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# BMP Optimization to Improve the Economic Viability of Farms in the Upper Watershed of Miyun Reservoir, Beijing, China

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Received: 18 May 2017; Accepted: 21 July 2017; Published: 24 August 2017

**Abstract:** Best management practices (BMPs) are being implemented to reduce non-point sources pollution in China and worldwide. There are many types of agricultural BMPs, but their effectiveness differs from farm to farm, depending on where they are applied, how they are applied, and how they are impacted by weather. Two farms (village Nan Wayao, VNWY and village Liu Jianfang, VLJF) with differing farm systems (crop-based mixed farm and dairy-based farms) located in the upper watershed of Miyun reservoir, Beijing, China were selected. We used the Integrated Farming System Model (IFSM) based on these two farms information to estimate total phosphorus (TP) and total nitrogen (TN) loss from 2000 to 2014, to identify (1) causes of farm nutrient imbalances, (2) key factors causing the imbalances, and (3) viable BMPs to reduce source and TN runoff at the farm scale. Results indicated that these farms had TP losses ranging from 8.2 to 160 kg/ha/year and TN losses from 73.7 to 1391.6 kg/ha/year. Using IFSM, physical (i.e., soil bulk density, available water content, and soil-P) and economic (i.e., diesel and farm loan interest rates) factors are more influential in determining nutrient loss from VNWY than VLJF. Rainfall patterns had a little effect on nutrient use and loss on the dairy farm in VLJF. Changes in available water content and soil bulk density had greater impact on the return for VNWY than VLJF, while changes in loan interest rates were more influential on VLJF. Maximum reductions in nutrient loss were obtained with implementation of the BMPs conservation tillage, reduced fertilizer and manure applications, buffer strips, and storage of poultry manure.

**Keywords:** best management practices; IFSM model; typical farms; nonpoint source pollution

## 1. Introduction

Unlike point sources, nonpoint sources are difficult to control, due to their diffuse nature, complex controlling mechanisms, uncertain flow pathways, and spatial and temporal variability [1–4]. Specifically, nutrients from agriculture nonpoint sources continue to be one of the major causes of water quality degradation of streams and lakes in China [5].

Implementation of BMPs has been shown to decrease nutrient loss and delivery to water bodies worldwide by source (e.g., rate, timing, and method of nutrient application) and transport controls (e.g., conservation tillage, runoff and erosion control) [6–8].

Identifying the potential effectiveness and economic benefits of BMPs before implementation is important in determining the BMPs that would be most appropriate in a given setting for achieving the desired nutrient loss reductions. Thus, quantifying the impact of BMPs under a wide range of environmental and agricultural scenarios is important to targeting critical source areas of nutrient loss and meeting water quality goals [9]. However, differences in geographical characteristics such as soil type, slope, and soil-p concentration can influence BMP effectiveness for different farms at a watershed scale. Also, farm characteristics, such as animal density, cropping strategies, and manure management can also impact BMP benefits [10].

Farmer adoption of BMPs is a primary step in water quality improvement, and BMP adoption rates are typically closely related to their cost [11]. For instance, the costs of establishing and maintaining BMPs are crucial to farmer adoption. Economic losses as a result of implemented BMPs are typically borne by farmers, who may be reluctant to adopt expensive BMPs. Additionally, economic interests between private and public sectors differ. BMPs that satisfy a farmer's desires to maximize profit and meet required regulations may not be the same as those that meet the public desire for maximized improvement to water quality [12–14].

Although many studies have evaluated BMP combinations in different regions of the world using simulation models [15,16], none of these studies have focused on the types of BMPs specifically appropriate for typical farms in north China. Evaluation of long-term BMP impacts using models has proven to be more cost-efficient than by long-term field monitoring [17,18]. For farming conditions in the north-eastern U.S., the Integrated Farming Systems Model (IFSM) allows for evaluation of BMPs from a whole-farm financial perspective [19], analyzing farm inputs and outputs to determine the cost of BMP implementation [20–22].

This paper reports research to (1) estimate P and N balance and budgets for farms in the upper watershed of the Miyun reservoir, (2) identify key factors causing farm P and N imbalance, and (3) determine the effectiveness of various BMPs on different farms. From this, an optimal combination of BMPs is obtained for the study farms that addresses P and N losses while ensuring the long-term sustainability of farms.

## 2. Materials and Methods

### 2.1. Study Areas

The Chaohe river watershed is located in the northwest portion of the upper watershed of the Miyun reservoir and encompasses a drainage area of 4888 km$^2$ (Figure 1). It is the source of drinking water of Beijing, China. Due to strict control of point source pollution by banning any municipal and industrial effluent discharge in the watershed, P and N loads originate mainly from non-point sources [23]. While the current water quality of the Miyun reservoir is mainly mesotrophic, increasing eutrophication of the Miyun reservoir has become the main problems for future water use [24]. Hilly terrain (elevations are from 150 to 400 m) and mountains (elevations from 400 to 800 m) occupy nearly 83% of the watershed. Average slope is about 20–35°, and average annual precipitation is 660 mm, and of this, 77% usually falls between July and September.

The major sources of TP and TN are from livestock and nutrient applications, which contribute 80–90% of TP and TN loads [25]. Agricultural activities in the watershed consist primarily of dairy farming, and land uses are typically pasture, corn, and hay crops that are grown to support dairy farming. Therefore, two typical farms were selected, located in the upper watershed of the Miyun reservoir, as being representative of agricultural activities, soil type, land use, and slope (Figures 2 and 3).

Representative weather, soil, cropping scenarios, management practices, and topography were obtained from the 2010–2014 China Agricultural Statistical Years Report [26], which indicates that crop and dairy farms in the upper watershed of the Miyun reservoir had an average size of 200 and 2500 ha, respectively. Two representative farms in the Fengning County, Hebei Province were Nan Wayao, a crop farm (VNWY) with an area of 1700 ha, and Liu Jianfang, a dairy farm (VLJF) with an area of 2500 ha. These farms were selected for detailed analysis because of data availability for modelling and their general similarity to other farms within the upper watershed of the Miyun reservoir.

