Simulating and evaluating best management practices for integrated landscape management scenarios in biofuel feedstock production

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Received April 10, 2015; revised August 3, 2015; accepted August 6, 2015
View online September 8, 2015 at Wiley Online Library (wileyonlinelibrary.com);
DOI: 10.1002/bbb.1579; Biofuel, Bioprod. Bioref. 9:709–721 (2015)

Abstract: Sound crop and land management strategies can maintain land productivity and improve the environmental sustainability of agricultural crop and feedstock production. This study evaluates a strategy of incorporating landscape design and management concepts into bioenergy feedstock production. It examines the effect of land conversion and agricultural best management practices (BMPs) on water quality (nutrients and suspended sediments) and hydrology. The strategy was applied to the watershed of the South Fork Iowa River in Iowa, where the focus was on converting low-productivity land to provide cellulosic biomass and implementing riparian buffers. The Soil and Water Assessment Tool (SWAT) was employed to simulate the impact at watershed and sub-basin scales. The study compared the representation of buffers by using trapping efficiency and area ratio methods in SWAT. Landscape design and management scenarios were developed to quantify water quality under (i) current land use, (ii) partial land conversion to switchgrass, and (iii) riparian buffer implementation. Results show that implementation of vegetative barriers and riparian buffer can trap the loss of total nitrogen, total phosphorus, and sediment significantly. The effect increases with the increase of buffer area coverage. Implementing riparian buffer at 30 m width is able to produce 4 million liters of biofuels. When low-productivity land (15.2% of total watershed land area) is converted to grow switchgrass, suspended sediment, total nitrogen, total phosphorus, and nitrate loadings are reduced by 69.3%, 55.5%, 46.1%, and 13.4%, respectively. Results highlight the significant role of lower-productivity land and buffers in cellulosic biomass and provide insights into the design of an integrated landscape with a conservation buffer for future bioenergy feedstock production. Published 2015. This article is a U.S. Government work and is in the public domain in the USA. Biofuels, Bioproducts and Biorefining published by Society of Industrial Chemistry and John Wiley & Sons Ltd.

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Keywords: riparian buffer; vegetative barrier; landscape design and management; bioenergy production; switchgrass; sediment; nutrient; nitrogen; phosphorus; South Fork Iowa River
Introduction

Since 1985, the US Department of Agriculture (USDA) National Resources Conservation Service (NRCS) has been recommending the development of conservation measures in agricultural landscapes. In the Midwest, conservation is particularly important because nitrate and phosphorus runoff from corn and soybean fields potentially affects downstream water quality. Historically, corn and soybean crops have been the dominant conventional feedstocks for biofuel production. In recent biofuel feedstock development, researchers began to investigate how we can mitigate potential negative impacts by incorporating cellulosic feedstock production and conservation practices. Conceptually, integrated landscape design and management can serve the purpose of maintaining land productivity while protecting water resources. This approach—a combination of land conversion to grow energy crops and implementation of best management practices (BMPs) for conservation practices—enables cellulosic biomass production while benefiting soil and water quality. Switchgrass, a high-energy herbaceous perennial, is regarded as a promising candidate for the production of second-generation biofuels because of its attributes for conservation. Switchgrass has long been selected for use in natural resource conservation programs for its effect on the control of soil runoff and nutrient leaching, limiting negative soil property changes, improving soil organic carbon content, and increasing biodiversity. One option for switchgrass application is to convert low-productivity land or idle land to switchgrass farms.

The NRCS defines conservation buffers as small areas or strips of land with permanent vegetation, designed to intercept such pollutants as nitrogen, phosphorus, pesticides, pathogens, herbicides, and sediments before they enter water bodies. Conservation buffers include riparian buffers, vegetative barriers, and others. A riparian buffer is set adjacent to a stream, whereas vegetative barriers are typically placed in field borders. Buffers have been applied to a considerable extent in agricultural lands, and water quality improvement has been demonstrated at various scales. This study focuses on vegetative barriers and riparian buffers.

