Cost-effectiveness and cost-benefit analysis of BMPs in controlling agricultural nonpoint source pollution in China based on the SWAT model

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Abstract Best management practices (BMPs) have been widely used in managing agricultural nonpoint source pollution (ANSP) at the watershed level. Most BMPs are related to land use, tillage management, and fertilizer levels. In total, seven BMP scenarios (Reforest1, Reforest2, No Tillage, Contour tillage, and fertilizer level 1–4) that are related to these three factors were estimated in this study. The objectives were to investigate the effectiveness and cost-benefit of these BMPs on ANSP reduction in a large tributary of the Three Gorges Reservoir (TGR) in China, which are based on the simulation results of the Soil and Water Assessment Tool (SWAT) model. The results indicated that reforestation was the most economically efficient of all BMPs, and its net benefits were up to CNY $4.36×10^7$ years^{-1} (about USD $7.08×10^6$ years^{-1}). Regarding tillage practices, no tillage practice was more environmentally friendly than other tillage practices, and contour tillage was more economically efficient. Reducing the local fertilizer level to 0.8-fold less than that of 2010 can yield a satisfactory environmental and economic efficiency. Reforestation and fertilizer management were more effective in reducing total phosphorus (TP), whereas tillage management was more effective in reducing total nitrogen (TN). When CNY 10,000 (about USD 162) was applied to reforestation, no tillage, contour tillage,

and an 0.8-fold reduction in the fertilizer level, then annual TN load can be reduced by 0.08, 0.16, 0.11, and 0.04 t and annual TP load can be reduced by 0.04, 0.02, 0.01 and 0.03 t, respectively. The cost-benefit (CB) ratios of the BMPs were as follows: reforestation (207 %) > contour tillage (129 %) > no tillage (114 %) > fertilizer management (96 and 89 %). The most economical and effective BMPs can be designated as follows: BMP1 (returning arable land with slopes greater than 25° to forests and those lands with slopes of 15–25° to orchards), BMP2 (implementing no tillage on arable land with slopes less than 15°), and BMP5 (0.8-fold less than that of 2010).

Introduction

Nonpoint source (NPS) pollution is a worldwide problem (Novotny 1999), which is primarily caused by local agricultural activities (Esen and Uslu 2008; Pandey et al. 2009; Tian et al. 2010; Lai et al. 2011). With the increasing importance of pollution prevention and the protection of natural water resources, many studies have been conducted on the control of agricultural nonpoint source pollution (ANSP) (Ouyang et al. 2010).

Among the measures to reduce ANSP, best management practices (BMPs) have proven to be a useful tool to control ANSP (Ice 2011). Recent developments in BMP

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optimization strategies (Veith et al. 2004; Gitau et al. 2006; Maringanti et al. 2009) and water quality models (Arnold et al. 1998; Tolson and Shoemaker 2007; Peng et al. 2011; Shen et al. 2012) have further improved the feasibility of implementing BMPs on large watersheds. However, managing ANSP at the watershed level is still an ongoing challenge, where trade-offs between environmental and economic objectives must be considered.

Many studies have evaluated the effectiveness of BMPs with a single objective or multiple objectives, such as those focused on the European response to the call for the Water Framework Directive (WFD) (Panagopoulos et al. 2012). Among all the single objective studies, part of these studies put an emphasis on the least cost objectives to selecting BMPs (Yang et al. 2003, 2005; Rashford and Adams 2007; Fröschl et al. 2008), and the other studies pursued the maximum environmental/economic benefits (Azzaino et al. 2002; Ancev et al. 2008). Because of the complex interactions among environmental factors, as well as constraints on local resources, the efficiency of implementing BMPs is largely site-specific.

The primary purpose of implementing BMPs is to reduce pollutants; therefore, many studies mainly focused on assessing the environmental effectiveness of BMPs (Arabi et al. 2006; Brlund et al. 2007; Sahu and Gu 2009; Lam et al. 2011). Furthermore, there were also many studies that evaluated the cost-effectiveness of BMPs with various stormwater models and methodologies because the cost of implementing BMPs limits their practical application (Gassman et al. 2006; Strauss et al. 2007; Guto et al. 2011; Panagopoulos et al. 2011). An experiment that was conducted by the US Department of Agriculture on an experimental watershed in Pennsylvania demonstrated that BMPs reduced pollutant loads by as much as 56 % and increased the net income by 109 % annually (Srivastava et al. 2002). Some researchers discovered that BMPs might become highly efficient at alleviating ANSP when some BMPs were used together (Zhang and Zhang 2011).