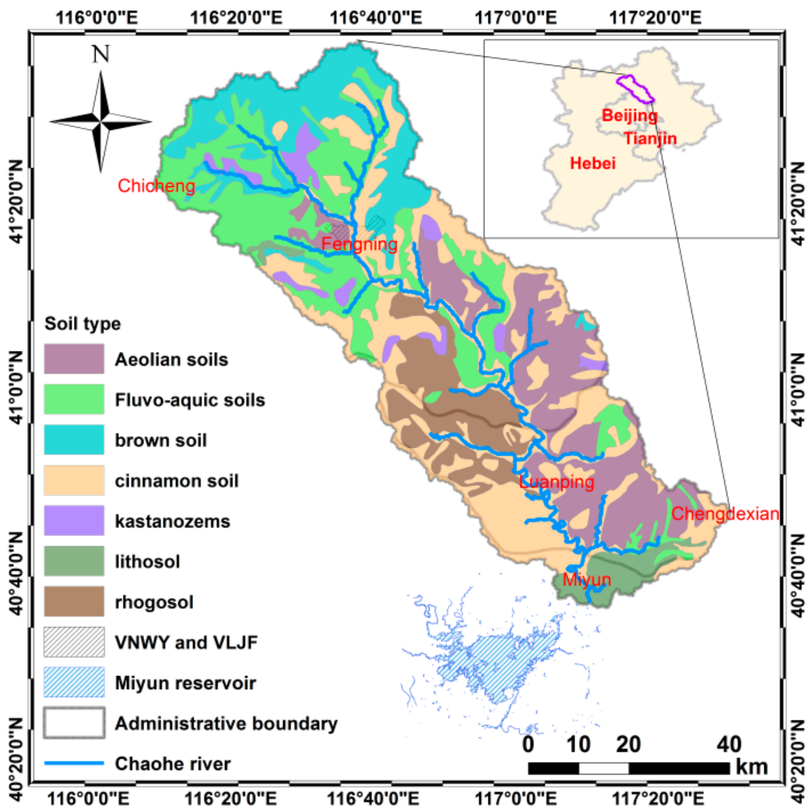


**Figure 1.** Location of the typical farms and study area with soil type.

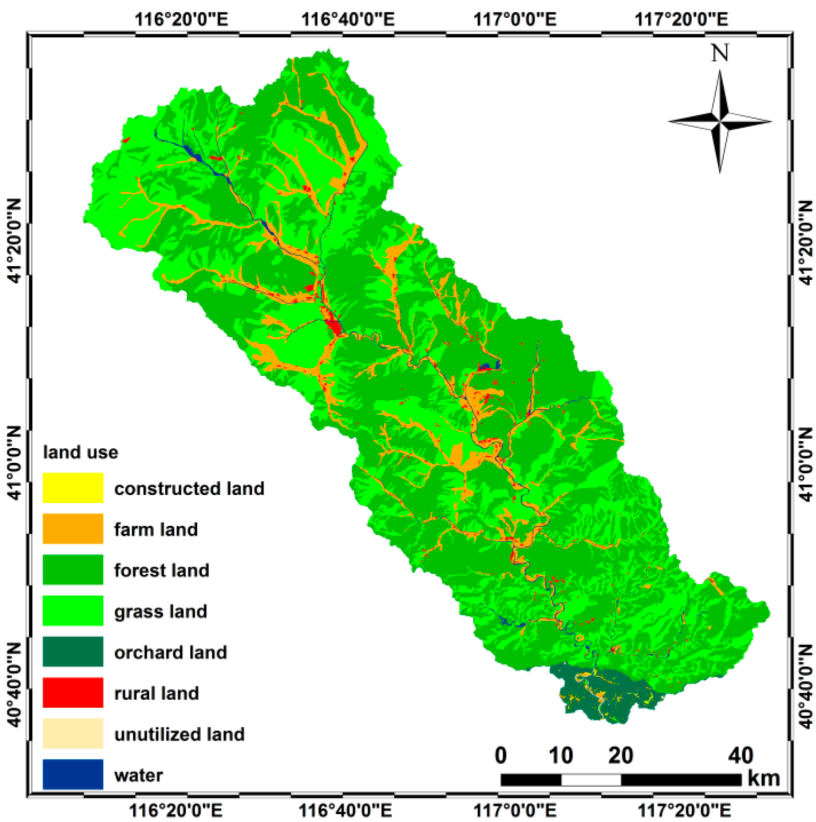


**Figure 2.** Land use of the upper watershed of the Miyun reservoir.

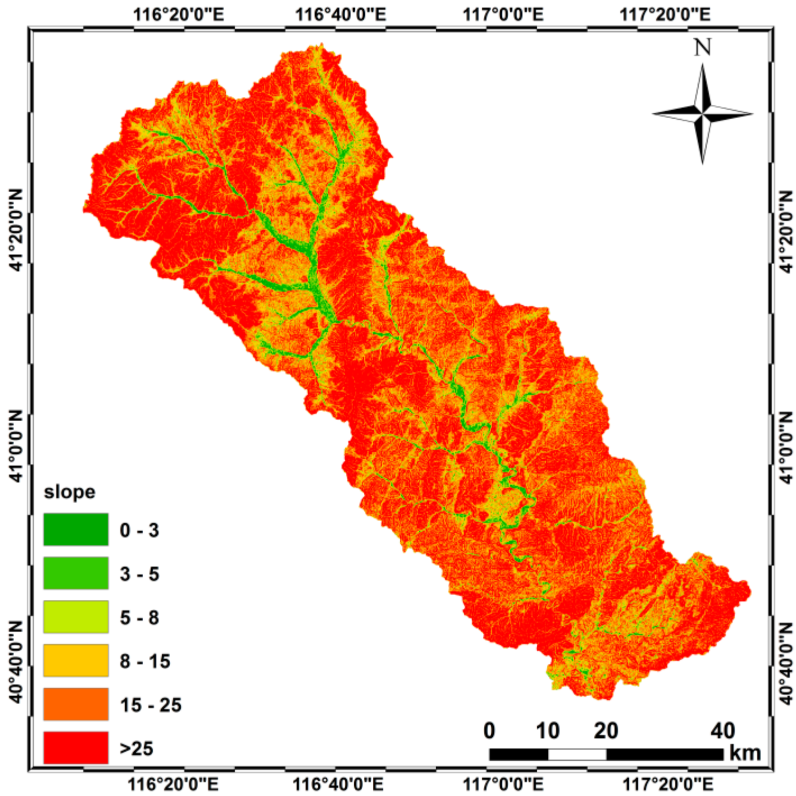


**Figure 3.** Slope classification of the upper watershed of the Miyun reservoir.

#### 2.1.1. Farm-VNWY

The VNWY farm has 207 ha of crop and soybean grown on cinnamon and brunisolic soils with slopes of 10° to 20°. Corn silage and soybean produced are used as feed for 300 Holstein dairy cows and also sold to increase farm income. Average annual milk yield is 1825 tons/year and the cows are fed a mixed ration of on-farm produced grass-legume, hay, corn silage, and corn meal. On average, corn yield is 1896 tons/year, soybean is 67.5 tons/year, and corn silage is 400.5 tons/year. Manure produced on the farm is stored in earthen pits during winter months when manure spreading is banned. About 80% of the manure produced on the farm is applied to corn fields. In addition, corn receives 750 tons/year fertilizer, it includes 308.8 tons/year N fertilizer, 110.3 tons/year P fertilizer and 330.9 tons/year K fertilizer.

#### 2.1.2. Farm-VLJF

This farm is a major producer of milk in Fengning County, maintaining 1532 Holstein dairy cows and 2700 pigs, and consists of 182 ha of corn area on cinnamon and brunisolic soils with slopes of 10° to 25°. All corn grown is used for corn silage production. In addition, the cows graze rotationally on farm pastures. Between 2000 and 2014, annual average milk yield was 16,078.2 tons/year, the corn yield was 2250 tons/year, and corn silage was 300 tons/year. About 90% of the manure produced was used to establish as fertilizer for first year grass-legume and corn crops, with the remainder spread on fields following hay harvesting. In addition, it used 660 tons/year fertilizer, including 271.8 tons/year N fertilizer, 97.1 tons/year P fertilizer and 291.1 tons/year K fertilizer.

### *2.2. Methods and Data Source*

In this study, the farm-scale model, IFSM, was used to assess nutrient budgets on the farms, and the economic viability and environmental impacts of the management strategies in place. IFSM is a comprehensive farm-scale model that simulates the long-term environmental and economic benefits of various technologies and management strategies of a farm system [27]. IFSM has been widely used in evaluating farming systems [28,29] to estimate crop growth, dairy (or beef) cow performance, nutrient balances (such as P, N, and K) from imported animal feed and fertilizer and exported animal and crop products, and farm economics, as well as estimating off-farm erosion and nutrient runoff.