Land and hydrologic models have been developed to describe land use and buffers. SWAT is a physically based, watershed-scale simulation model for assessing hydrologic properties and water quality associated with land cover and land use. The model incorporates key parameters and variables, including hydrology, topography, soil properties, weather information, erosion, crop growth, and agricultural inputs and management practices. SWAT simulates buffers by using two methods. The first, the trapping efficiency method, uses the width of buffers as a key parameter, where trapping efficiency is calculated by the reduction of sediment and nutrient loadings transported by in-surface runoff through buffers. The second method, vegetative filter strip (VFS), which was developed by Munoz-Carpena, was derived from 22 published studies. The VFS calculates buffer efficiency on the basis of the ratio of total land area to buffer area (area ratio method). The trapping efficiency method allows for convenient application with only one parameter (buffer width), whereas users have more flexibility with the ratio method, in which runoff concentrations and fractions of water flow concentrations can be defined as inputs. Previous studies investigated impacts of different buffer widths from 9 to 50 m on water quality in agricultural land. A buffer width of greater than 50 m was also considered. Switchgrass and Bermuda grass were often selected as buffer crops. Most studies showed positive improvement in water quality with the application of a buffer. However, literature on the methodology selection and evaluation of buffers (vegetative barriers and riparian buffers) at the watershed scale is limited.

The purpose of this study is to (i) evaluate the representation of buffers in SWAT modeling; (ii) quantify the impacts of vegetative barriers and riparian buffers on water quality in future biofuel feedstock production scenarios, including land conversion to switchgrass; and (iii) study the application of a riparian buffer. The study area is located at the South Fork Iowa River (SFIR) watershed in central Iowa, which covers 80,029 ha, and is predominately agricultural land (Fig. 1). Major crops include corn and soybeans. The study further compares the model resolution, assumptions, and application range at the sub-basin scale. Results highlight the capabilities and limitations of characterizing buffer areas on agricultural land and provide insights into integrated landscape design and conservation management for future bioenergy feedstock production.

Scenarios

Three scenarios were developed for this study and applied to the SFIR watershed to evaluate water quality and hydrology under the following proposed land use scenarios:

- Scenario 1. Current land use
- Scenario 2. Partial land conversion to switchgrass
- Scenario 3. Riparian buffer implementation
Scenario 1 represents the current landscape in the SFIR watershed, based on the SWAT model simulation of the historical record for 2000–2009. The second scenario, partial land conversion to switchgrass, represents a landscape design where low-productivity land and idle land are converted to grow switchgrass. Scenario 3 – riparian buffer implementation – assumes that a 30 m and a 50 m buffer are installed in the entire stream network in the SFIR watershed.

Data source and methods

SWAT base model development

The SWAT base model was developed, calibrated, and validated by using 10 years (2000–2009) of meteorological and monitoring data from the National Oceanic and Atmospheric Administration (NOAA), US Geological Survey (USGS), and Conservation Effects Assessment Project (CEAP), as well as land cover, four-year crop rotation, management operation, stream networks, and USGS monitoring data. Observed monthly stream-flow data were obtained from USGS gauging station #05451210 at 42.315°N (latitude) and 93.152°W (longitude). The ArcSWAT 2012.10 model was used to simulate hydrologic properties, suspended solids, and nutrients. This SWAT base model includes 39 sub-basins and 1517 hydrologic response units (HRUs) in the SFIR watershed. Tile drainage was simulated because about 80% of the agricultural watershed is tile drained. The calibration and validation time frames selected were from 2000 to 2005 and from 2006 to 2009. After application of such conservation practices as vegetative barriers and riparian buffers at the watershed and sub-basin scale, the trapping efficiency and area ratio methods within SWAT were compared. Nutrients (nitrogen and phosphorus) and suspended sediments from runoff flow and lateral flow from the sub-basin and watershed outlet were analyzed. Alamo switchgrass was selected as the buffer species for planting in the riparian buffer. It also grows as a biomass feedstock where the land is converted from idle land and low-productivity land.

Input data

The Digital Elevation Model (DEM) with a 30 m resolution was obtained from the National Hydrography dataset (NHD, http://nhd.usgs.gov/). The HRUs were defined for 5% land use, 10% soil class, and 10% slope over sub-basin areas. A land use map was created from remote sensing data, which were collected on an annual basis from the Crop Data Layer (CDL) database as geographic information system (GIS) raster format files (these data are available at http://nassgeodata.gmu.edu/CropScape/). Four-year crop rotations of mainly corn and soybean combinations and based on years 2007, 2008, 2009, and 2010 were used for this study. Sequences of the four-year rotations were classified into eight different
Partial land conversion to switchgrass

The scenario is a proposed landscape design with corn-soybean rotations and newly established switchgrass where low-productivity land and idle land are converted to switchgrass. A proposed landscape design scenario was developed by integrating production of agricultural crops and energy crops (Ian et al.38). The scenario covers current and future land use and resulting changes in corn, soybean, pasture, forest, idle land, and switchgrass.