Except the environmental effectiveness of BMPs, benefit of BMPs was not neglected either. Agricultural BMPs cannot be implemented successfully without the support of farmers because the associated costs of implementing BMPs are generally high, and this high cost might deter farmers from using these methods. The importance of farmers in reducing ANSP loads has been discussed abroad (Grolleau and McCann 2012). However, most previous studies in China mainly focused on environmental effectiveness, and few studies considered the balance of ANSP control and farmers' interests (Shang et al. 2012).

China is a developing country, and the demand for food and resources is extraordinary due to its enormous population. Therefore, the impact of farmers on implementing BMPs is great, particularly in China. Indeed, farmers are not likely to adopt BMPs to control ANSP if they cannot obtain some compensation (Gong et al. 2010). To protect the environment, it is necessary to perform a cost-benefit analysis of BMPs to assist decision-makers with planning to provide the greatest level of environmental protection with limited resources and funding.

Additionally, previous studies have always ignored landowner opportunity costs, which could lead to a substantial underestimation of the true social costs (Trenholm et al. 2013). Opportunity cost is an important consideration in analyzing any potential BMP to reduce pollution. The landowner's willingness-to-accept (WTA) is bounded below by opportunity costs because a landowner will not accept a value of BMPs that is less than the value that can be achieved through continued production (Lennox et al. 2013).

The Xiangxi River watershed was selected as the study area. The objectives of this study were to evaluate the cost-effectiveness and cost-benefit of BMPs in reducing ANSP while considering the detailed cost and economic returns and, ultimately, identifying the most environmental and economic BMPs, which are based on the Soil and Water Assessment Tool (SWAT) model. The results will provide the information that is necessary to aid in decision-making for reducing pollution at an affordable cost in the Xiangxi River watershed.

Materials and methods

Site description

The Xiangxi River, which is 94-km long with a catchment area of 3099 km^2, is one of the main tributaries of the Yangtze River in the Three Gorges Reservoir (TGR), with the shortest distance from the Three Gorges Project Dam (Fig. 1). The main agriculture crops are rice and wheat in the valleys. Terraced fields are often used for corn, potatoes, and tea (Xu et al. 2010).

The Three Gorges region is a rapidly developing area. Since the impoundment of TGR in 2003, the
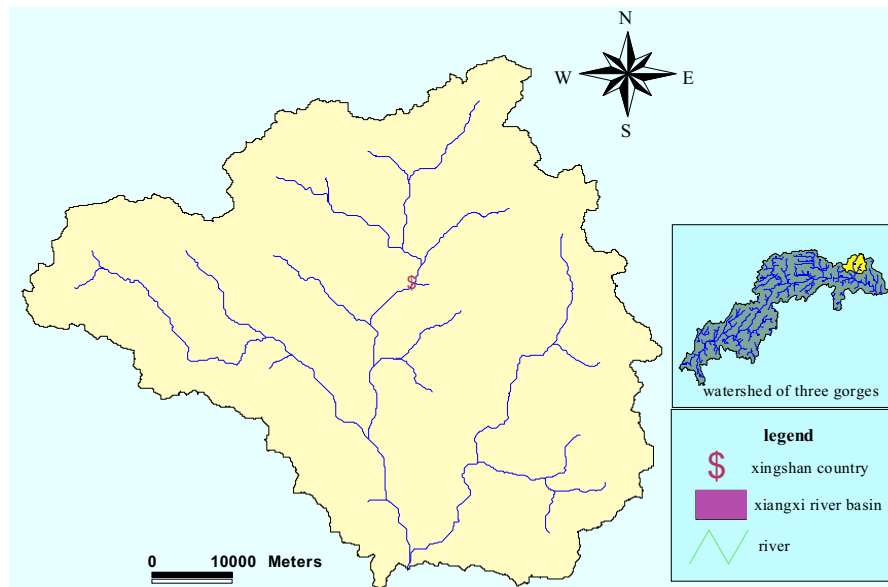
Fig. 1 Location of Xiangxi River watershed

pollution and algal blooms that occur within certain branches of the reservoir have attracted much attention from society (Tian et al. 2010). For the relatively intense agricultural activities and irrational land use patterns, ANSP has proven to be one of the main sources (Liu and Wang 2009; Shen et al. 2010). Studies have focused on reducing ANSP in the TGR (Shen et al. 2010; Wu et al. 2010; Wang et al. 2011).

SWAT model

The SWAT, which is an important semidistributed, process-oriented hydrological model, was used to simulate the ANSP in this study.

