, and R^2 values were mostly above 0.5, which meant that a satisfactory fitness was achieved between predicted values and observations.

Spatial nitrate NPS loads under different crops and landscapes

In all landscapes, the TN and NO_3-N exports from cornfield were larger than those from soybean fields within the same landscape (Table 2) because of higher rates of fertilizer application. The N application rates of corn and soybean fields were 75 and 150 kg/ha, respectively, according to the crop

Table 1 | Calibrated values of key SWAT parameters

Parameter	Meaning	Initial value	Calibrated value
SURLAG	Surface lag for runoff	4	3
EPCO	Plant uptake compensation factor	1	0.85
ESCO	Soil evaporation compensation factor	1	0.5
N	Manning's n for channels	0.025	0.02
CN2	Runoff curve number	70	65
SOL_AWC	Available water capacity of the soil layer	0.6	0.8
SOL_NO_3	Initial NO_3 concentration (mg/kg) in the soil layer	2.3 (measured value)	–
NPERCO	Nitrate percolation coefficient	0.5	1

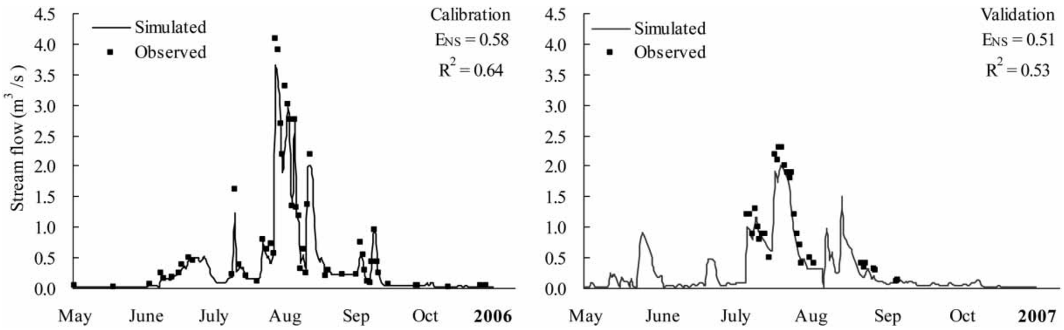

Figure 2 | Streamflow calibration and validation results.

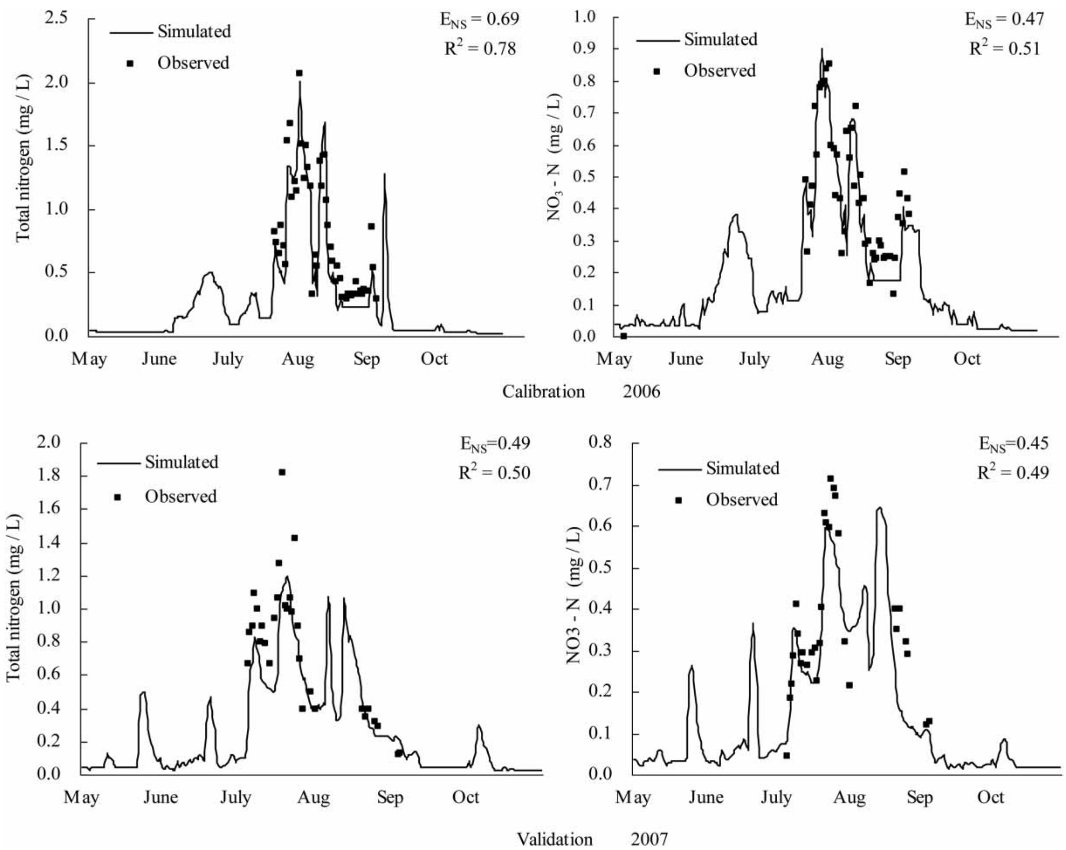

Figure 3 | Total nitrogen and nitrate-nitrogen calibration and validation results.