The IFSM input data needed to represent the study farms, included data regarding farm characteristics, machinery, and weather. Farm characteristics data were obtained by farm interviews and consists of detailed information on crop type and extent, soil types, soil attribute data such as soil bulk density (SBD), available water content (AWC), and slope, type of dairy cows, numbers of cows of different ages, manure handling strategies, and equipment and structures used in managing the livestock and crops. The machinery input included data related to machine type, size, hours of use, and associated costs. For both farm and machinery data, the data was gathered by questionnaire from the study farms between April and September, 2014 (Appendix A). Economic data includes prices of farm commodities produced, purchased feeds, and farm products sold off-farm. These data were obtained from the China Agricultural Statistics Yearbook. Weather data includes daily values of TP precipitation, maximum and minimum temperatures, and solar radiation. These data were obtained from National Climate Data Center database for the closest station (Dage station) to the study farms. For the two study farms, IFSM simulation of average annual predictions were performed using 15 years of historical weather data.

### *2.3. BMPs Scenarios*

Baseline and selected alternative farm planning scenarios were modelled for each farm (Table 1) [30–32]. The baseline scenarios represent current production systems of studied farms without BMPs. The alternative farm planning scenarios involve combinations of in-place BMPs. Targeted farm-scale BMPs address P source and transport factors, along with the positive or negative economic impact of BMP implementation.

**Table 1.** Scenario descriptions and modeling.

| Scenario | Description |
|---|---|
| Baseline | Current farming system; conditions before management changes |
| Conservation tillage | Reduce soil erosion, N mineralisation and P mobilisation |
| Timing of chemical fertilisation | Reducing the risk of nutrient transport |
| Contour Farming | Reducing surface runoff and erosion |
| Filter strips | Delay runoff Trap sediments and nutrients |
| Fertilizer reduction 30% | Reducing N and P inputs to soil |
| Poultry numbers reduction 30% | Reducing N and P inputs to soil |
| Storage of poultry manure | Reducing manure N content |
| Manure spread during the dry season | Reducing the risk of transport |
| Fence | Reducing the risk of poultry manure directly into streams |

### *2.4. Modeling Validation*

Detailed information on farm and machinery was obtained from 200 questionnaires conducted in 2014. IFSM predictions of crop production, manure production, and milk production were simulated over 15 years based on the weather stations in Dage County. IFSM crop yield factors and forage feed-level were obtained from measured or recorded data. Crop growth rate curves were adjusted until predicted yield and nutrient content values matched the farm record data. Forage feed-level factor was adjusted by constraining the feed rates for energy and protein content per cow per day. Feeding limit values used for energy and protein concentration were based on the typical feed rate data obtained from the farm questionnaires.

When the input data were set up, we could compare the predicted and measured values for production of corn, soybean, grass, and milk. Similarly, estimated and measured input and output of TP and TN were compared. The 15 year simulations were analyzed by descriptive statistical analysis.