The sensitivity analysis was conducted to find the most sensitive parameters for the modeling output and to be employed in the calibration process. Latin hypercube one-factor-at-a-time (LH-OAT) sampling (van Griensven and Meixner 2006) was employed to determine the parameter sensitivity to stream flow, TN, and TP. The sequential uncertainty fitting algorithm (SUFI-2) was used for calibration and uncertainty analysis (Abbaspour et al. 2007; Yang et al. 2008). This algorithm proved that 3 to 5 years of data were enough for ideal calibration and validation (Moriasi et al. 2007).

Nash–Sutcliff and R^2 were the evaluation indicators, which were calculated by the following Eqs. (1) and (2) (Liu et al. 2013):

$$R^2 = \frac{\left[\sum_{i=1}^{n}\left(O_i - \overline{O}\right)\left(P_i - \overline{P}\right)\right]^2}{\sum_{i=1}^{n}\left(O_i - \overline{O}\right)^2 \sum_{i=1}^{n}\left(P_i - \overline{P}\right)^2} \quad (1)$$

$$E_{NS} = \frac{\sum_{i=1}^{n}\left(O_i - \overline{O}\right)^2 - \sum_{i=1}^{n}\left(P_i - O_i\right)^2}{\sum\left(O_i - \overline{O}\right)^2} \quad (2)$$

where n is the number of observations, O_i and P_i are the observed and predicted values at each comparison point i, respectively, and $\overline{O}$ and $\overline{P}$ are the arithmetic means of observed and predicted values, respectively.

Input data

The basic database included the digital elevation model (DEM), soil and land-use data (2010), land management data (2010), climate data (2000–2010), water quality data, and water quantity data (2002–2010) of the Xiangxi River.

Landsat 5 TM (30-m resolution) satellite imagery was analyzed to produce land-use data. Forests, dry lands, and grasslands were the main land-use types, and forests accounted for 87.37 % of the total study area. Crop management practices included planting, fertilizing, irrigating, and harvesting. In this study, current crop management practices and the fertilizer application for the main crops in the study area were

determined by surveying local agricultural authorities and farmers in 2010.

Cost-effectiveness and cost-benefit analysis

Land use, tillage management, and fertilizer levels were the key factors that significantly influenced the ANSP of the Xiangxi River watershed (Liu et al. 2013); therefore, in this study, seven scenarios of BMPs that were related to these factors were selected to evaluate the cost-effectiveness and the cost-benefit (Table 1). Conventional management practices that were employed in the model assessment were not included in the economic assessment because these practices served as a background. The simulation background included background for the reforestation region (BR) and for the tillage region (BT). The water quality meets the Quality Standard for Surface Water of China (GB 3838–2002) after using BMPs.

For land-use management, the costs of reverting farmlands back into forests and orchards were divided into three parts: economic loss that would be caused by the reduction of crop yields, construction costs, and maintenance costs. The farmers' economic loss that would be caused by the reduction of crop yields can be calculated by opportunity cost, which is the grain income if the same field remains used to grow crops. The grain income can be calculated by:

$$F = Y \times (1 + R) \times a \times P \qquad (3)$$

where F indicates the farmers' income from grains, Y stands for the crop yields, R is the increased rate of crop yield, a is the total cropped area, and P is the price of grains.

The construction and maintenance costs of soil and water conservation forests (SWCFs) and economic forests (EFs) can be calculated by:

$$C = \sum B_{ij} \times A_j \qquad (4)$$

where C indicates the total construction and maintenance costs of SWCFs and EFs, I indicates construction or maintenance, j indicates SWCFs or EFs, B_{ij} stands for the construction or maintenance cost of SWCFs or EFs (Yang et al. 2002), and A_i represents the area of SWCFs or EFs.

Concerning the costs of fertilizer and tillage management, the calculation equation is:

$$C'_n = (I + D_n) \times a \qquad (5)$$

where C'_n indicates the total costs of fertilizer or tillage management in all cropped areas, n indicates fertilizer or tillage management, I represents the per-acre cost of conventional tillage, D_n represents the difference in values of fertilizer or tillage management compared with conventional tillage, and a is the total cropped area.

The impact of BMPs on nutrient yield was termed the environmental effectiveness, and the mean annual nutrient yields of all BMP scenarios were simulated by the SWAT model. The benefits included the direct yield return and the indirect soil erosion benefit value from reducing soil loss. The direct yield return included only the income of grains and could be calculated using Eq. (3).