growing requirement and local traditional management practice. The exports of TN and NO_3-N from both cornfields and soybean fields increased inversely with altitude, i.e. exports from highlands were less than exports from slope-lands, which were less than those from lowlands (Table 2).

ACM scenario

A scenario based on the spatially optimized adjustment of crop plantings was assessed. It was based on converting soybean crops into corn crops in highland areas, and converting corn crops into soybean crops in lowland areas (Figure 4).

The changes in total crop planting area are listed in Table 3. Areas of soybeans before and after the ACM scenario were 669 and 654 ha respectively, and those of corn were 621 and 636 respectively. The total areas of soybean and corn planting over the whole small agricultural watershed were maintained, and the changes before and after ACM scenario implementations were slight. The total

Table 2 | Nitrogen NPS exports under two different crops and three landscapes

Crop	Landscape	NO_3-N (kg/(ha·yr))	Total N (kg/(ha·yr))
	Highland	1.09	3.13
Soybean	Slope-land	1.85	5.23
	Lowland	2.93	7.32
	Highland	1.64	3.98
Corn	Slope-land	2.59	7.78
	Lowland	3.48	9.81

amount of N application slightly increased from 143.325 t before ACM to 144.450 t after ACM due change of 15 ha cornfield into soybean field under the proposed ACM scenario (Table 3).

Effects of ACM scenario on nitrogen NPS loading

As shown in Table 3, the ACM practice, which converts cornfield in slope-land and lowland into soybean field and correspondingly converts soybean field in highland into cornfield, would not distinctly alter the total area of the two main crops in the study watershed. The effectiveness of the ACM practice with regard to nitrogen NPS pollutant exports was evaluated using the SWAT model, and the results are presented in Figure 5. It was observed that TN and NO_3-N concentrations in the stream flow under the ACM practice would be lower than the current condition (Figure 5). The total NO_3-N exports of the whole watershed before and after the ACM scenario were 2322 and 6326 kg/yr respectively, and TN exports were 6326 and 5722 kg/yr respectively. This resulted in a reduction of annual exports of NO_3-N and TN of 9.5% and 10.7%, even though the total amount of fertilizer application increased slightly by 1125 kg under the ACM scenario.

Table 3 | Watershed characteristics and current and proposed land use

Characteristic	Current	Proposed
Soybean (ha)	668.7	653.9
Corn (ha)	621.0	635.8
Others (ha)	7.8	7.8
Total area (ha)	1297.5	1297.5
Maximum elevation (m)	249.5	
Minimum elevation (m)	220.3	
Average elevation (m)	232.7	
Average slope (%)	7.8	
Annual precipitation (mm)	592.6	

DISCUSSION

To alleviate the impacts of agricultural activities on water quality, it is usually proposed to reduce the crop area or farming intensity in watersheds. Management practices based on modified fertilization, tillage practices, vegetative buffer strips, etc. have also been widely applied to control NPS pollutant exports from farmland (Behera & Panda 2006; Ullrich & Volk 2009; Liu *et al.* 2013). However, land-use scenarios in previous studies have mainly been concerned with changes of arable and vegetable land components (Zeng *et al.* 2010; Liu *et al.* 2013). Few studies have considered the re-distribution of crops to maintain grain yields while improving water quality.

Liu *et al.* (2013) illustrated that the conversion of high slope cropland into forests can reduce nitrogen and phosphorous NPS pollutant exports. Our previous study in the same area showed that lowland soils in the agricultural watershed had the highest nutrient concentrations compared with other landscapes (Fang *et al.* 2005; Zeng *et al.* 2010). The

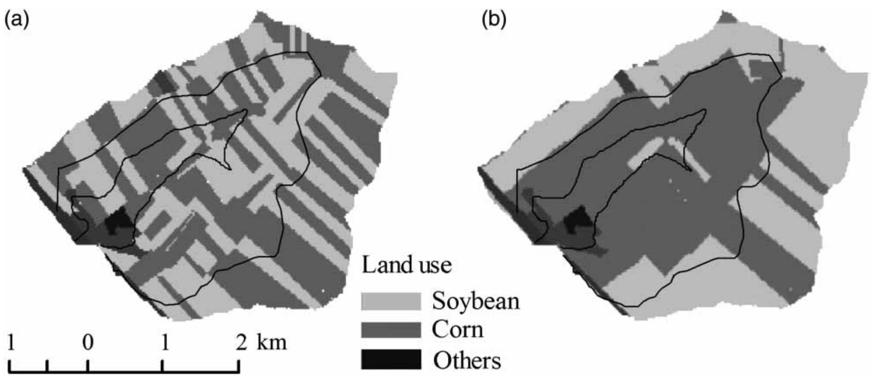

Figure 4 | Current land-use (a) and proposed land-use (b) scenarios.