Simulating buffers – trapping efficiency and area ratio method

In this study, two different empirically based methods (trapping efficiency and area ratio) in SWAT were applied to model buffers as vegetative barriers and riparian buffers in the SFIR basin. Buffer widths of 5 m, 10 m, 15 m, 20 m, 25 m, and 30 m for vegetative barriers and 30 m and 50 m for riparian buffers were used in the trapping efficiency method (Supporting information A). The area ratio method is modeled at the HRU level in SWAT (Supporting information B). Ratios of buffer-implemented area to total field area from 1:10, 1:30, 1:40, 1:60, and 1:100 were evaluated for vegetative barriers, which are equivalent to 10%, 3.33%, 2.5%, 1.67%, and 1% of the agricultural area. For the riparian buffer, additional steps were taken to simulate the buffer area separately from the total field area. Other parameters include 0.5 for the fraction of the HRU that drains to the most concentrated 10% of the filter strip area and 0 for the fraction of the flow within the most concentrated 10% of the filter strip that is fully channeled. An agricultural area with a slope of 2–5% was selected for applying vegetative barriers. The riparian buffer areas were calculated by ArcGIS. The current SWAT version has limitations on the riparian features. For enhanced deposition associated with riparian buffers from upstream areas, the following values for the stable stage of the stream channel were assigned in SWAT: 0.2 for channel cover factor (CH_COV2)37 and 0.1 (natural streams, heavy timber, and brush) for Manning’s n value (CH_N2) in the main channel.

SWAT model calibration and validation

Calibration techniques for this study included manual calibration based on sensitivity analysis, auto-calibration by using SWAT calibration, and uncertainty procedures.
(CUP), as well as calibrated values from previous studies. The SWAT parameters selected for calibration, descriptions of the parameters, and calibrated values are shown in Table S1. Observed and simulated monthly streamflows and nitrate loadings are shown in Figs S1(a) and S1(b). Monthly flows have seasonal trends, with a peak in May (for most years), in both simulated and observed values. Nitrate loadings show a pattern similar to streamflows, with peaks during the growing season. The model performance was evaluated by using the coefficient of determination ($R^2$), Nash-Sutcliffe efficiency (NSE), percent bias (PBIAS), and ratio of the root mean square error to the standard deviation of measured data (RSR) (Table S2). A SWAT model is considered satisfactory if monthly NSE $> 0.5$, RSR $\leq 0.70$, and PBIAS $< \pm 25$ for streamflow and $\pm 25 \leq$ PBIAS $< \pm 40$ for nitrogen and phosphorus. For this study, the performance between observed and simulated stream flow was generally good or satisfactory for the calibration and validation periods (NSE 0.60–0.67; $R^2$ 0.72–0.85). The nitrate-loading performance was good or satisfactory (NSE 0.70–0.71, $R^2$ 0.76–0.80) (Table S2).

### Results and discussion

#### Effect of vegetative barrier

Vegetative barriers were evaluated by using the trapping efficiency and ratio methods. Figure 3(a) shows percent of reduction in suspended sediment yield (SS), organic nitrogen (ORGN), organic phosphorus (ORGP), total nitrogen (TN), total phosphorus (TP), and nitrate (NO$_3$) in the SFIR watershed with different buffer widths determined by using a trapping efficiency method. Vegetative barriers are most effective in control sediments. At a 30 m buffer, sediments decreased significantly by 70.7%, 68.0% for organic N, 63.7% for organic P, 55.5% for total N, and 59.0% for total P. Water quality indicators N, P, and SS are sensitive to initial placement of buffer. Even with a 5-m buffer width, reduction of sediments (42.2%), organic nitrogen (39.9%), organic phosphorus (38.6%), total nitrogen (30%), and total phosphorus (35.2%) could be achieved. The extent of reduction is not linear to the buffer width. With the same increment of buffer width (i.e., 5 m), the reductions were more pronounced with a change from zero to 5 m than with a change from 5 m to 10 m. For example, the reduction of sediments was 52% with a 10 m vegetative barrier, which is a small improvement compared with 42% when buffer width changed from zero to 5 m (Fig. 3(a)). Using the same modeling method, Moriasi et al. reported a 70% reduction of sediment loss when a 10 m Bermuda grass buffer was applied to agricultural lands in the Cobb Creek sub-watershed, OK. Differences in the study are the result of watershed geology, soil property, hydrology, agricultural crops, and land use. Nitrate is less responsive to the vegetative barriers. Implementing a 5 m buffer resulted in a reduction in nitrate of only 3.6%, although an increase in buffer width to 30 m could reduce nitrate by 6-fold (19.9%). Results indicate that organic nitrogen makes up a significant portion (>50%) of the total nitrogen in the watershed, suggesting that a vegetative buffer can trap organic nitrogen more efficiently than it can trap nitrate. The reduction rates remain flat when the buffer width increased beyond 30 m.