The benefits from the reduction of nutrients that are lost can be calculated by defensive expenditures, which were widely used to estimate the value of environmental public goods (Antoci et al. 2005; Escofet and Bravo-Pena 2007; Antoci and Borghesi 2010; Dupont and Jahan 2012). If nutrients are lost from the soil, then more chemical fertilizers will be required to maintain soil fertility (Bartik 1988; Hamilton 1994; Tiezzi 2002). Therefore, the value of nutrients reduction by BMPs can be calculated through the cost of additional chemical fertilizers if BMPs are not applied by farmers. The formula is as follows:

$$E_m = T_m \times S_m \times P_m \qquad (6)$$

where E_m is the loss of TN or TP, m represents TN or TP, T is the total nutrient loss of ANSP in the study area, S_m is the coefficient of TN or TP that is converted to diammonium phosphate (DAP), and P_m is the price of DAP.

DAP, which is usually used as a fertilizer by local farmers, was selected as the conversion intermediary. The conversion rates for TN and TP into DAP were 28/132 and 31/132, respectively, and the P concentration was higher than N in DAP. In addition, the TN loss was generally larger than TP in the study area. Thus, the environmental benefits can be calculated only by the benefits of TN that are preserved by the BMPs.

In total, the cost-effectiveness ratio (CE) and cost-benefit ratio (CB) of each BMP were calculated by:

Effectiveness / Cost ratio

$$= \text{environmental effect} / \text{total cost} \qquad (7)$$

Benefit / Cost ratio $=$ net benefits / total cost $\qquad (8)$

Table 1 The scenarios and simulation results of BMPs based on SWAT model

BMP	Descriptions	Area (acre)	Cost (CNY/year/acre)	Simulation results (t/year)	
				TN	TP
BMP1	Reforest1[a]	11,963	3383	389	103
	Reforest2[a]		4486		
BMP2	NT (no tillage on slopes below 15°)	33,328	963	1061	210
BMP3	CT (contour tillage on slopes below 15°)	33,328	1077	1154	218
BMP4	0.5 times of fertilizer level in 2010	33,328	820	780	161
BMP5	0.8 times of fertilizer level in 2010	33,328	948	1217	186
BMP6	1.3 times of fertilizer level in 2010	33,328	1160	1872	358
BMP7	1.5 times of fertilizer level in 2010	33,328	1245	2231	409
BR	Background for reforest region	11,963	1231	557	186
BT	Background for tillage region	33,328	1033	1560	269

[a] Reforest1 means returning farmland with slopes >25° to ecological forest and reforest2 means returning farmland with slopes of 15–25° to orchards

Results and discussion

Model simulation results

Based on the sensitivity analysis, CN2 (SCS runoff curve number) and ALPHA-BF (base flow recession constant) were highly sensitive to flow, TN, and TP. Additionally, ESCO (soil evaporation compensation factor), CANMX (maximum canopy storage), and TIMP (snow pack temperature lag factor) were more sensitive to flow; nitrogen percolation coefficient (NPERCO) and surface runoff lag time (SURLAG) were more sensitive to TN; and TIMP and phosphorus percolation coefficient (PPERCO) were more sensitive to TP. These parameters were employed in the following calibration process.

The calibration and validation were performed based on the monthly observed flow and TN data from 2006/1 to 2010/12, whereas TP data were from 2007/1 to 2010/12 (Fig. 2). The calibration period was from 2006/1 to 2008/12, and the validation period was from 2009/1 to 2010/12 in this study. All the R^2 were larger than 0.8, and E_{NS} was larger than 0.7. Therefore, the results were considered "satisfactory" in reference to the guidelines that were developed by Moriasi et al. (2007).

The description, application area, unit cost, and simulation results of selected BMPs scenarios can be found in Table 1. In the Xiangxi River watershed,

there were 11,963 acres of farmland that might implement BMP1, and there were 33,328 acres of farmland that might implement BMP1–BMP7. In 2010, the simulated loads of TN and TP in these areas were 2117 and 455 t, respectively. With the implementation of land-use management, the reforestation effectively reduced the loss of nutrients, and the proportion of reduced TN and TP were 30.16 and 44.62 %, respectively.

For tillage management, the implementation of NT and CT was also effective in reducing TN and TP compared with the results of BT. The implementation of NT could reduce TN by 31.99 % and TP by 21.93 %. In addition, the implementation of CT could reduce TN by 26.03 % and TP by 18.96 %. In contrast with reforestation, both NT and CT were more effective in reducing TN than TP.

For fertilizer management, the reduction efficiency of fertilizer scenarios in reducing TN and TP was positive for the fertilizer level in this study area. The loss of TP was more than that of TN with increasing chemical fertilizer applications.

