Modeling the biogeochemical effects of rotation pattern and field management practices in a multi-crop (cotton, wheat, maize) rotation system: a case study in northern China

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Abstract. A cropping system with rotations between cotton and winter wheat-summer maize (W-M) is widely adopted in northern China. Optimizing the crop rotation in concert with the related field management practices of this system is crucial for reducing its negative impacts on climate and environmental quality. In this study, the approach used to identify the best management practice (BMP) relied on biogeochemical model simulations to determine the negative impact potential (NIP) and a set of constraints. The BMP is referred to as the scenario with the lowest NIP that satisfies the given constraints. All the variables of interest were generated using the DeNitrification-DeComposition version 95 (DNDC95) model with minor modifications relating to the NO production during nitrification. The modified DNDC95 model showed satisfactory performance in simulating the variables of interest with the available observations for two adjacent plots cultivated with cotton and W-M. The simulations of rotation patterns indicated that the proper rotation of cotton and W-M can simultaneously benefit the crop yields, soil carbon sequestration and greenhouse gas mitigation. Monte Carlo simulations with 6000 scenarios showed that the BMP for the system involved 3 consecutive years of cotton rotating with 3 continuous years of W-M. These practices used 18% less nitrogen fertilizer (i.e., 90 and 353 kg N ha⁻¹ yr⁻¹ for cotton and W-M, respectively) and 18% less irrigation water (i.e., 62–189 and 238–418 mm yr⁻¹ for cotton and W-M, respectively) under sprinkling than the conventional practices, incorporated 90% of crop residues, and adopted the current deep tillage (20–30 cm) for cotton but reduced tillage (10 cm) for W-M. In addition, three other alternative BMPs were also
screened with overlapping ranges of uncertainty. However, field confirmation of these BMPs resulting from the model-based virtual experiments is still required.

1 Introduction

Globally, fiber crops (i.e., cotton) and cereals such as wheat and maize have long played a relevant role in human society because they are primary sources of materials for the textile and food industries. In China, although cotton cultivation only covers 2.0–3.9% of the annual crop harvest area (there was a cotton lint production of 5.3–7.6 million metric tons from 2007–2016), the cultivation of cereals is quite large. Wheat and maize accounted for 39% and 26% of the harvest area and represented 129 and 220 million metric tons of grain, respectively, in 2016 (China Statistical Yearbook, 2017).

Northern China is both the second most important area of cotton production and the largest region of the winter wheat-summer maize double-cropping system (i.e., both crops are harvested within a year, and they are hereinafter referred to as W-M) in the country (e.g., Cui et al., 2014). Crop rotations of cotton and W-M have commonly been grown in this region, alternating every 3–5 years (e.g., Liu et al., 2010, 2014). During the last few decades, the yields of cotton, wheat and maize have been increased by employing intensified agricultural management practices, such as increased fertilizer inputs, advanced irrigation methods and so on (Han, 2010). A recent study indicated that the cotton cropping system in northern China persistently functioned as an intensive carbon or net greenhouse gas (GHG) source compared to W-M (Liu et al., 2019). These previous studies have revealed that the change in the storage of soil organic carbon (△SOC), net ecosystem GHG emissions (NEGE) and other biogeochemical processes involving the multiple cropping systems in northern China are likely closely related to the rotation pattern of cotton and W-M (e.g., Liu et al., 2010, 2014, 2019; Lv et al., 2014).

To maintain high productivity, the three-crop rotation systems for cotton and W-M in northern China are characterized by large additions of synthetic nitrogen fertilizers and irrigation water (e.g., Chen et al., 2014; Galloway et al., 2004), at 60–140 and 550–600 kg N ha\(^{-1}\) yr\(^{-1}\), and 140–200 and 90–690 mm yr\(^{-1}\) for cotton and W-M, respectively (Ju et al., 2009; Liu et al., 2014; Wang et al., 2008). High nitrogen and water inputs can result in high release potentials for nitrogenous pollutants, and they can induce a series of environmental problems, such as increased nitrate (NO\(_3^-\)) leaching for water
pollution (e.g., Collins et al., 2016). In addition, other field management practices, e.g., tillage and crop residue treatment, can also affect the emissions of reactive nitrogen and contribute to negative environmental effects (e.g., Zhang et al., 2017b; Zhao et al., 2016). Therefore, the evaluation of multiple-cropping systems (e.g., rotations of cotton and W-M) is shifting from a single-goal method aimed at increasing crop yields to a multi-goal approach (e.g., Cui et al., 2014; Garnett et al., 2013; Zhang et al., 2018). A multi-goal strategy aims to simultaneously sustain/increase crop productivity to ensure food security, increase SOC content to improve soil fertility, mitigate NEGE to alleviate climate warming, reduce ammonia (NH₃) volatilization and nitric oxide (NO) emission to secure air quality, and abate NO₃⁻ leaching to protect water quality.

An objective method is applied to identify the best management practice (BMP), which evaluates each decision variable with price-based proxies or other measures and screens the best option with the minimal negative impact potential (NIP) under the given constraints at an annual scale (e.g., Cui et al., 2014; Xu et al., 2017). To screen the BMP using the multi-goal approach, it is essential to quantify the biogeochemical effects of management practices at an annual scale. As field experiments often focus only on the decision variables of very few management practices during short periods (e.g., Ding et al., 2007; Liu et al., 2010, 2015; Wang et al., 2013a, b), the process-oriented biogeochemical models have the potential to overcome this limitation, through models such as the DeNitrification-DeComposition (DNDC) (e.g., Chen et al., 2016; Giltrap et al., 2010; Li, 1992, 2000; Zhang et al., 2017a), DAYCENT (e.g., Delgrosso et al., 2005) and LandscapeDNDC (e.g., Haas et al., 2012).