Changes in water quality indicators based on the area ratio method are presented in Fig. 3(b). Similarly, sediments had the most pronounced responses to an increase in vegetative barrier area from 1% (1:100) to 10% (1:10), which is represented by its reduction from 17.5% to 32.4%. The reduction of organic P (from 10.8% to 18.0%) was similar to reductions in organic N (9.2–17%). Total phosphorus decreased by 9.5–15.7%. Reduction of total nitrogen ranged from 7.0% up to 12.8% and was primarily affected by minimal reductions in nitrate (0.9–1.0%). Sahu and Gu reported that vegetative barriers with switchgrass covering 10% to 50% of the sub-basin area resulted in a higher reduction (55–90%) in NO$_3$ in the Walnut Creek watershed, IA, than is shown in the results from this study. A vegetative barrier was most effective in reducing sediment loadings in the watershed (followed by organic N and organic P) and less effective in nitrate control in the SFIR watershed.

#### Effect of riparian buffer

To understand the computation process and be better able to interpret model simulation results, we developed detailed riparian buffer measurements according to the watershed land maps across the entire stream network. As indicated in Fig. 4, implementing riparian buffer reduced the loss of all of the water quality indicators (suspended sediment, organic N, organic P, total N, total P, and nitrate) evaluated. An increase in buffer width (from 30 m to 50 m) resulted in higher reduction rates (Fig. 4). Among them, organic P and total phosphorus showed the largest reduction in a 30 m buffer. At a 50 m riparian buffer, approximately 6% of the nitrogen, phosphorus, and sediments loss can be avoided. Again, nitrate reduction was the lowest – 3% by using trapping method (Fig. 4). Note that at the watershed scale, the area ratio of 30 m riparian...
buffer to total watershed land is about 1.9%. With the similar area ratio, vegetative barriers could reduce sediment and nutrient loss by 6–17% (Fig. 3(b), ratio 1:100 [1% area]) and thus would be the preferred choice for this watershed.

When buffers were applied to riparian areas, similar results were found for the trapping efficiency and ratio methods with a 30 m buffer (Fig. 4). The two methods responded similarly to an increase in buffer width in the riparian area. At the 50 m level, the trapping method yielded slightly higher reductions, although the difference between the two methods is relatively small. The projection for nitrate loadings by the two methods varied. The trapping efficiency method is noticeably more sensitive to the installment of a riparian buffer at 30 m, whereas the ratio method is quick to respond to a change in buffer width to 50 m. Reduction of nitrate loss increased from 1.3% (30 m) to 3.3% (50 m) when using the trapping efficiency method, compared with 0.3% (30 m) and 1.8% (50 m) by using the ratio method—a six-fold increase. This study showed both methods can bring comparable riparian buffer representation when consistent assumptions are used in modeling. The trapping method tends to give slightly optimistic results at a 50 m buffer width.

![Figure 3. Reduction rates of suspended sediment (SS), organic N (ORGN), organic P (ORGP), total nitrogen (TN), total phosphorus (TP), and nitrate loadings (NO₃) when the vegetative barriers were applied to the agricultural fields, by using a trapping method (a) with the six buffer widths (5 m, 10 m, 15 m, 20 m, 25 m, and 30 m) and a ratio method (b) with five ratios of buffer-to-watershed area (1:100, 1:60, 1:40, 1:30, and 1:10). Values in parenthesis indicate percent of buffer lands in the watershed. The NO₃ reduction rates were around 1% for all scenarios when a ratio method was applied as vegetative barriers.](image-url)
Results suggest a sizable portion of nitrate loss in this watershed may not be occurring via surface runoff.