BMP1, BMP2, and BMP3 simultaneously prevented the soil erosion. However, BMP4, BMP5, BMP6, and BMP7 were all related to fertilization which had little relation in controlling soil erosion. Considering that some BMPs had little relation in controlling soil erosion, the cost-benefit analysis of soil erosion of BMPs was not further discussed.

Table 2 Environmental effectives and economic benefits of land use management (CNY10⁴)

	Cost	Benefits		Annual net benefits
		Economic	Environmental	
First year	3410	0	0	−3410
Second year	3410	0	0	−3410
Third year	1502	0	0	−1502
Fourth year	1502	8656	190	7344
Fifth year	1502	9122	190	7810
Sixth year	1502	9122	190	7810
Seventh year	1502	9122	190	7810
Eighth year	1502	9122	190	7810
Ninth year	1502	9122	190	7810
Tenth year	1502	9122	190	7810
Total	21,086	63,386	1330	43,630
Average	2109	6339	133	4363
BR	1473	2549	0	1076
DV	636	3790	133	3287

Benefit and effectiveness of BMPs

Land-use management

During the first 3 years of BMP implementation, the environmental benefits were not obvious because the BMP project was under construction (Table 2). In the third year, costs were decreased to CNY 1.502×10^7 (about USD 2.439×10^6), which only included maintenance and opportunity costs. The economic returns of economic forests will begin in the fourth year, and economic returns of water conservation forests will begin in the fifth year. Although the total investment

obtained economic returns through the fourth year, the entire investment can be returned in the fifth year due to the high return rate of orchards. Accurate related land-use and meteorological data for 2011–2021 cannot be obtained; therefore, the environmental effects of reforestation were calculated based on the simulation results for 2011. In addition, it is assumed that there are no environmental effects in the first 4 years (including the 3-year construction period), and in the following years, the environmental benefits are CNY 1.9×10^6 years^{-1} (about USD 3.085×10^5 years^{-1}), which are identical to that in 2011. The annual average benefits were CNY 3.29×10^7 (about USD 5.343×10^6) for the first 10 years after the reforestation practice was applied.

The CE ratio of reforestation on the reduction of TN and TP were 8 and 4 % in 10 years, respectively, which indicates that CNY 10,000 (about USD 162) can reduce 0.08 t of TN and 0.04 t of TP. The CB of reforestation was 207 %. Furthermore, CB even reached 200 % without considering the environmental benefits. Therefore, reforestation is an economical and environmental BMP to be adopted by local governments and farmers in the long term.

Tillage management

The environmental benefits of NT were CNY 5.65×10^6 years^{-1} (about USD 9.18×10^5 years^{-1}). The cost of NT was decreased by approximately CNY 70 acre^{-1} year^{-1} (about USD 11.37 acre^{-1} year^{-1}) compared with BT, and NT invested CNY 6.07×10^6 years^{-1} (about USD 9.86×10^5 years^{-1}) less than BT in total (Table 3). Additionally, because of the increased crop yields, the economic benefits were increased by CNY

Table 3 Environmental effectives and economic benefits of tillage management (CNY10⁴ years⁻¹)

BMP	Cost	Benefits		Annual net benefits	CER		CBR
		Economic	Environmental		TN	TP	
BT	3442	7107	\	3665	\	\	\
BMP2 (NT)	3210	8884	565	6239	16 %	2 %	194 %
NT-DV	−607	1777	565	2949	\	\	\
BMP3 (CT)	3590	8671	459	5540	11 %	1 %	154 %
CT-DV	148	1564	459	1875	\	\	\

BT background of tillage region, *NT* no tillage, *CT* contour tillage, *NT-DV* difference value of no tillage, *CT-DV* difference value of contour tillage

Table 4 Environmental effectives and economic benefits of fertilizer application management (CNY10^4 years^{-1})

Fertilizer	Costs	Benefits		Net benefits	CER		CBR
		Economic	Environmental		TN	TP	
Actual	3442	7107	0	3665	\	\	\
BMP4	2733	4975	882	3124	29 %	4 %	114 %
BMP5	3159	7107	318	4266	9 %	3 %	129 %
BMP6	3867	7815	−353	3595	−8 %	−2 %	96 %
BMP7	4151	8325	−759	3415	−16 %	−3 %	89 %

1.78×10^7 years^{-1} (about USD 2.89×10^6 years^{-1}). Thus, the annual net benefits increased to CNY 2.95×10^7 years^{-1} (about USD 4.79×10^6 years^{-1}). For CT, although this method costs CNY 3.59×10^7 years^{-1} (about USD 5.83×10^6 years^{-1}) (more than the cost of BT), CT obtained significant environmental and economic returns. Obviously, the CB of NT (194 %) was larger than that of CT (154 %). NT was more efficient than BT, whether environmental or economical; therefore, NT should be considered a priority for widespread application.