The DNDC model was selected in this study to investigate the biogeochemical effects of various cotton and W-M rotation patterns and their field management practices in southwestern Shanxi Province. The model version applied in this study, the DNDC95, has been modified from that of Cui et al. (2014), and it has been validated using comprehensive field measurements of cotton and W-M at the selected field site. The aim of this case study was to (i) validate the performance of the modified DNDC95 for the cotton and W-M cropping system, especially for the decision variables at an annual scale; (ii) investigate the biogeochemical effects of different rotation patterns between the cotton and W-M and those of the field management practices; and, (iii) identify the BMP by considering the rotation pattern and field management using a multi-goal strategy. These efforts were undertaken to test
the hypothesis that the sustainable intensification of the three-crop cultivation system that is focused on enhancing crop yields and simultaneously reducing environmentally negative impacts can be achieved through the optimization of the rotation pattern and associated field management practices.

2 Materials and methods

2.1 Brief introduction to the DNDC95 and its modification

The DNDC95 model used in this study is one of the latest DNDC versions (www.dndc.sr.unh.edu/model/GuideDNDC95.pdf). This model consists of two components with six modules in total. Driven by the given primary ecological factors, the former component simulates the field states of a soil-plant system, such as the soil chemical and physical status, vegetation growth and organic matter decomposition. Driven by the soil-regulating variables yielded by the former component, the latter component simulates the core biogeochemical processes of carbon and nitrogen transformations and the physical processes of liquid and gas transportations and thus the annual dynamics of net ecosystem exchanges of carbon dioxide (CO₂) (NEE); emissions of methane (CH₄), nitrous oxide (N₂O), NH₃ and NO; and NO₃⁻ leaching and the inter-annual dynamics of SOC and NEGE. These features enable the model to investigate the integrative biogeochemical effects of the rotation patterns of multiple crops and/or other management practices based on comprehensive validation. The minimum inputs used to facilitate the model simulation include (i) the meteorological variables of daily precipitation and maximum/minimum temperature; (ii) the soil (cultivated horizon) properties of the clay fraction, bulk density, SOC content and pH; (iii) the crop parameters for the yield potential, thermal degree days (TDD) for maturity, and the mass fractions and carbon-to-nitrogen (C/N) ratios of the grain, root and leaf plus stem; (iv) the management practice variables of sowing and harvest (dates), fraction of incorporated/retained residue at harvest, tillage (date and depth), irrigation (date, method and water amount), and fertilization (date, type, method, nitrogen amount and C/N ratio of organic manure); and (v) other variables (annual means of the NH₃ concentration in the atmosphere and the ammonium plus NO₃⁻ concentration in rain water). For more details about the model, please see Li et al. (1992) and Li (2000, 2007, 2016).

To improve the model performance during daily NO simulations for cotton cropping system, the
production process for NO (NO\textsubscript{p}) during nitrification was modified. For the original version by Cui et al. (2014), the NO production was simply quantified as a fixed fraction (0.003) of nitrification (F\textsubscript{ni}), which reflected a constant production rate of NO during nitrification. For the modified version, the effect of the soil moisture (SM in water-filled pore space (WFPS)) on NO production was incorporated in view of that applied during the N\textsubscript{2}O production process in nitrification (Eq. (1)). The maximum NO production rate (K\textsubscript{n}) was calibrated as 0.03 using the observed daily NO fluxes from 2007–2008 for the cotton cropping system. The incorporated soil moisture effects indicated that high soil moisture facilitated the production of NO during nitrification under the concept of an “anaerobic balloon”:

\[ \text{NO}_p = K_n \cdot F_{\text{ni}} \cdot \text{SM}^{3.0} \]  

(1)

2.2 Brief introduction to the selected field site and model validation

The field site (34°55.50′N, 110°42.59′E, altitude of 348 m) selected for this modeling case study is located at Dongcun Farm, near Yongji County, Shanxi Province, in northern China. The site is subject to a temperate continental monsoon climate, and it had an annual precipitation of 580 mm and a mean air temperature of 14.4 °C from 1986–2010 (Cui et al., 2014). Cotton, winter wheat and summer maize are the major crops grown at this farm and the surrounding regions. Field experiments were performed on two adjacent plots (each of which was 100 m wide and 200 long) for cotton and W-M in 2007–2010. The soil of the land cultivated with cotton and W-M was clay loam, with approximately 38% and 32% clay (< 0.002 mm), 57% and 50% silt (0.002–0.05 mm), 5% and 18% sand (0.05–2 mm), 10.0 and 11.3 g kg\textsuperscript{-1} SOC, 1.1 and 1.1 g kg\textsuperscript{-1} total nitrogen and pH (in H\textsubscript{2}O) of 8.0 and 8.7 at a 0–10 cm depth and bulk densities (0–6 cm depth) of 1.20 and 1.17 g cm\textsuperscript{-3} (Liu et al., 2010, 2011, 2012). A sprinkler system was applied to both plots. For more detailed information on the field experiments and observed data, please refer to Cui et al. (2014), Liu et al. (2010, 2011, 2014, 2015) and Wang et al. (2013a, b).

The modified model was validated in the plot cultivated with cotton. The daily meteorological data from 2004–2010 were obtained directly from Cui et al. (2014). The measured data were used directly for the minimum required soil properties. The input data on the field capacity and wilting point in the WFPS were 0.65 and 0.2, respectively, as cited from Cui et al. (2014). The crop parameters for cotton were directly determined by the field measurements, which were 1900 kg C ha\textsuperscript{-1} for potential
grain (1.2 times the mean of the measured values), 0.41 and 25, 0.16 and 40, and 0.43 and 40 for the mass fractions and C/N ratios of the grain, root and leaf plus stem, respectively, and 3600 °C for the TDD. Detailed management practices (Table S1) were obtained from Li et al. (2009) and Liu et al. (2014). Compared with the conventional fertilizer application rate of 110–140 kg N ha⁻¹ yr⁻¹ for the cotton, the fertilizer doses for 2007 and 2008 were reduced to 66–75 kg N ha⁻¹ yr⁻¹ by local farmers to avoid the overgrowth of the leaves in place of seeds or lint. The measured data used for calibration and validation were available for the soil (5 cm depth) temperature, topsoil (0–6 cm) moisture and N₂O and NO (the daily NO fluxes from 2007–2008 were used for the Kᵦ calibration and the data from 2008–2009 were used for validation) emissions from 2007–2009 (Liu et al., 2010, 2014), CH₄ uptake fluxes (Liu et al., 2019), grain yields, and NEE (Liu et al., 2019). In addition, because the model has been modified from the version used by Cui et al. (2014) for W-M in the adjacent plot, the W-M simulations were performed with the modified version again, using the crop parameters and other inputs adopted by Cui et al. (2014). The cotton and W-M validation data are detailed in Table S2. Thus, to identify the BMP, both the validations of cotton and W-M for the cumulative N₂O, NO and CH₄ under various field managements, NH₃ and NEE were also analyzed in this study.