Results from IFSM were reliable with a variable coefficient of 0.01 to 0.1 (Tables 2 and 3). As average relative errors were under 20%, IFSM estimates can serve as datasets for further analysis of BMPs effectiveness (Table 4). In Table 4, simulated data were output from IFSM and measurement data were collected from 200 questionnaires in 2014.

**Table 2.** Descriptive statistics analysis of nutrients balance in VNWY from 2000 to 2014.

| Indicators | Average (AV) | Standard Deviation (SD) | Coefficient of Variation (CV) |
|---|---|---|---|
| Input-N (kg/ha) | 137 | 2.0 | 0.03 |
| Output by agricultural products-N (kg/ha) | 15.7 | 3.7 | 0.24 |
| Volatilization-N (kg/ha) | 14.5 | 0.6 | 0.04 |
| Leaching-N (kg/ha) | 6.2 | 6.8 | 1.10 |
| Denitrification-N (kg/ha) | 26.9 | 7.9 | 0.29 |
| Surplus-N (kg/ha) | 73.7 | 2.8 | 0.06 |
| Input-P (kg/ha) | 16.8 | 0.3 | 0.03 |
| Output by agricultural products-P (kg/ha) | 2.7 | 0.5 | 0.18 |
| Losses-DP (kg/ha) | 0.1 | 0.1 | 1 |
| Losses-PP (kg/ha) | 5.8 | 0.7 | 0.12 |
| Surplus-P (kg/ha) | 8.2 | 0.4 | 0.07 |
| Economic benefits (¥) | $5.8 \times 10^6$ | 7971 | 0.01 |

Note: DP means dissolved phosphorus and PP means particulate phosphorus.

**Table 3.** Descriptive statistics analysis of nutrients balance in VLJF from 2000 to 2014.

| Indicators | Average (AV) | Standard Deviation (SD) | Coefficient of Variation (CV) |
|---|---|---|---|
| Input-N (kg/ha) | 2761.8 | 185.9 | 0.13 |
| Output by agricultural products-N (kg/ha) | 170.6 | 16.0 | 0.09 |
| Volatilization-N (kg/ha) | 457.6 | 126.1 | 0.28 |
| Leaching-N (kg/ha) | 85.1 | 169.4 | 1.99 |
| Denitrification-N (kg/ha) | 656.9 | 155.3 | 0.24 |
| Surplus-N (kg/ha) | 1391.6 | 100.95 | 0.08 |
| Input-P (kg/ha) | 336 | 8.0 | 0.05 |
| Output by agricultural products-P (kg/ha) | 31.4 | 2.9 | 0.09 |
| Losses-DP (kg/ha) | 2.9 | 2.3 | 0.79 |
| Losses-PP (kg/ha) | 141.7 | 6.8 | 0.05 |
| Surplus-P (kg/ha) | 160 | 5.45 | 0.04 |
| Economic benefits (¥) | $3.3 \times 10^7$ | 24,921 | 0.001 |

Note: DP means dissolved phosphorus and PP means particulate phosphorus.

**Table 4.** Validation of the results from IFSM model.

| Validation Indicators | Mean Annual Yield | | | N in Feed (%) | | | P in Feed (%) | | |
|---|---|---|---|---|---|---|---|---|---|
| | **Simulated** | **Measured** | **Relative Error** | **Simulated** | **Measured** | **Relative Error** | **Simulated** | **Measured** | **Relative Error** |
| | | | | **VNWY** | | | | | |
| Corn (ton) | 1769.6 | 1896 | −6.7% | 9.6 | 12 | −20.0% | 46.9 | 40 | 17.2% |
| Soybean (ton) | 65.4 | 67.5 | −3.1% | - | - | - | - | - | - |
| Grass (ton) | 363.12 | 400.5 | −9.3% | 10.14 | - | - | 44.5 | - | - |
| Milk (ton) | 2188.8 | 1825 | 19.9% | - | - | - | - | - | - |
| Input-N (kg/ha) | 137 | 100.51 | 36.3% | - | - | - | - | - | - |
| Output-N (kg/ha) | 63.3 | 44.31 | 42.9% | - | - | - | - | - | - |
| Surplus-N (kg/ha) | 73.7 | 56.2 | 31.1% | - | - | - | - | - | - |
| Input-P (kg/ha) | 16.8 | 14.3 | 17.5% | - | - | - | - | - | - |
| Output-P (kg/ha) | 8.6 | 7.9 | 8.9% | - | - | - | - | - | - |
| Surplus-P (kg/ha) | 8.2 | 6.4 | 28.1% | - | - | - | - | - | - |
| Average Relative Errors | - | - | 20.1% | - | - | - | - | - | - |
| | | | | **VLJF** | | | | | |
| Corn (ton) | 2172.1 | 2250 | −3.5% | 9.7 | 12 | −19.2% | 43.9 | 40 | 9.7% |
| Vegetable (ton) | 1257.4 | 1680.7 | −25.2% | - | - | - | - | - | - |
| Grass (ton) | 280 | 300 | −6.7% | 9.67 | - | - | 39.8 | - | - |
| Milk (ton) | 19,013.7 | 16,078.2 | 18.3% | - | - | - | - | - | - |
| Input-N (kg/ha) | 2761.8 | 2658.9 | 3.9% | - | - | - | - | - | - |
| Output-N (kg/ha) | 1370.2 | 1304.2 | 5.1% | - | - | - | - | - | - |
| Surplus-N (kg/ha) | 1391.6 | 1354.7 | 2.7% | - | - | - | - | - | - |
| Input-P (kg/ha) | 336.0 | 298.7 | 12.5% | - | - | - | - | - | - |
| Output-P (kg/ha) | 176.0 | 157.2 | 12.0% | - | - | - | - | - | - |
| Surplus-P (kg/ha) | 160.0 | 141.5 | 13.1% | - | - | - | - | - | - |
| Average Relative Error | - | - | 11.0% | - | - | - | - | - | - |

## 3. Results and Discussion

### 3.1. Baseline Simulations

For the VNWY, the predicted average nutrients surplus of TN and TP are 73.7 and 8.2 kg/ha/year, respectively, which is significantly higher than other areas with similar geographic features. Because the amount of TP and TN added in fertilizer (825 kg/ha) and manure (112 t/ha) greatly exceeded crop requirements/uptake, runoff of excess N and P is a major factor determining water quality impairment. In addition, bare or fallow land due to one season's growth of corn and soybeans (from April to September) leads to an increase in soil losses during storm events when the 75% precipitation occurs during the rainy season (from June to September) [33].