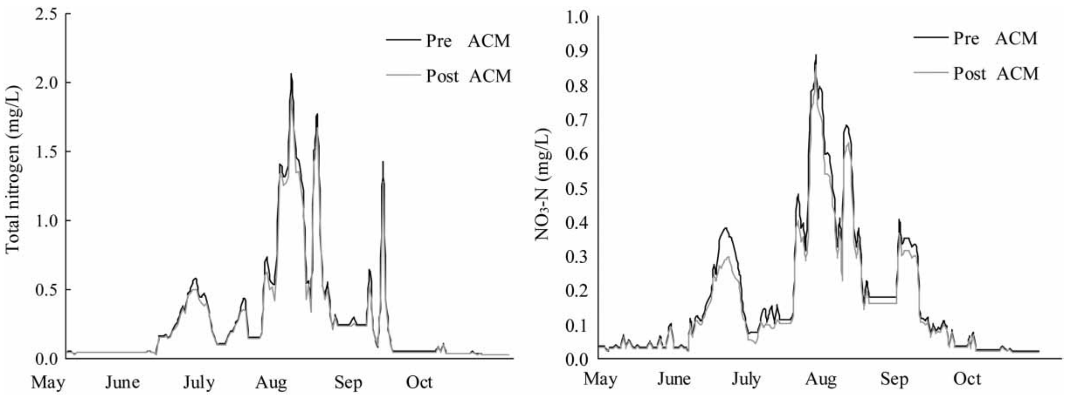

Figure 5 | Comparison of total nitrogen and nitrate nitrogen concentrations for the period from May 2006 to October 2006.

results in this study indicated that lowland had the highest nitrogen exports than slope-lands and highlands, even though it had the mildest slope (Table 2). Comparatively, cornfield in lowland showed higher NPS nitrate export risk than soybean field because of more chemical fertilizer demand (Table 2). Therefore, the spatial adjustment of crop plantings within the agricultural watershed based on the NPS pollutant exports offers a way to mitigate potential NPS pollution without reducing the total crop coverage and grain yield.

CONCLUSIONS

The eco-hydrological SWAT model was used to simulate stream flow and nitrogen exports from a typical small agricultural watershed, in the most fertile black-soil region in northeast China. The model was calibrated and validated against observed stream flows and nitrate-nitrogen and TN concentrations. After validation, the model was used to assess the impact of converting soybean fields into cornfields in highland areas and converting cornfields into soybean fields in lowland. This spatial adjustment would lead to no more than 5% change in the overall areas of corn and soybean crops within the watershed, but would result in reductions of 9.5% NO_3-N exports and 10.7% TN exports annually. It can be concluded that the re-distribution of crops within a watershed can maintain grain yields while improving the water quality in receiving waters.

ACKNOWLEDGEMENT

This research was sponsored by the National Natural Scientific Foundation of China (51279196 and 31100329).

REFERENCES

Arabi, M., Govindaraju, R. S. & Hantush, M. M. 2006 Role of watershed subdivision on evaluation of long-term impact of best management practices on water quality. *Journal of the American Water Resources Association* **42** (2), 513–528.

Arnold, J. G. & Fohrer, N. 2005 SWAT2000: current capabilities and research opportunities in applied watershed modelling. *Hydrology Process* **19** (3), 563–572.

Arnold, J. G., Srinivasan, R., Muttiah, R. S. & Williams, J. R. 1998 Large-area hydrologic modeling and assessment: Part I. Model development. *Journal of American Water Resource Association* **34** (1), 73–89.

Behera, S. & Panda, R. K. 2006 Evaluation of management alternatives for an agricultural watershed in a sub-humid subtropical region using a physical process based model. *Agriculture Ecosystem & Environment* **113** (1–4), 62–72.

Boskidis, I., Gikas, G. D., Sylaios, G. K. & Tsihrintzis, V. A. 2012 Hydrologic and water quality modeling of lower Nestos River basin. *Water Resources Management* **26** (10), 3023–3051.

Bracmort, K. S., Arabi, M., Frankenberger, J. R., Engel, B. A. & Arnold, J. G. 2006 Modelling long-term water quality impact of structural BMPs. *Transactions of the ASAE* **49** (2), 367–374.