Therefore, NT and CT are both rewarding and worth promoting, considering the costs and benefits of controlling ANSP, and this conclusion was consistent with previous studies (Ouyang et al. 2008; Liu and Wang 2009; Tian et al. 2010). Notably, although NT and CT can reduce fuel/equipment operation times, labor, nutrient loss in the soil, and can increase crop production, these methods were not widely used. The reason may be that NT and CT require new specialized machinery (such as a no-till drill) and technical guidance, whereas local farmers were lacking these resources. Thus, the government should provide scientific guidance and allowance for specialized machinery to encourage local farmers to apply NT and then CT according to farmland area.

Fertilizer management

The cost-effectiveness of BMP4-7 was shown in Table 4. The environmental benefits of BMP4 were the highest for BMP4-7. The economic benefits of BMP7 were the highest of BMP4-7 due to the increasing crop yield. The net benefit of BMP5, CNY 4.27×10^7 (about USD 6.93×10^6), was the highest of all, which represented an increase of CNY 6.01×10^6 (about USD 9.76×10^5) compared with the original fertilizer condition. The CE of BMP4 on the reduction of TN and TP were 29 and 4 %, respectively, which were higher than the other fertilizer scenarios. However, the CB of BMP5 was 129 %, which was the highest of all. BMP5 not only reduced the cost but also increased environmental benefits, and its net benefit was the highest of BMP4-7. Thus, BMP4 was the most environmentally friendly, and BMP5 was the most economically worthwhile.

The reduction of chemical fertilizers may not only control ANSP but also significantly reduce crop yields. Furthermore, a decrease in crop yields will lead to the

**Table 5** The reduction preference on TN and TP of BMP1-7 in study area

	BMP simulation (t)		Background (t)		Reduction loads (t)		Reduction percent (%)	
	TN	TP	TN	TP	TN	TP	TN	TP
BMP1	389	103	557	186	168	83	30.2	44.6
BMP2	1061	210	1560	269	499	59	32.0	21.9
BMP3	1154	218	1560	269	406	51	26.0	18.9
BMP4	780	161	1560	269	780	108	50.0	40.1
BMP5	1217	186	1560	269	343	83	22.0	30.8
BMP6	1872	358	1560	269	−312	−89	−20.0	−33.1
BMP7	2231	409	1560	269	−671	−140	−43.0	−52.0