**Land area and biomass production in riparian buffer**

Switchgrass was grown on the riparian buffers and could be harvested as feedstock for biofuel production. Figure 6 presents a switchgrass biomass yield map, riparian application areas, and total biomass production at the sub-basin level in the SFIR watershed. Switchgrass yield varies from 15.3 to 23.7 tonnes/ha across the sub-basins (Fig. 6(a)). The location of a riparian buffer depends on the stream network (Fig. 2). At the sub-basin level, buffer areas vary from 0 to 176.6 ha (Fig. 6(b)) when a 30 m riparian buffer was
Scenario comparisons — impact of landscape change on water quality and quantity

To further understand the extent of the benefits of land conversion and buffer to water quality, three landscape scenarios were evaluated: current land use (Scenario 1), land conversion to switchgrass (Scenario 2), and riparian buffer application (Scenario 3). Figure 7 shows a land-use map for Scenario 2, where partial land conversion emphasizes a change across agriculture, pasture, forest, urban, and switchgrass in the SFIR watershed. This scenario describes a switch of land use from current (Fig. 8(a)) to an integrated agriculture and biofuel production landscape (Fig. 8(b)), with a significant increase in switchgrass area (15.2% of the total land area in the watershed). Total agricultural land decreased by 14.2%, of which 6.1% is from continuous corn and 8.1% is from other types of corn/soybean rotations. Changes in urban area, forest, and pasture are minimal (<1%) in Scenario 2 (Fig. 8). With Scenario 3, at 30 m of width, the riparian buffer accounts for 2.4% of total agricultural land and 1.9% of the total land in the watershed. The 2.4% buffer area is mostly from agricultural land.

Cropland conversion to grow switchgrass and riparian buffer implementation can significantly improve water quality in the SFIR watershed (Fig. 9). Both future scenarios (2 and 3) lead to a reduction of nutrient and sediment loss. When a riparian buffer with a 30 m width was installed (Scenario 3), the reductions at the watershed scale are 1.6% for suspended sediment, 1.3% for nitrate loadings, 1.2% for total nitrogen, and 2.4% for total phosphorus. The primary reason for this result is that less land (1.9%) is converted to buffer as compared with the land conversion rate under Scenario 2 (15.2%). The reduction of nutrients and sediments is also heterogeneous at the sub-basin.
level: from 0% to 55.3% for suspended sediment, 0.3% to 14.4% for nitrate loading, 0.4% to 41.2% for total nitrogen, and 0.5% to 45.1% for total phosphorus (Fig. 9). There is a unique distribution pattern of changes in nutrient and sediments across the watershed in Scenario 3. Suspended sediment, nitrate, total nitrogen, and total phosphorus had more reductions in the upstream region than in the downstream region (Fig. 9). Total phosphorus decreased across the watershed, whereas sediments, nitrate, and total nitrogen experienced an increase in a few sub-basins despite a decrease in a majority of the sub-basins.

The reduction of watershed loadings was more pronounced with Scenario 2. Converting a selected portion of cropland to switchgrass (Scenario 2) results in significant reductions in suspended sediments (69.3%), nitrate loadings (13.4%), total nitrogen (55.5%), and total phosphorus (46.1%) in the SFIR watershed. Suspended sediments showed the highest reductions watershed-wide, followed by total nitrogen, total phosphorus, and then nitrate. The degree of reduction varies substantially across the sub-basins. With few exceptions in some sub-basins where nutrients and sediments may increase, the reduction ranged from 9.6% to 81.7% for suspended sediment, from 1.9% to 32.2% for nitrate, 9.1% to 72.5% for total nitrogen, and 1.3% to 66.1% for total phosphorus at the sub-basin level (Fig. 9).