For the VLJF, the average nutrients surplus of TN and TP estimated by the IFSM model was 1391.6 and 160 kg/ha/year, respectively. These surpluses result from inefficient feeding of livestock (i.e., N and P in feed greater than that needed by livestock) accentuate the surplus. The TN and TP surplus was greater than for other areas in China, such as the TN surplus of 363 kg/ha in Three Gorges Reservoir Watershed [34], and the 472 kg-N/ha surplus in She Yuchuan watershed in Miyun County [35]. In addition, high bulk soil density (SBD) is 1.7 g·cc$^{-1}$ of local soils, and hence the lower water storage capacity [23] results in a greater risk of rainfall-induced runoff and, thereby, nutrient loss in runoff.

### 3.2. Identification of Key Factors That Influence the Nutrient Reduction

Sensitivity analysis of baseline scenarios for VNWY and VLJF, indicated that there was a negative linear relationship with return to management. For the VNWY, percentage change in profit was about 2 times greater when interest rates were lowered, compared to the percentage change in profit when diesel prices decreased (Figure 4). Sensitivity to these economic parameters appeared to be greater for the VLJF than the VNWY farm, and loan interest rates were the most influential. VLJF had a lower baseline return than VNWY and, therefore, if the return decreased by the same amount for both villages, VLJF would show a greater percentage change. Secondly, VLJF had more agricultural infrastructure construction than VNWY. Therefore, VLJF paid maintenance and capital costs for animal housing, feed and manure storage, machinery, and milking equipment, while the primary cost for VNWY was mainly machinery.

Soil-P concentration influenced estimated P runoff. As the concentration of soil-P increased, estimated TP runoff increased (Figures 4 and 5). Increasing the soil-P concentration from baseline conditions by 25% and 50% increased TP runoff by 48% and 86%, respectively, for VLJF and 45% and 82%, respectively, for VNWY. The slope of the linear increase in estimated TP runoff with increasing soil-P concentration was 0.5 for VNWY and 0.7 for VLJF.

In Figures 4 and 5, it is apparent that available water content (AWC) and moist bulk soil density (SBD) influenced the simulated outputs with less linear responses than were seen for the economic and soil P parameters. From a general perspective, the sensitivity of the environmental outputs to the soil parameters is similar between the two farms. Economically, the dairy farm (VLJF) was less sensitive to soil variables than the crop farm (VNWY), because the dairy farm was more diversified due to its crop and milk production.

As available soil water storage (AWC) decreased, $NO_3$-N leaching and sediment runoff increased (Figures 4 and 5, respectively). With less AWC, there was minimal impact on volume of water runoff, but more water was drain percolated to the groundwater. The increased water drainage increased N leaching.

Lower AWC also created crop water stress and decreased yields, which can be seen by looking at the impact of decreased AWC on profitability in Figures 4 and 5. As AWC increased, there was little impact on any of the simulated outputs for either VNWY or VLJF. This is likely due to the fact that soil can only store the water that is provided by rainfall. Therefore, in the baseline condition, rainfall being supplied to the soil through precipitation did not reach the storage capacity of the soil. By increasing

AWC, there was no change in the amount of water stored by the soil. Conversely, when the AWC of the soil was decreased below the baseline, precipitation was supplied to the soil for which there was no room for storage. With less water contained within the soil, there was less water available to plants, which resulted in greater plant water stress, lowering yields, and decreased farm returns.

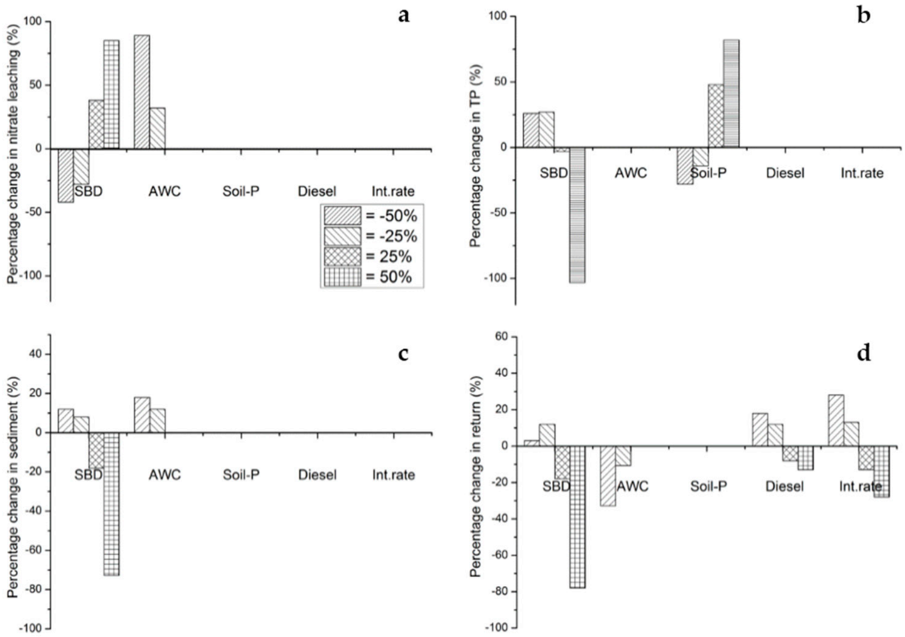


**Figure 4.** Sensitivity analysis at VNWY showing impact of changing input parameters (SBD = soil bulk density, AWC = available water content, Soil-P = soil phosphorus concentration) on (**a**) nitrogen leaching; (**b**) TP runoff; (**c**) sediment loss and (**d**) return to management.