2.3 Scenario settings and simulations

To investigate the biogeochemical effects of the rotation pattern and management practices, two levels of scenarios were explored. The level-I scenarios considered the rotation patterns. These patterns were set for a 6-year cycle based on surveys of local farmers (Liu et al., 2010, 2011, 2014). There were six level-I scenarios in total, which are hereinafter referred to as R₀, R₁, ..., R₅, and the number of the rotation indicated the years of consecutive cotton planting. For instance, R₀ denotes a 6-year monoculture of W-M; R₂ represents 2-year continuous cotton cropping rotated with 4 years of consecutive W-M; etc. Because the local farmers typically did not cultivate cotton monocultures in this region for longer than five years, the longest cotton monoculture was set as 5 years for the level-I scenarios. The transitions between cotton and W-M are detailed in Table S3. To study the biogeochemical effects of the rotation pattern, the baseline simulations of the level-II scenario (Tables S3–4) for each rotation pattern were analyzed.
The level-II scenarios addressed five field management factors, which were the (i) fertilizer dose, (ii) water amount and (iii) method of irrigation, (iv) incorporated/retained fraction of crop residues, and (v) depth of tillage. The values of the five factors used for the baseline were known as the observations for the conventional management practices in the experimental region (Tables S1, S3 and S4). The nitrogen application rates of the baseline were 110 and 430 kg N ha\(^{-1}\) yr\(^{-1}\) for cotton and W-M, respectively. Over the last few decades, the fields in this region have mostly been flood-irrigated (Liu et al., 2010), which was chosen as the baseline condition. The baseline timings and water amounts were established by referring to the 10- to 30-d cumulative precipitation prior to the individual irrigations and the recorded timings and water amounts of conventional management practices in both plots. Thus, the irrigation frequencies and annual cumulative water amounts of the baseline during the 18-year period (Table S4) vary from 1 to 3 times and 75 to 230 mm yr\(^{-1}\) for cotton and 4 to 6 times and 290 to 510 mm yr\(^{-1}\) for W-M. In addition, 100% residue incorporation and conventional tillage to a depth of 20–30 cm were applied for the baseline conditions. To screen the BMP of six rotation patterns in the interaction with all the considered management practices, the variation in the fertilizer amount, irrigation amount and residue incorporation rate was set as 40% of the baseline to the baseline (N44/172 to N110/430), 40% of the baseline to the baseline (I40 to I100) and 0 to 100% (R10 to RI100). The irrigated method and tillage factors consisted of flood (IF) and sprinkle (IS) irrigation and no-till (T0) and reduced tillage (5 cm and 10 cm, T5 and T10) for W-M and conventional tillage (20–30 cm, T20). We assumed that the frequency distributions of all the factors were uniform. Monte Carlo simulations, at 1000 combined field management scenarios, were used to screen the BMP for each rotation pattern, and the final BMP was selected from the BMPs of six rotation patterns in light of the 6000 combined scenarios.

An 18-year simulation was performed to assess the biogeochemical effects of the rotation patterns and management practices. These simulations were driven by the meteorological data observed at the Yuncheng station (approximately 60 km east to the experimental site) from 1996–2013 (http://data.cma.cn/data/cdcindex/cid/6d1b5efbdcbf9a58.html). To stabilize the carbon and nitrogen dynamics and reduce the residual effects of the initial conditions (Zhang et al., 2015), a spin-up of 12 years was performed (i.e., a period of two 6-year rotation cycles) before the 18-year simulations
The spin-up was driven by the same rotation pattern and field management practices as each scenario. For each scenario, the average values for each crop yield and the other decision variables were the averages of the 18-year simulations.

2.4 Method for identifying the best management practices

An objective method jointly relying on three constraints and NIPs was adopted in this study to identify the BMP. These constraints included (i) stable or increased crop yields, (ii) stable or increased SOC, and (iii) reduced NEGE. In the present study, the NEGE was the residual of the annual sum for the CH$_4$ and N$_2$O emissions minus the \( \Delta \)SOC and was quantified as a CO$_2$ equivalent (CO$_{2\text{eq}}$) quantity for the 100-year time horizon, at 1 for CO$_2$, 34 for CH$_4$ and 298 for N$_2$O (IPCC, 2013). The NIP was used to evaluate the potential for a climatically and environmentally integrative impact, which was a price-based proxy quantity in USD ha$^{-1}$ yr$^{-1}$. The NIP was determined by using the quantities of individual decision variables and their coefficients as mass-scaled price-based proxies (Eq. (2)).

\[
\text{NIP} = k_1 \text{NEGE} + k_2 \text{NH}_3 + k_3 \text{NO} + k_4 \text{N}_2\text{O}_{\text{ODM}} + k_5 \text{NL}
\] (2)

In Eq. (2), the NEGE, NH$_3$, NO, N$_2$O$_{\text{ODM}}$, and NL represent the multi-goal decision variables of the net ecosystem GHG emission (Mg CO$_{2\text{eq}}$ ha$^{-1}$ yr$^{-1}$), NH$_3$ volatilization, NO emission, release of N$_2$O as depleted ozone layer matter and hydrological nitrogen loss (mainly by NO$_3^-$ leaching), respectively (kg N ha$^{-1}$ yr$^{-1}$ for all the nitrogen compound variables). The coefficients \( k_1, k_2, k_3, k_4 \) and \( k_5 \) are mass-scaled price-based proxies for the NEGE, NH$_3$, NO, N$_2$O$_{\text{ODM}}$, and NL, respectively. Their values as presented in Cui et al. (2014) were directly used in this study, and they were 7.00 USD Mg$^{-1}$ CO$_{2\text{eq}}$ and 5.02, 25.78, 1.33 and 1.92 USD kg$^{-1}$ N for \( k_1, k_2, k_3, k_4 \) and \( k_5 \), respectively.