Fig. 2 The calibration and validation results of monthly flow, TN and TP in the outlet of Xiangxi River watershed
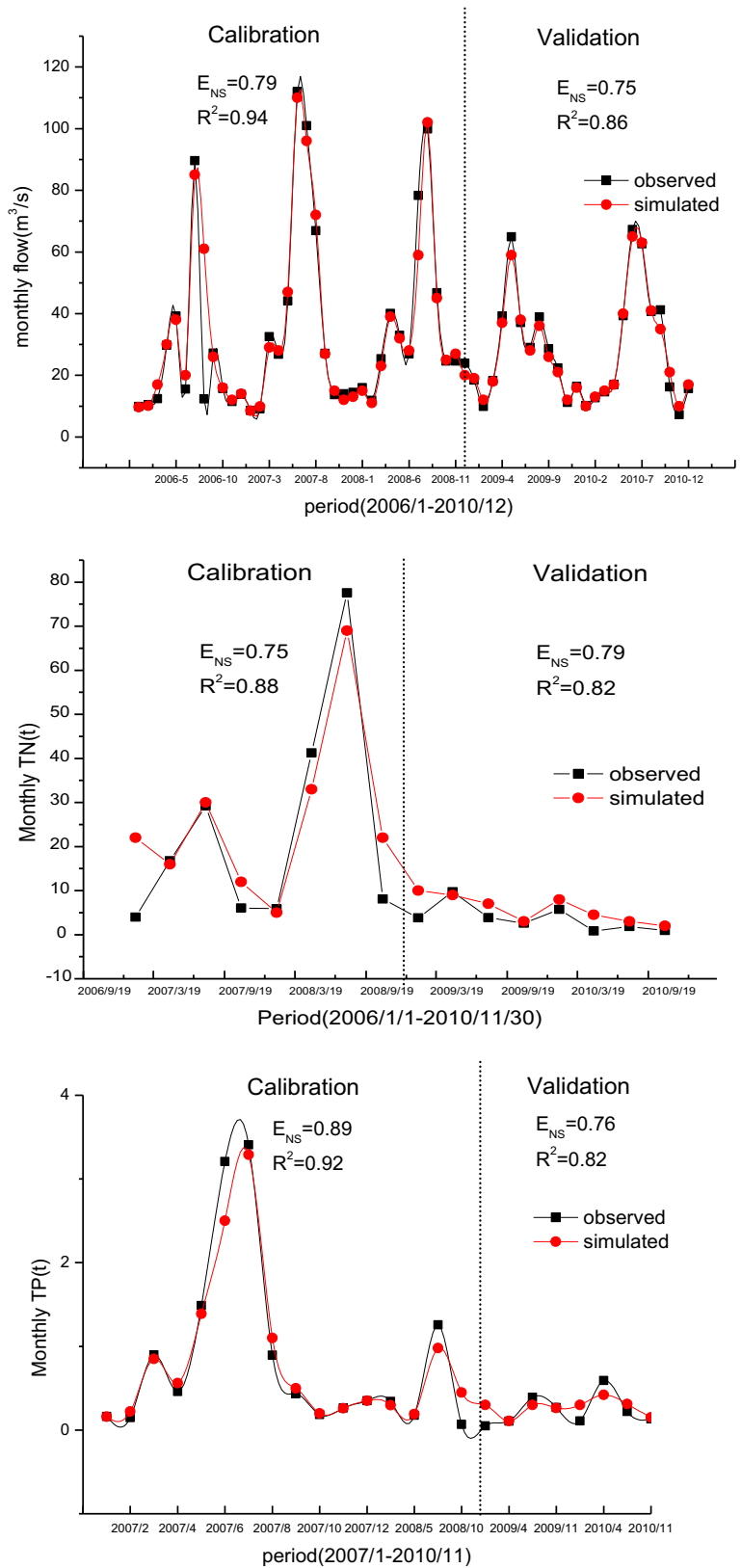
Fig. 3 The CE and CB of BMP
1–5
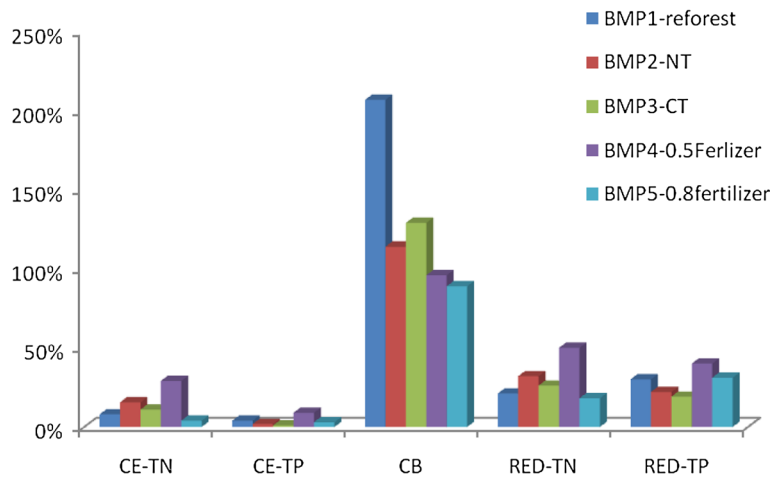
loss of farmers' income, which is not easily accepted by farmers. Therefore, the fertilizers should be reduced within a certain range. Thus, BMP5 will be more reasonable for local farmers than BMP4.

Comparison of BMPs' effectiveness

The rate of reduction in nutrient loads for different BMPs was compared to analyze the most appropriate BMP for TN and TP reduction (Table 5).

From Table 5, BMP1 can control TP better than TN; this result indicated that reforestation management is more effective in reducing pollutants that primarily move with surface runoff and erosion (a great part of TP) than in reducing pollutants that are significantly transported with subsurface flow as well (NO$_3$-N) (Panagopoulos et al. 2011). Previous studies also obtained similar conclusions. For example, Wu et al. (2012) noted that the contribution rate of TP loading that was generated by land use was from 67.5 to 68.5 %, and the contribution rate of TN loading was from 56.5 to 58.5 %.

Tillage management can reduce more TN loads than TP loads in the Xiangxi River watershed. According to Niu et al. (2011), minimum tillage can enhance the soil organic matter and TN accumulation; additionally, the tillage system did not have an apparent influence on the TP content. Giri et al. (2012) also concluded that NT could reduce more TN than TP. Panagopoulos et al. (2011) found that when fertilizer management was combined with CT and NT, the TN reduction greatly improved compared with TP. However, a 30-year simulation by Tuppad et al. (2010) found that conservation

tillage could reduce 3.6 and 1.4 % of TN and TP, respectively, and contour tillage could reduce TN by 11.9 % and TP by 11.5 %.