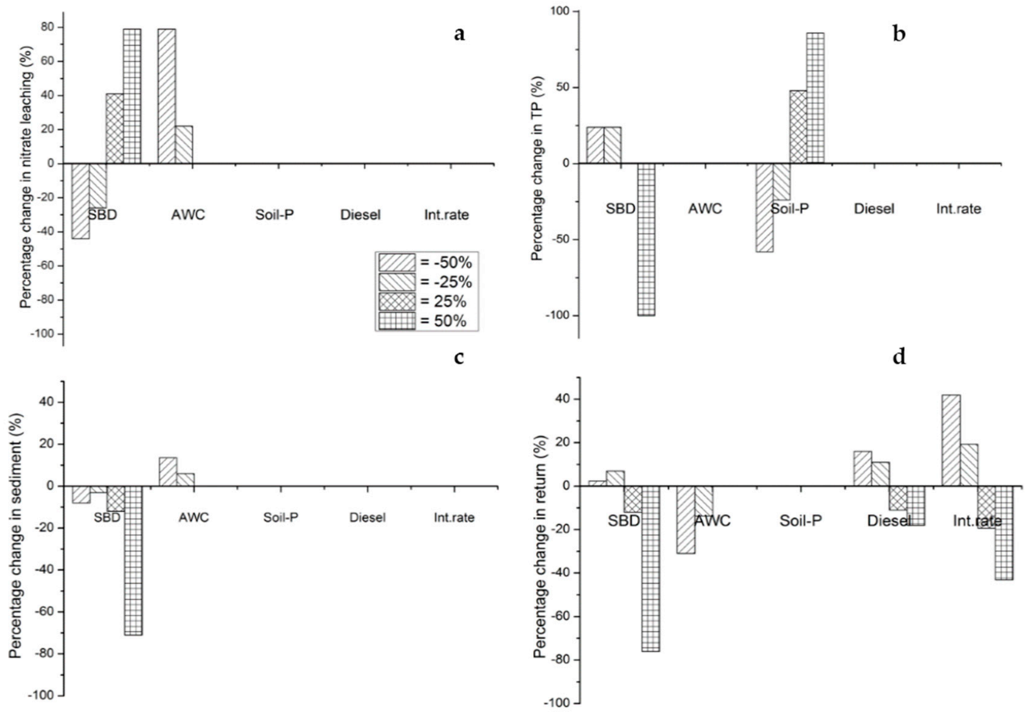


**Figure 5.** Sensitivity analysis at VLJF showing impact of changing input parameters (SBD = soil bulk density, AWC = available water content, Soil-P = soil phosphorus concentration) on (**a**) nitrogen leaching; (**b**) TP runoff; (**c**) sediment loss and (**d**) return to management.

Generally, soil bulk density (SBD) had little impact on any of the outputs except $NO_3$-N leaching (Figures 4 and 5) unless it was raised by 50%. The impact of varying SBD on $NO_3$-N leaching was greater than other factors. The range of bulk densities used to test model sensitivity (0.725–2.175 g/cc) was much greater than the range of bulk densities for the soils of the region (1.2–1.7 g/cc), therefore, impacts seen in this sensitivity analysis are likely more pronounced than those expected for any of the soils in the region. That said, it should be noted that the response of TP runoff to changing soil bulk density does not correspond to the response in sediment runoff for changing bulk density. For decreasing bulk density values, sediment runoff stayed relatively unchanged for both farms, while the TP runoff increased. The majority of TP runoff was as particulate P (up to 80% of TP runoff was PP) [36]. Therefore, we would expect TP runoff and sediment runoff to exhibit similar relationships. It is possible that low bulk density soils can bind more P than high-density soils, and thus, the concentration of P in the sediment runoff is higher for the low bulk density soils. It is also evident that N leaching is lower for all the tested bulk density values than it is for the baseline. Nitrogen leaching decreases for higher bulk density soils which infiltrate more precipitation than the baseline soil. This suggests that bulk density has an impact on N concentration in the leachate.

### 3.3. Assessment of BMPs on Farm System Scenarios

BMP scenarios simulated with IFSM showed the potential changes over baseline conditions that these selected BMPs may have on environmental effectiveness and farm economic profitability. Figures 6 and 7 are the comparison of the environmental effectiveness and economic profitability of different BMPs for VNWY and VLJF.

All BMPs have the potential to reduce TNTN, TP and sediment losses based on average effectiveness of practices estimated by IFSM in VNWY and VLJF. TN, TP, and sediment can be potentially reduced by 68% (storage of poultry in VLJF), 71% (storage of poultry in VLJF), 83% (conservation tillage), respectively, while the return can be decreased by up to 56% (storage of poultry in VLJF).

Conservation tillage will have maximum reduction efficiency for TN, TP and sediment in VNWY, with an effectiveness of 43%, 61%, and 83%, respectively, while the return will increase by 10.9%. However, when conservation tillage was implemented on VLJF; TN, TP, and sediment was decreased by only 13%, 20% and 41%, respectively, and return increased by 1.2%. This indicated that less soil disturbance allows more crop residue to remain on the soil surface, which reduces soil erosion and facilitates better infiltration of precipitation. The observed reductions in sediment, PP, and TP loss with conservation (or reduction) compared to conventional tillage are supported by similar findings from field studies [37,38]. These studies also found P and sediment loss to be highly related for all tillage systems, as reduced tillage systems greatly reduce sediment-P losses and in turn TP losses.

For VNWY, buffer strips will also produce the best possible results for TN, TP, and sediment control; the effectiveness for TN, TP and sediment was 55%, 47%, and 78%, respectively. However, farm income decreased by 27%. For VLJF, buffer strips also dramatically decreased TN, TP, and sediment loss (by 65%, 59%, and 73%, respectively); similar to VNWY, farm income decreased by 26%. Other studies reported similar findings that the effectiveness of contour strip cropping was 75% and 65% for TN and TP, respectively [12]. Similarly, [39] showed that the effectiveness of riparian forest buffers were 56% with slopes of 0–3% and 36% with slopes of 8–15%. Farm income decrease resulted from the conversion of crop land to non-production forest or grass buffers. This cost could be mitigated, in part, by taking advantage of any applicable buffer cost-share programs, as could many of the BMPs discussed here [40].