In Eq. (2), a lower NIP indicates a better set of management practices that can exert smaller negative impacts on the climate and environment. Accordingly, the BMP was identified as the scenario with the lowest NIP among the scenarios that could satisfy all three constraints. According to the BMP screening method used in this study, a solid validation of the cumulative emissions of N$_2$O, NO, NEE and CH$_4$ was the basis for identifying the BMP, rather than those at the daily scale.
2.5 Statistics and analysis

The statistical criteria of the (i) index of agreement (IA) (Eq. (3)), (ii) Nash-Sutcliffe efficiency index (NSI) (Eq. (4)) (e.g., Moriasi et al., 2007; Nash and Sutcliffe, 1970), (iii) determination coefficient ($R^2$) (Eq. (5)) and slope of a zero-intercept univariate linear regression (ZIR) of observations ($o$) against simulations ($s$) (Jiang, 2010) and (iv) model relative bias (MRB) (Eq. (6)) (e.g., Congreves et al., 2016; Willmott and Matsuura, 2005) were simultaneously used to evaluate the model validity. In Eqs. (3–6), $k$ and $n$ ($k = 1, 2, ..., n$) denote the $k$th pair and the total pair number of the values, respectively, and $\bar{o}$ represents the mean of the observations. The IA index falls between 0 and 1, with a value closer to 1 indicating a better simulation, and vice versa. An NSI value between 0 and 1 shows acceptable model performance. Better model performance is indicated by a slope and an $R^2$ value that is closer to 1, and vice versa. The MRB is expressed as a percentage, wherein $\bar{s}$ denotes the average of the simulations.

In this study, the MRBs of the cumulative N$_2$O, NO, NEE and CH$_4$ amounts were regarded as the relative uncertainty of the model validation, and they were further used to estimate the relative uncertainty of each scenario based on the error transfer formula (Eqs. (S1–S4)).

\[
IA = 1 - \frac{\sum_{k=1}^{n} (s_k - o_k)^2}{\sum_{k=1}^{n} (s_k - \bar{o})^2 + \sum_{k=1}^{n} (o_k - \bar{o})^2}
\]  

(3)

\[
NSI = 1 - \frac{\sum_{k=1}^{n} (o_k - s_k)^2}{\sum_{k=1}^{n} (o_k - \bar{o})^2}
\]  

(4)

\[
R^2 = 1 - \frac{\sum_{k=1}^{n} (o_k - \bar{o}_k)^2}{\sum_{k=1}^{n} (o_k - \bar{o})^2}
\]  

(5)

\[
MRB = 100 \left| \frac{\bar{s} - \bar{o}}{\bar{o}} \right|
\]  

(6)

In this study, the ZIR analysis, variance analysis, and graphical comparison were performed with SPSS Statistics Client 19.0 (SPSS Inc., Chicago, USA) and Origin 8.0 (OriginLab, Northampton, MA, USA) software.
3 Results

3.1 Model validation

3.1.1 Validation for the cotton cropping system

The seasonal dynamics and magnitudes of the soil (5 cm) temperature and topsoil (0–6 cm) moisture were predicted well by the model simulations (Figs. 1a–b). The sound model performance was indicated by the IA, NSI, and ZIR slope and the $R^2$ values of 0.98 and 0.83, 0.93 and 0.15, 0.93 and 0.83, and 0.95 ($n = 677, P < 0.001$) and 0.42 ($n = 432, P < 0.001$) for the temperature and moisture, respectively.

To compare the cotton yields (seeds plus lint) over three consecutive years (2008–2010), the simulations and observations were also highly consistent, with an MRB of 6%, which was less than two times the spatial coefficient of variations (CVs) (39–56%) for the measurements (Liu et al., 2014, 2019).

The simulated seasonal patterns and peak emissions of N$_2$O and NO generally matched the observations (Figs. 1c–d). The simulations showed a relatively low modeling efficiency for daily fluxes, as indicated by the IA, NSI, and ZIR slope and the $R^2$ values of 0.77, < 0, 0.48 and 0.40 ($n = 592, P < 0.001$), respectively, for N$_2$O and the values of 0.78, < 0, 0.54 and 0.39 ($n = 333, P < 0.001$), respectively, for NO. In comparison, the modified model significantly improved the model performance for the daily NO fluxes, especially for emissions in the spring. The IA, NSI, and ZIR slope and the $R^2$ values increased from 0.62 to 0.78, -1.03 to -0.04, 0.37 to 0.54 and 0.09 to 0.39, respectively.

In addition, the simulated annual N$_2$O and NO emissions during the two consecutive experimental years were comparable with the observations, with MRBs of 2% and 11%, respectively, both of which were less than two times the spatial CVs (23–50%) for the measurements (Liu et al., 2014).

The simulated NEE flux is one component of the ΔSOC, which is a key factor that is considered during BMP identification. The simulation suggested that the model captured the seasonal fluctuations, which were negative during the cotton-growing season, but positive or neutral during the remaining periods (Fig. 1e). The IA, NSI, and ZIR slope and $R^2$ were 0.76, 0.38, 0.85 and 0.39 ($n = 365, P < 0.001$), respectively, for the daily NEE simulation. For the annual cumulative NEE in 2009 and 2010,
the model simulation showed an MRB of 10%, which was less than the reported uncertainty (25%) of the observations (Wang et al., 2013a).

For the CH₄ uptake, the observations and simulations showed similar seasonal variations (Fig. 1f), with the IA, NSI and ZIR slope and an $R^2$ of 0.68, < 0, 0.72 and 0.15 ($n = 69$, $P < 0.01$), respectively. The model simulation of the annual cumulative CH₄ uptake in 2009 and 2010 yielded an MRB of 2%, which was less than two times the spatial CVs (13–17%) of the observations (Liu et al., 2019).