Darnault, C. J. G. & Ghannadi, S. K. 2009 Fate of environmental pollutants. *Water Environment Research* **81** (10), 2019–2029.

Di Luzio, M., Srinivasan, R. & Arnold, J. G. 2002 Integration of watershed tools and SWAT model into BASINS. *Journal of the American Water Resource Association* **38** (4), 1127–1141.

Easton, Z. M., Walter, M. T. & Steenhuis, T. S. 2008 Combined monitoring and modeling indicate the most effective agricultural best management practices. *Journal of Environmental Quality* **37** (5), 1798–1809.

Fang, H. J., Yang, X. M., Zhang, X. P. & Liang, A. Z. 2005 Study on soil erosion and deposition of black soils on a sloping cultivated land using 137Cs tracer method. *Acta Ecologica Sinica* **25** (6), 1376–1382 (in Chinese with English abstract).

Green, C. H. & van Griensven, A. 2008 Autocalibration in hydrologic modeling: Using SWAT2005 in small-scale watersheds. *Environmental Modelling & Software* **23**, 422–434.

Lam, Q. D., Schmalz, B. & Fohrer, N. 2011 The impact of agricultural Best Management Practices on water quality in a North German lowland catchment. *Environment Monitoring and Assessment* **183** (1–4), 351–379.
Liu, R. M., Zhang, P. P., Wang, X. J., Chen, Y. X. & Shen, Z. Y. 2013 Assessment of effects of best management practices on agricultural non-point source pollution in Xiangxi River watershed. *Agricultural Water Management* **117**, 9–18.
Motovilov, Y. G., Gottschalk, L., Engeland, K. & Rodhe, A. 1999 Validation of a distributed hydrological model against spatial observations. *Agricultural and Forest Meteorology* **98–99**, 257–277.
Nash, J. E. & Sutcliffe, J. V. 1970 River flow forecasting through conceptual models part I: a discussion of principles. *Journal of Hydrology* **10** (3), 282–290.
National Environmental Protection Bureau (NEPB). 2002 *Standard Methods for the Examination of Water and Wastewater (Version 4)*. China Environmental Science Publish Press, Beijing (in Chinese).
Neitsch, S. L., Arnold, J. C., Kiniry, J. R. & Williams, J. R. 2001 *Soil and Water Assessment Tool User's Manual: Version 2000*. Blackland Research Center, Texas Agricultural Experiment Station, Temple, Texas, USA.
Nossent, J. & Bauwens, W. 2012 Multi-variable sensitivity and identifiability analysis for a complex environmental model in view of integrated water quantity and water quality modeling. *Water Science and Technology* **65** (3), 539–549.
Novotny, V. 2003 *Water Quality: Diffuse Pollution and Watershed Management*. 2nd edn, John Wiley, New York, USA.
Rao, N. S., Easton, Z. M., Schneiderman, E. M., Zion, M. S., Lee, D. R. & Steenhuis, T. S. 2009 Modeling watershed-scale effectiveness of agricultural best management practices to reduce phosphorus loading. *Journal of Environmental Management* **90** (3), 1385–1395.
Ullrich, A. & Volk, M. 2009 Application of the Soil and Water Assessment Tool (SWAT) to predict the impact of alternative management practices on water quality and quantity. *Agricultural Water Management* **96** (8), 1207–1217.
Williams, J. R. & Berndt, H. D. 1977 Sediment yield prediction based on watershed hydrology. *Transactions of the American Society of Agricultural Engineers* **20** (6), 1100–1104.
Zeng, Z. X., Liu, X. L., Wang, K. L., Zeng, F. P., Song, T. Q. & Song, X. J. 2010 Strategy of grain yield stability cooperated with harmonious water environment quality of small agricultural watershed. *Environmental Science* **31** (8), 1784–1788 (in Chinese with English abstract).
Zhang, X. Y. & Zhang, M. H. 2011 Modeling effectiveness of agricultural BMPs to reduce sediment load and organophosphate pesticides in surface runoff. *Science of the Total Environment* **409** (10), 1949–1958.
Zhao, X. F., Yang, L. R., Shi, Q., Ma, Y., Zhang, Y. Y., Chen, L. D. & Zheng, H. F. 2008 Nitrate pollution in groundwater for drinking and its affecting factors in Hailun, northeast China. *Environmental Science* **29** (11), 2993–2998 (in Chinese with English abstract).
Zhou, T., Wu, J. G. & Peng, S. L. 2012 Assessing the effects of landscape pattern on river water quality at multiple scales: A case study of the Dongjiang River watershed, China. *Ecological Indicators* **23**, 166–175.

First received 24 October 2013; accepted in revised form 29 January 2014. Available online 11 February 2014