The total return to management for VLJF was not positively influenced by many of the BMP scenarios (Figures 6 and 7). Conservation tillage and fertilizer reduction were the only scenarios that increased farm profit (2% and 17%, respectively). The increase in profit for conservation tillage was a result of better crop yields, which were propagated through more efficient use of the manure nutrients. The increase in profit for fertilizer reduction was the result of a lower fertilizer consumption cost because of the smaller amount of fertilizer required.

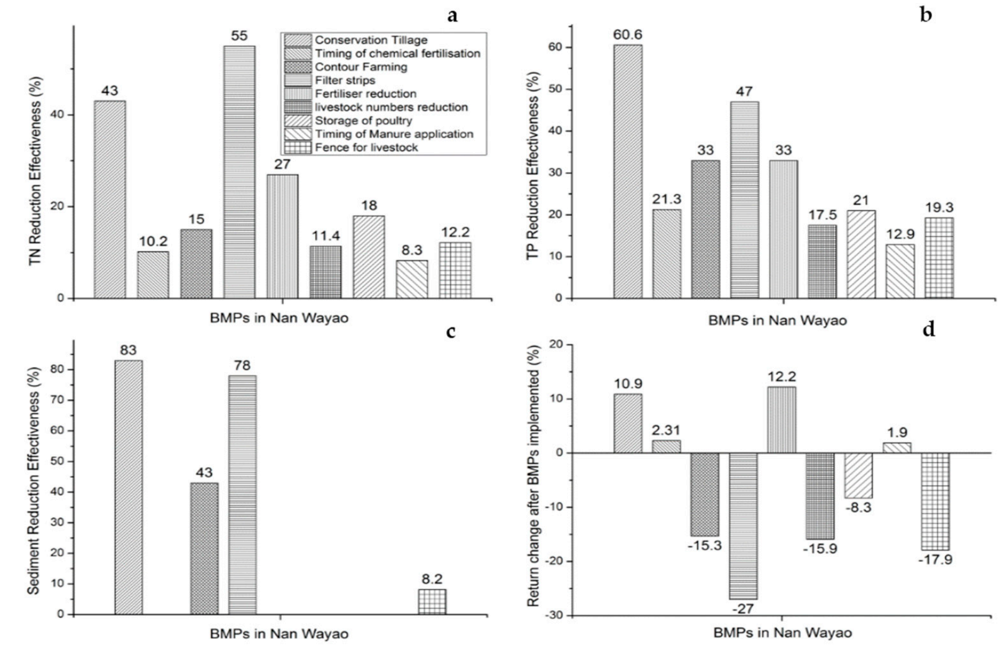


**Figure 6.** BMP assessment at VNWY, (**a**) the TN reduction effectiveness; (**b**) TP reduction effectiveness; (**c**) sediment reduction effectiveness and (**d**) return change after BMPs implemented respectively.

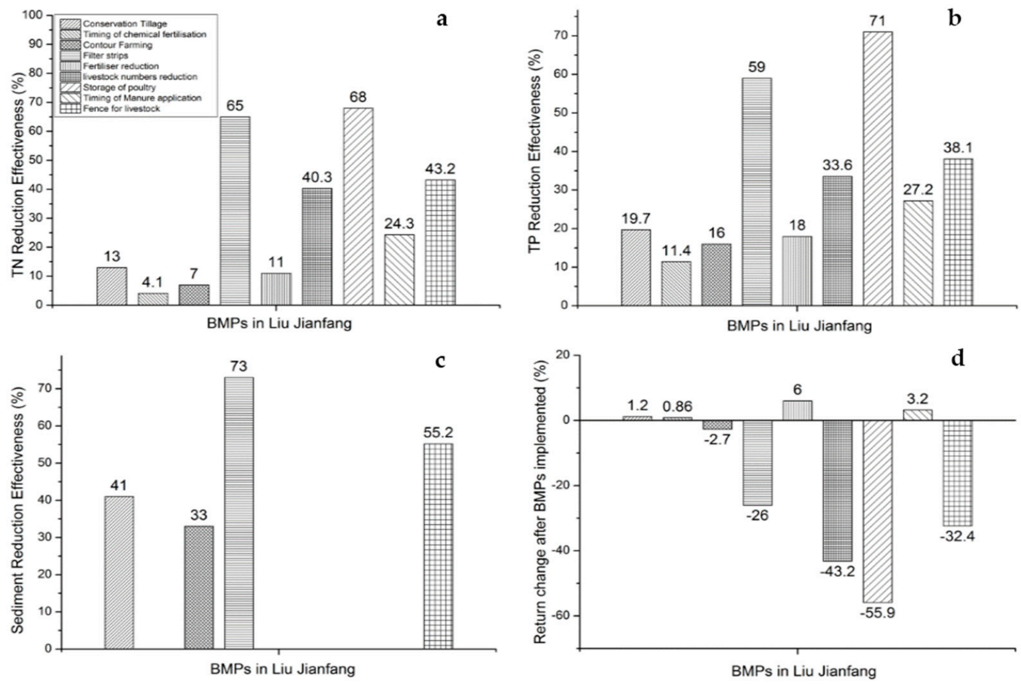


**Figure 7.** BMP assessment at VLJF, (**a**) the TN reduction effectiveness; (**b**) TP reduction effectiveness; (**c**) sediment reduction effectiveness and (**d**) return change after BMPs implemented respectively.

Overall, for VNWY and VLJF farms, conservation tillage, fertilizer reduction, buffer strips and storage of poultry appeared to have the greatest environmental benefit for the least cost to the farmer. Nutrient loss reductions from conservation tillage were comparable to buffer strips and storage of poultry, while the profitability of the former practice was greater. Reduced tillage resulted in substantial reductions of TP and sediment loss and provided a minimal increase in net return.