3.1.2 Validation of the cumulative emissions of both cropping systems used for BMP identification

To screen the BMP of the cotton and W-M rotation system under various management practices based on the annual simulation results, the model performances for the cumulative N₂O, NO, NEE and CH₄ were required for validation. According to the updated results of Cui et al. (2014) and this study using the modified model, the model showed satisfactory performances for simulating the cumulative variables, with ZIR slope and the $R^2$ values of 0.90 and 0.83 ($n = 12$, $P < 0.001$), 0.90 and 0.94 ($n = 11$, $P < 0.001$), 0.98 and 0.99 ($n = 5$, $P < 0.001$), and 0.99 and 0.91 ($n = 7$, $P < 0.001$) for the cumulative N₂O, NO, NEE and CH₄, respectively, which provided a solid basis for the BMP identification at this site scale (Fig. 2). These results suggested that the DNDC95 model could be applicable in investigating the biogeochemical effects of different rotation patterns between the cotton and W-M and the effects of different management practices.

3.2 Biogeochemical effects of different cotton and wheat-maize rotation patterns

Figure 3 illustrates the dynamics of the crop yields and each decision variable resulting from the consecutive simulations over 18 years for all the rotation pattern options subject to the field management practices of the baseline scenario (Table S5). Figure 4 shows the relationship between the annual average of each decision variable and the number of consecutive years of cotton monoculture within the rotation pattern options.

The average grain yields for the cotton, wheat and maize were not significantly different among the various rotation pattern options, with averages of 3.5, 4.8 and 6.7 kg dry matter ha⁻¹ for cotton, wheat and maize, respectively (Figs. 3a–c).

For the dynamic changes in the annual SOC stocks, the values were generally positive for W-M.
but negative for the cotton, except for the first year after the transition to this fiber crop. As indicated by Fig. 3d, the simulated SOC contents over the 18-year period increased for $R_0$, $R_1$, $R_2$ and $R_3$ but decreased for $R_4$ and $R_5$. The annual average $\Delta$SOC increased significantly ($P < 0.001$) with an increase in the consecutive years of cotton monoculture from 0 to 5 within the 6-year rotation cycle (Fig. 4a). The rotation pattern options with baseline management showed small variations in the CH$_4$ uptake (Fig. 3e), with the annual uptakes ranging from 1.6 to 2.1 kg C ha$^{-1}$. However, the annual averages for the CH$_4$ uptake increased significantly ($P < 0.001$) with the increased consecutive years of cotton monoculture (Fig. 4b). For N$_2$O, the annual emissions showed large inter-annual variations (Fig. 3f), with a CV of 26–48%. In addition, the annual average emissions of this gas decreased significantly from 4.6 to 2.6 kg N ha$^{-1}$ (Fig. 4c) after increasing consecutive years of cotton monoculture ($P < 0.001$). As a result, the NEGE was significantly promoted ($P < 0.01$) (Figs. 3g and 4d).

Regarding the gaseous air pollutants NH$_3$ and NO, the simulated annual emissions ranged from 17 to 103 and 0.5 to 3.3 kg N ha$^{-1}$, respectively (Figs. 3h–i). Figures 4e and f show that the average annual emissions of both gases were significantly reduced after increasing the consecutive years of cotton monoculture ($P < 0.001$). The annual NO$_3^-$ leaching of the different rotation patterns displayed significant inter-annual variations (Fig. 3j), with CVs of 41–69%. Thus, the annual averages for NO$_3^-$ leaching changed insignificantly in response to the consecutive years of cotton monoculture (Fig. 4g).

The NIP varied significantly among the various rotation pattern options ($P < 0.001$), declining from 610 to 324 USD ha$^{-1}$ yr$^{-1}$ with increased consecutive years of cotton monoculture (Fig. 4h). For the three constraints, the crop yields showed no obvious differences among the various rotation patterns. Both $R_0$ and $R_3$ represent the typical rotation patterns in the region. The simulations for the former indicate the greatest increase in SOC and the lowest NEGE but the highest NIP, while those for the latter show the greatest SOC loss and the largest NEGE but the lowest NIP (Figs. 4a, d and h). These patterns indicate that neither typical rotation pattern is sustainable.

3.3 Identification of best management practices

The Monte Carlo simulation showed that only 51, 22, 16, 9 and 16 of the 1000 combined scenarios from $R_0$ to $R_5$ simultaneously satisfied the three constraints, while no scenario met all the
The screened BMPs for the five rotation patterns indicated that a reduction in the amount of fertilizer and irrigation water can be applied for all the rotation patterns, with the declines of 15–21% and 18–27% for the BMPs (87–94 and 334–367 kg N ha⁻¹ yr⁻¹, and 55–189 and 211–418 mm yr⁻¹ for the cotton and W-M, respectively). In addition, when compared with flood irrigation, sprinkle irrigation was adopted for all the BMPs except that for R₄. The rate of residue incorporation for the BMPs ranged from 55–90%, which increased with the increased consecutive cotton monoculture years. Regarding the depth of tillage, except for the 10 cm and no-tillage treatment for the BMPs of R₃ and R₄, the depths of other rotation patterns were all 5 cm. Compared with the baseline of each rotation excluding the R₅, the NEGE, NH₃ volatilization, NO₃⁻ leaching and NIP of the BMPs decreased by more than 4%, 20% 41% and 27%, respectively. When ranking the NIPs of each rotation BMP, the final BMP was identified as the BMP of R₃ (N90/353_I82_IS_RI90_T10), with an NIP of 327 USD ha⁻¹ yr⁻¹.

Although the NIP of the BMP for R₄ was slightly lower than that for R₃, the NEGE and ΔSOC were 20% higher and 71% lower than that of the final BMP, respectively, and the technology required for no-tillage, such as planting, was not widely available.