In this study, when fertilizer application was reduced, the reduction of TP was much greater than that of TN. This result is because rapidly available phosphorus contents were easy to be transferred in runoff and because decreased fertilizer application can significantly reduce this part of phosphorus loss. Lee et al. (2010) determined that the fertilizing control amount for crops showed a greater TP reduction than filter stripes or the regulation C and P factors of USLE. Tuppad et al. (2010) also estimated that manure incorporation could reduce TN by 2.8 % and TP by 9.7 %.

Multiobjective optimization of BMPs

Based on the aforementioned analysis, the reduction of TN loads accounted for most of the nutrient loads and can almost represent all the environmental benefits. The reasons may be the poor availability of phosphorous with the acidic nature of the soils that exist in the Xiangxi River watershed (Tian et al. 2010). The top five BMPs for TN reduction were BMP4>BMP2>BMP3>BMP1>BMP5, and the top five BMPs for TP reduction were BMP4>BMP5>BMP1>BMP2>BMP3.

The reforestation practice, with the least-cost, obtained the most appreciated benefits (Fig. 3). The reasons were as follows. (1) Most of the investments of land-use management were concentrated in the construction period which last 2–3 years and there were little investments after construction. However, for conservation tillage and fertilizer management, large investments

were required and remained unchanged every year. (2) Different kinds of practices were applied to different area. Land-use management was applied to 11,963 acres, whereas conservation tillage and fertilizer management were applied to 33,328 acres. (3) Land-use management obtained appreciated environmental benefits, which rendered this process more economical. NT and CT also obtained appreciated reduction results, although with less cost. NT was the second most efficient in reducing TN, second only to BMP6 (0.5-fold reduction in the fertilizer level). The CB ratios of the BMPs were as follows: reforestation (207 %) > contour tillage (129 %) > no tillage (114 %) > fertilizer management (96 and 89 %). As the ranking indicates from the CB ratio, CT was the second most economically efficient, ranking only second to reforestation. Fertilizer management can reduce TN and TP by a large margin, although not as economically as other methods.

A variety of ANSP control measures, which were discussed in this study, are not mutually exclusive and thus can be applied simultaneously. The suggested combinations of BMPs for the study area were BMP1 (reforestation), BMP2 (no tillage), and BMP5 (0.8-fold reduction in the fertilizer level). The economic and environmental benefits of implementing the combined BMPs within the watershed were CNY 1.64×10^7 years^{-1} (about USD 2.66×10^6 years^{-1}) and CNY 2.48×10^6 years^{-1} (about USD 4.03×10^5 years^{-1}), respectively, and achieved net benefits of CNY 1.6×10^8 years^{-1} (about USD 2.60×10^7 years^{-1}). Ultimately, such measures will be in accordance with the common developmental goals for the economy and environment, although, in actuality, straight tillage will be accepted more easily by local farmers.

Conclusions

Among these seven BMPs scenarios, the top five cost-effective BMPs for TN reduction were BMP4>BMP2>BMP3>BMP1>BMP5, and the top five cost-effective BMPs for TP reduction were BMP4>BMP5>BMP1>BMP2>BMP3. The ranking of CB ratios were BMP1>BMP3>BMP2>BMP4–7. Reforestation and fertilizer management were more effective in reducing TP loading, and tillage management was more effective in reducing TN loading.

BMP1 (reforest) was the most economically efficient of all BMPs, and its annual net benefits were up to CNY 4.36×10^7 years^{-1} (about USD 7.08×10^6 years^{-1}). As for the tillage practice, BMP2 (NT) was more environmentally friendly, and BMP3 (CT) was more economically efficient. To balance ANSP control and farmers' crop yield, the fertilizer practice must reduce the fertilizer level to BMP5 (0.8-fold reduction of 2010 levels). The net benefits of BMP5 were CNY 4.27×10^7 years^{-1} (about USD 6.93×10^6), with an increase of CNY 6.01×10^6 years^{-1} (about USD 9.76×10^5) compared with 2010.

Thus, the optimal BMPs for controlling ANSP were selected as follows: BMP1 (returning arable land with slopes that are greater than 25° to forests and those lands with slopes of 15–25° to orchards), BMP2 (implementing NT on arable land with slopes that are less than 15°), and BMP5 (0.8-fold reduction of 2010 levels). The net benefits of these optimal BMPs were CNY 1.49×10^8 years^{-1} (about USD 2.42×10^7 years^{-1}).

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