Increased manure storage resulted in more TN volatilization, in part due to manure storage characteristics, but also because less nitrogen was lost to leaching. Storage of manure resulted in manure application during colder times of the year [41]. Volatilization from the manure storage was substantial because manure storage was top-loaded on the study farms. Top-loaded manure storage appears to be the most common manure storage in the Miyun Reservoir region. The crust that forms on bottom-loaded manure storages has been found to decrease N volatilization losses [42]. Thus, had a bottom-loaded manure storage system been used in place of a top-loaded storage system, total farm N volatilization would likely have decreased with increasing manure storage time. Decreased fertilizer application slightly decreased TN and TP loss and resulted in no impacts on sediment, but resulted in a better net return for the farm. Buffer strip was a beneficial practice, reducing P and sediment runoff with significantly impact on net return. Environmentally, the greatest reductions for all BMPs and loss metrics resulted from a conservation tillage and buffer strip.

## 4. Conclusions

(1) The IFSM enabled a comprehensive evaluation of alternative farm planning strategies prior to their implementation. Two baseline farms were developed to simulate typical farms in the upper watershed of the Miyun reservoir; a crop farm (VNWY) and a dairy farm (VLJF). Type and timing of tillage practices is the key factor for the nutrient losses in VNWY; manure with higher nutrient content and the soil type are two key factors for nutrient losses in VLJF.

(2) The sensitivity analysis demonstrated that the key factors that heavily influence BMPs' effectiveness are physical and economic parameters. Changes in soil physical parameters, such as available water content and soil bulk density, had a greater impact on the return for the VNWY than for VLJF, while changes in interest rates were more influential at VLJF. However, actual farms could differ from the baseline model in many other ways. Differences in size, crop rotations, animal numbers and a variety of other farm characteristics could have considerable impacts on the simulated environmental and financial outputs; therefore, application of the baseline simulation results to actual farms should be exercised with caution.

(3) Based on reduction of sediment and nutrient losses and impact on farm profitability by BMP scenarios simulation, the most cost-effective management strategies are often the simplest to implement. Nutrient management and strip cropping reduced environmental losses with very little or no cost to farmers. Some of the best practices, at baseline conditions, have already been adopted by many farms in the area (i.e., the conservation tillage at VNWY, or the buffer filter strip and storage of poultry on the VLJF).

(4) The cost-effectiveness BMP combinations is a feasible policy option for China, because the Chinese government recently initiated the "Ten-Measures Action Plan for the Prevention of Water Pollution" strategy. This strategy is particularly relevant to this research study, with ongoing research and outreach efforts that promotes water environmental stewardship among the agricultural community. These results provide technical support for the development of nonpoint source pollution control programs and strategies in China.

**Acknowledgments:** This work was supported by National Natural Science Foundation of China (No. 41601551, 41271495).

**Author Contributions:** Runzhe Geng conceived and designed the methodology, figures, conducted the data collection, data analysis and wrote the paper; Peihong Yin performed the literature search, figures and wrote a part of the paper; Qianru Gong analyzed the data and drew the figures, Xiaoyan Wang performed the literature search and Andrew N. Sharpley designed the methodlogy with Runzhe Geng, and made the literature search.

**Conflicts of Interest:** The authors declare no conflict of interest.

## Appendix A

| Information of Crop and Soil | | |
|---|---|---|
| **Crop Area (give typical values over the past ten years)** | | |
| Grass | | acres |
| Pastureland | | acres |
| Corn | | acres |
| Wheat | | acres |
| Soybean | | acres |
| **Predominant Soil Type(Check one which should represent the average over the farm)** | | |
| Deep loamy sand | | |
| deep clay loam | deep loam | deep sandy loam |
| Medium loamy sand | | |
| medium clay loam | medium loam | medium sandy loam |
| Shallow loamy sand | | |
| shallow clay loam | shallow loam | shallow sandy loam |
| **Pastureland** | | |
| Life of stand | | Years |
| Average annual yield | | ton |
| Maximum expected yield | | ton |
| Maximum annual irrigation | | mm |
| Manure of total | | % |
| Nitrogen | | kg N/ac |
| Phosphorus | | kg $P_2O_5$/ac |
| Potash | | kg $K_2O$/ac |
| **Grass** | | |
| Life of stand | | Years |
| Average annual yield | | ton |
| Maximum expected yield | | ton |
| Maximum annual irrigation | | mm |
| Manure of total | | % |
| Nitrogen | | kg N/ac |
| Phosphorus | | kg $P_2O_5$/ac |
| Potash | | kg $K_2O$/ac |
| **Corn** | | |
| Plant population | | plant/ac |
| Average annual grain yield | | ton |
| Maximum expected yield | | ton |
| Average annual silage yield | | ton |
| Minimum expected yield | | ton |
| Relative maturity index | | days |
| Maximum annual irrigation | | mm |
| Manure of total | | % |
| Preplant nitrogen | | kg N/ac |
| Anhydrous ammonia | | kg N/ac |
| Nitrogen | | kg N/ac |
| Phosphorus | | kg $P_2O_5$/ac |
| Potash | | kg $K_2O$/ac |

| Wheat | |
|---|---|
| Average annual grain yield | ton |
| Maximum expected yield | ton |
| Average annual silage yield | ton |
| Minimum expected yield | ton |
| Maximum annual irrigation | mm |
| Manure of total | % |
| Nitrogen | kg N/ac |
| Phosphorus | kg $P_2O_5$/ac |
| Potash | kg $K_2O$/ac |
| **Soybean** | |
| Plant population | plant/ac |
| Average annual grain yield | ton |
| Maximum expected yield | ton |
| Average annual silage yield | ton |
| Minimum expected yield | ton |
| Relative maturity index | days |
| Maximum annual irrigation | mm |
| Manure of total | % |
| Preplant nitrogen | kg N/ac |
| Anhydrous ammonia | kg N/ac |
| Nitrogen | kg N/ac |
| Phosphorus | kg $P_2O_5$/ac |
| Potash | kg $K_2O$/ac |

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