The identified BMP for the cotton and W-M rotation system showed the following management features: (i) both cotton and W-M are cultivated for three consecutive years within a 6-year rotation cycle; (ii) the present crops and the current schedules of planting, harvesting, fertilization (date, depth, and splits) and irrigation (date and times) are adopted; (iii) urea is applied at a 18% lower rate, namely, 90 and 353 kg N ha⁻¹ yr⁻¹ for cotton and W-M, respectively; (iv) 18% less water is used for irrigation by sprinkling than the conventional level; (v) the rate of crop residue incorporation is 90% at harvest; and (vi) conventional tillage (20–30 cm depth) for cotton but reduced tillage (10 cm depth) for W-M are applied. In comparison to the R₃ baseline, i.e., the currently applied field management practices, the identified BMP could produce stable crop yields and enlarge the ΔSOC (by 4% on average) while decreasing the NEGE (by −4% on average), NH₃ volatilization (by −23% on average), NO emissions (by −9% on average) and NO₃⁻ leaching (by −44% on average) (Table 1).

3.4 The uncertainty of the best management practice

Compared with the simulation results by the model version of Cui et al. (2014), the $R^2$ of ZIR by
the modified model for the cumulative N₂O, NO, NEE and CH₄ increased by 0–8%, and thus reduced the model uncertainty for validation at an annual scale. In addition, the relative uncertainty resulting from the model validation was calculated based on the MRB and error transfer formula (Eqs. (S1−4)). The MRBs of the cumulative N₂O, NO, NEE and CH₄ for cotton and W-M were 2% and 8%, 11% and 11%, 10% and 4%, and 2% and 2%, respectively, and the MRB of the cumulative NH₃ for W-M was 6%. These percentages were used to calculate the relative uncertainty of the NIP for all 6000 scenarios.

For the BMP of each rotation pattern, the scenarios, for which the uncertainty ranges had some overlap with that of the BMP, showed no significant differences from one another. Thus, 6, 7, 4, 3 and 0 alternative scenarios were selected for the BMPs of R₀, R₁, R₂, R₃ and R₄, respectively, with an average relative uncertainty of 3.7%. For the final identified BMP of N90/353_I82_IS_R190_T10 involved in the R₃ rotation pattern, the relative uncertainty of the NIP was 3.1%, ranging from 317 to 338 USD ha⁻¹ yr⁻¹. There were three other alternative scenarios (N94/366_I94_IS_R175_T20, N94/366_I91_IS_R195_T10 and N97/378_I88_IS_R170_T5) in R₃, which indicated the trade-off effects of different field managements, such as the opposite effect of reduced residue incorporation (decrease ΔSOC) and tillage depth (increase ΔSOC) on the ΔSOC. These scenarios were also regarded as alternative BMPs for the system (Table 1).

4 Discussion

4.1 Model performance

The DNDC model has been widely applied in agricultural systems around the world. The modified model version used in this study showed good performance in simulating the crop yields, NEE, NH₃, CH₄ uptake, emissions of N₂O and NO and related soil factors for the land cultivated with cotton and W-M under various field management treatments. The satisfying validations of both cropping systems, especially for the decision variables at an annual scale used for the scenario analysis, suggest that the DNDC95 model can be applied to quantify the decision variables and related factors for the cotton and W-M rotation system under different management practices.

The well-simulated soil environmental factors (soil temperature and moisture) and crop yields provided a solid basis for further simulating the decision variables to quantify the NIP under any
condition. The soil environmental factors and crop yields are the key factors regulating the biogeochemical processes and indicator of essential processes in plant nitrogen uptake (Chirinda et al., 2011; Kröbel et al., 2010). For the simulations of the N\(_2\)O and NO emissions, discrepancies in daily emissions generally occur in DNDC models and other current biogeochemical models due to the complex interactions among soil environmental factors and carbon and nitrogen processes (e.g., Bell et al., 2012; Chirinda et al., 2011; Cui et al., 2014; Lehuger et al., 2011; Zhang et al., 2015), which resulted in the time lags between the observations and simulations. For the cotton in this study, the underestimated daily NO fluxes in the spring in the model from Cui et al. (2014) was improved by the modified model. However, the improvements in the daily NO fluxes did not significantly affect the annual cumulative emissions, which were not major contributors to the annual emissions (Liu et al., 2015). The temporal variations in both the observed and simulated NEE indicated that the cotton field frequently assimilated atmospheric CO\(_2\) during the vigorous growth stages but emitted CO\(_2\) to the atmosphere during the other periods. However, the abrupt NEE increases during the growing season on cloudy or rainy days were still not well simulated due to the calculation of plant growth relying on cumulative daily temperatures over 0 °C and the TDD parameter (e.g., Cui et al., 2014). However, this defect did not result in significant biases in the cumulative NEE. Therefore, the identified BMPs that depended on the simulated annual NEE were reliable. For the simulations of other nitrogen losses from the cotton field, the NO\(_3^-\) leaching accounted for 9–12% of the applied fertilizer nitrogen for model validation, which was comparable with the field measurements of 16–17% (Liu et al., 2014).

The model validation suggests that the satisfactory simulation of decision variables at an annual scale provided a solid basis for the BMP identification, but the scientific processes for determining the photosynthesis and ecosystem respiration in CO\(_2\) fluxes (both as the NEE components) on cloudy and rainy days still require improvements in future studies. Because there were no observations of NH\(_3\) volatilization and NO\(_3^-\) leaching from the experimental cotton field, this validation study did not include both decision variables. Thus, future studies still required further validation of the model performance using comprehensive observations covering both decision variables as well as others.
4.2 Biogeochemical effects of the rotation pattern and management practices

The scenario analysis relying on model simulations in this study showed that environmental contamination can be reduced while i) sustaining crop yields, ii) increasing soil carbon sequestration and iii) decreasing the net ecosystem GHG emissions. Reductions in environmental contamination are attributed to the better synchronization of crop nitrogen requirements and soil nitrogen availability.

For cotton, a period of 5 consecutive years is usually applied as the longest cotton monoculture to stabilize its yields. In addition, balanced elemental nutrients have been applied during cotton cultivation, and thus the negative effect of monoculture on cotton yields can be offset in practice (Han, 2010). Because the DNDC model assumes balanced nutrient supplies for any crops as well as optimum phytosanitary conditions, the negative effects of monoculture are not accounted for here (e.g., Li, 2017).