To analyze the effect of future scenarios on nutrient distribution, we further analyzed nitrate surface runoff and lateral flow under the three scenarios. Nitrate loadings at the watershed outlet accumulated from surface runoff and lateral flow are summarized in Table 1. Noticeably, the nitrate loadings in surface runoff stream decreased by 0.223 kg/ha and by 0.055 kg/ha when Scenarios 2 and 3 were applied, respectively. The amount of reduction in runoff nitrate is equivalent to 46% according to Scenario 2 relative to current land use (Table 1). On the contrary, changes in nitrate loading in lateral flow were minimal in Scenario 2 (0.8%). There were no changes in nitrate in groundwater under both scenarios. Scenario 2 reduced 13.4% of nitrate from the total of surface runoff, lateral flow, and ground water. Scenario 3 had similar and lower-level reductions (1.3%) of nitrate at a fraction (~10%) of the land conversion in Scenario 2. With an increase of land coverage by riparian buffer, a higher level of nitrate reduction can be expected. Results suggest land conversion to switchgrass represented by Scenario 2 can be most effective to curtail nitrate in surface runoff. Furthermore, a riparian buffer can have a positive impact by reducing nitrate loss in both surface runoff and lateral flow.
Figure 9. Current land use and percent changes of suspended sediment (SS), nitrate (NO₃), total nitrogen (TN), and total phosphorus (TP) compared to the base model, when different scenarios were applied to the South Fork Iowa River watershed.

Conclusion

The SWAT model was applied to evaluate buffers and integrated landscape management for agriculture and biofuel production by quantifying their impacts on stream flow, suspended sediment, and nutrients in the SFIR watershed. Both approaches can effectively mitigate nitrogen, phosphorus, and suspended sediment loadings for surface streams and runoffs. Nitrate reduction is less extensive. A vegetative barrier is most effective in reducing sediments loadings in the watershed, followed by organic N and organic P, and less effective in nitrate control in the SFIR watershed. A riparian buffer showed a similar level of nitrate reduction and is most effective in removing...
phosphorus, followed by nitrate and sediments. The magnitude of effect increases with an increase in the land area covered by switchgrass, as a buffer or as dedicated biomass farmland. SWAT represents a riparian buffer well with both the trapping efficiency and area ratio methods when consistent assumptions are applied.

Under a landscaping design (Scenario 2) in which switchgrass was grown in low-productivity land, suspended sediment, total nitrogen, and total phosphorus were reduced significantly. Installation of a riparian buffer with switchgrass for the entire watershed could have a similar effect, whereas water yield (resource) remains unchanged. While land conversion to switchgrass farming is able to capture a significant amount of nitrate in runoff, implementation of a riparian buffer can trap a similar level of nitrate from both lateral flow and surface runoff in the watershed studied. Moreover, a 30 m riparian buffer with switchgrass yields 26,074 metric tonnes of biomass per year, which translates to 4 million liters of biofuel production. The study highlights key approaches in integrated biomass and agriculture development. A careful landscape design and management of current agricultural lands while incorporating appropriate BMPs can effectively improve water quality and strengthen soil erosion control, with minimal impact on water resources, while producing food, feed, and feedstock for bioenergy and bioproducts. The concept can be integrated with other watershed management programs to enhance sustainability of land, water, and the ecosystem.

**Acknowledgments**

This work was funded by the US Department of Energy, Office of Energy Efficiency and Renewable Energy, Bioenergy Technologies Office (BETO). The authors would like to thank Ian Bonner, Kara Cafferty, and Jacob Jacobson from Idaho National Laboratory for developing the land use change scenarios. We also thank Kristen Johnson of BETO for the encouragement and support throughout the study. The submitted manuscript has been created by UChicago Argonne, LLC, Operator of Argonne National Laboratory (Argonne). Argonne, a US Department of Energy Office of Science laboratory, is operated under Contract No. DE-AC02-06CH11357. The US government retains for itself, and others acting on its behalf, a paid-up nonexclusive, irrevocable worldwide license in said article to reproduce, prepare derivative works, distribute copies to the public, and perform publicly and display publicly, by or on behalf of the Government.

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**Table 1. Nitrate loadings in various flows in the watershed.**

|                        | Scenario 1 | Scenario 2 | Scenario 3 |
|------------------------|------------|------------|------------|
| Surface runoff (kg N/ha) | 0.485      | 0.262      | 0.480      |
| Surface runoff change  | –          | –0.223 (-46.0%) | –0.055 (-1.2%) |
| Lateral flow (kg N/ha)  | 1.109      | 1.118      | 1.093      |
| Lateral flow change    | –          | 0.009 (0.8%) | –0.016 (-1.4%) |
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