The simulated positive annual changes in the SOC for W-M were mainly attributed to the incorporation of the full aboveground residues (at rates of 5.1–7.0 Mg C ha$^{-1}$ yr$^{-1}$), which favored for carbon sequestration (Han et al., 2016). However, the negative annual changes in the SOC for the cotton cropping system resulted from notable CO$_2$ emissions over a long fallow season relative to that of W-M (Liu et al., 2019). As a remarkable carbon sink, the W-M under the incorporation of the full crop residues could completely compensate for the SOC lost during the first cotton-planting year following the W-M cultivation. Thus, the annual change in the SOC was generally positive during the first cotton cultivation year. The rotation patterns of $R_0$ acted as net GHG sinks since the increased SOC exceeds the increased N$_2$O emission related to W-M cultivation, while the others all functioned as net GHG sources. The higher fertilizer application rate for W-M than for cotton resulted in the more reactive nitrogen remaining in the soil (Chen et al., 2014; Ju et al., 2009), thereby stimulating higher emissions of nitrogenous air pollutants and N$_2$O in the trials with fewer cotton cultivation years. Therefore, the appropriate rotation pattern of cotton and W-M can realize sustainable intensification with maximum yield and economic benefits, a balanced soil organic carbon budget and minimal negative impacts on the environment.

Northern China, as the most important agricultural region, experienced an increase in crop yields by a factor of 2.8 from 1980–2008, during which the application of mineral fertilizers increased by a factor of 5.1. The rapid increase in fertilizer use has resulted in excessive nitrogen remaining in the soil,
posing potential risks for the environment (Chen et al., 2011; Zhang et al., 2017b). To solve this problem, a reduction in fertilizer application was proposed in several previous studies (e.g., Chen et al., 2011, 2014; Liu et al., 2012). The results of the scenario analysis in this study indicated that, for all the rotation patterns, further reducing the farmer-optimized nitrogen doses by 15–21% (87–94 and 334–367 kg N ha⁻¹ yr⁻¹ for the cotton and W-M, respectively) could sustain the crop yields while greatly decreasing the emissions of nitrogenous gases. In addition to fertilization, over-irrigation has also been ubiquitous in northern China for a long time, and it threatens the water security of this region due to the sharply declining groundwater table and water pollution (Gao et al., 2015; Ju et al., 2009).

For this reason, only management options for reducing the amount of irrigation water should be considered under the severe shortage of water resources. In addition, adopting sprinkling irrigation instead of flood irrigation for an equal amount of water showed positive effects on the crop yields, indicating improved irrigation efficiency (Zhang et al., 2017b). This result indicates that rather than blindly using larger nitrogen doses, increasing the water-use efficiency through the application of alternative irrigation techniques could be a pathway to sustaining crop yields with reduced nitrogen addition. Through a ban on burning crop residues in fields, the return of these residues to the field is strongly suggested by the government. The simulated results indicated that this practice can simultaneously increase crop yields, soil carbon storage and emissions of N₂O and NO while decreasing the NEGE. These simulations were consistent with the results of field observations (Liu et al., 2011). Reduced tillage practices have been promoted in China in recent decades. To facilitate the decomposition of woody cotton residues and avoid outbreaks of diseases and pests due to the continuous implementation of reduced tillage or no-tillage practices, the tillage practices were only adjusted in the W-M plots, while deep tillage was maintained for cotton when setting the tillage scenarios. The simulations showed that the reduced tillage or no-tillage practices could sustain the crop yields and reduce the NH₃ volatilization and NO₃⁻ leaching (e.g., Zhao et al., 2016).

As shown above, an appropriate combination of the rotation pattern and management practices can satisfy the three constraints while resulting in the lowest NIP. The direct observations from the field experiments are usually far less sufficient for screening this type of appropriate combination due to limited resources and labor. However, identifying the appropriate combination is one of the purposes of
4.3 Evaluation of the best management practice

The scenario analysis was effective at screening for the BMP. The BMP could sustain the crop yields of the three-crop rotation system, increase the SOC stock, mitigate the N$_2$O emissions and NEGE, reduce the emissions of NH$_3$ and NO, and reduce the NO$_3^-$ leaching due to the enhanced resource use efficiency in response to the reduced nitrogen-fertilizer dose and irrigation water amount. Hence, the BMP could result in a more dramatically reduced NIP than the others. In addition, the alternative scenarios with overlapping ranges of uncertainty were also chosen as BMP alternatives, although the increase in fertilizer and irrigation increased the negative effects to some extent. Because the identified BMP was based on the sufficient validation only at this site, it should be the potential BMP in this region, but additional validations for other sites in this region are still required to confirm the BMP.

The uncertainty of the model validation for the screened BMP was evaluated in this study (3.1%). However, there are three other unquantifiable factors. The first is the possible limitation of the applied model, which cannot simulate the potential effects of monoculture on weeds and diseases, as well as yields. The continuous cultivation of these crops, especially for cotton, could lead to challenges in weed and disease management. In addition, the continuous no-tillage scenarios for W-M could also increase the weed and disease pressure. However, these effects could not be adequately addressed by the current model. Thus, the proper parameterization of the monoculture and no-tillage effects on the weeds and diseases as well as the yields would be beneficial for screening the more realistic and effective BMP.

The second concern is the insufficient data for model validation. Due to the lack of observations, the model simulations on NH$_3$ fluxes for cotton cultivation and those on NO$_3^-$ leaching in both the cotton and W-M cropping systems were not validated. The DNDC model has been established by following the mass conservation law. In other words, this model can accurately reflect the mass balance of the nitrogen budget for the simulated soil layer (0–50 cm depth). This model principle implies that
only one budget item could be omitted for validation. This item is usually soil nitrogen loss through the production of dinitrogen gas, mainly by denitrification, which is very difficult to measure in situ (e.g., Wang et al., 2013). For both cropping systems, the nitrogen lost through this pathway could be almost fully inhibited in the topsoil, wherein the soil moisture contents were often lower than 60% WFPS (Linn and Doran, 1984; Liu et al., 2011, 2014). The model principle also implies that the uncertainty in the NO\textsubscript{3}\textsuperscript{−} leaching simulation during cotton cultivation might have been larger than that of W-M cropping system since the former has one more decision variable (i.e., NH\textsubscript{3} volatilization) not directly validated by observations. These situations suggest that the current uncertainties may not be reduced unless the simulations of both NH\textsubscript{3} volatilization and NO\textsubscript{3}\textsuperscript{−} leaching can be validated in addition to the other validated variables.

The third consideration is the method applied for identifying of the BMP. The current method only considers the biogeochemical effects on the decision variables and crop yields as one of the three constraints. This method excludes other factors, such as those related to the costs of the management practices, thereby likely resulting in uncertainty. Although the method applied in this study still has some deficiencies, this case study has potential application to more comprehensive situations, which can be easily and automatically implemented as long as the simulations for all the decision variables and crop yields can be validated using comprehensive observations.

5 Conclusions

An approach was proposed and applied to identify the best management practice of crop rotation in the interaction with field management practices based on the negative impact potentials and a set of constraints. The NIP of a scenario was defined as the linear function of five decision variables, including the NEGE, ammonia volatilization, nitric oxide release, emission of nitrous oxide in the form of depleted ozone layer matter, and nitrate leaching. This study used three variables, i.e., the crop yield, SOC content, and NEGE, to specify the applied constraints that were stable/increased the crop yields and SOC contents and reduced the NEGE. All the decision variables and those related to constraints were generated through model simulation. The BMP was referred to as the scenario with the lowest NIP among the possibilities capable of simultaneously satisfying the three constraints.
This case study focuses on a multi-crop cultivation system with a rotation between cotton and W-M, which has been widely adopted in northern China. Version 95 of the DeNitrification-DeComposition (DNDC95) model, with minor modifications of NO production during nitrification, was used to validate two adjacent plots cultivated with cotton and W-M. The modified model exhibited a satisfactory performance in simulating the decision and constraint variables under the available field observations. When relying on the Monte Carlo simulations driven by 6000 management scenarios, the effects of various rotation patterns and field management choices on the variables of interest were investigated, and the BMP for each rotation pattern and the final BMP for the cropping system were identified. The simulation results of the rotation patterns indicated that the proper rotation of the cotton and W-M can be simultaneously beneficial for the economy (crop yields), soil fertility (soil carbon sequestration) and climate (GHG mitigation). The final BMP for the system could be a rotation of 3 consecutive years of cotton rotated with 3 continuous years of W-M that uses 18% less fertilizer and 18% less irrigation water through sprinkling compared to the current conventional practices. This BMP would incorporate 90% of the crop residues and adopt conventional deep tillage (20–30 cm) for cotton but reduced tillage (10 cm) for W-M. This study emphasizes the need to make comprehensive observations that fully cover the decision and constraint variables and related soil factors to facilitate effective BMP screening by relying on virtual experiments using a biogeochemical model such as the DNDC model.

Author contribution

Xunhua Zheng, Chunyan Liu and Jiang Zhu contributed to the further development in data management and enhanced scientific efficacy and effectiveness. Wei Zhang performed the simulations and prepared the manuscript with contributions from all co-authors. Chunyan Liu, Kai Wang, Rui Wang and Zhisheng Yao designed and carried out the experiments. Feng Cui and Siqi Li applied the un-modified model in adjacent plot of winter wheat-summer maize cropping system.

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Table 1 Simulated decision variables, negative impact potential (NIP; USD ha\(^{-1}\) yr\(^{-1}\)) and relative uncertainty of NIP (NIP\(_u\)) for the best management practices and alternatives.

| Scenarios\(^a\) | R  | \(\Delta\text{SOC}\) | \(\text{CH}_4\) | \(\text{N}_2\text{O}\) | NEGE | \(\text{NH}_3\) | NO | NL | NIP | NIP\(_u\) |
|-----------------|----|-------------------|----------------|--------------------|------|----------|----|----|-----|---------|
| BAS             | R\(_3\) | 0.14              | -1.9           | 3.6                | 1.06 | 57       | 1.6 | 58 | 453 | 3.0%    |
| \(\text{BMP}\(_3\)\) | R\(_3\) | **0.15**          | **-1.9**       | **3.5**            | **1.01** | **44**  | 1.5 | 33 | 327 | **3.1%** |
| \(\text{BMP}\(_{a1}\)\) | R\(_3\) | 0.07              | -1.9           | 3.0                | 1.06 | 46       | 1.4 | 36 | 339 | 3.2%    |
| \(\text{BMP}\(_{a2}\)\) | R\(_3\) | 0.16              | -1.9           | 3.7                | 1.03 | 46       | 1.5 | 37 | 347 | 3.1%    |
| \(\text{BMP}\(_{a3}\)\) | R\(_3\) | 0.11              | -1.8           | 3.3                | 1.05 | 48       | 1.5 | 33 | 348 | 3.2%    |

\(^a\) BMP, best management practice. BAS, BMP, BMP\(_{a1}\), BMP\(_{a2}\) and BMP\(_{a3}\), baseline management practices, the best management practices (BMP) and the three BMP alternatives, which are encoded as N110/430_I100_IF_RI100_T20, N90/353_I82_IS_RI90_T10, N94/366_I94_IS_RI75_T20, N94/366_I91_IS_RI95_T10 and N97/378_I88_IS_RI70_T5, respectively. For the meanings of these codes, refer to section 2.3. R\(_3\), 3 consecutive years of cotton rotated with 3 continuous years of W-M. The decision variables include annual change in soil organic carbon (\(\Delta\text{SOC}; \text{Mg C ha}\(^{-1}\) yr\(^{-1}\)), methane (\(\text{CH}_4; \text{kg C ha}\(^{-1}\) yr\(^{-1}\)) and, nitrous oxide (\(\text{N}_2\text{O}\)) releases, net ecosystem greenhouse gases emission (NEGE; \(\text{Mg CO}_2\text{eq ha}\(^{-1}\)\)), ammonia (\(\text{NH}_3\)) volatilization, nitric oxide (NO) emission and nitrate leaching (NL) (kg N ha\(^{-1}\) yr\(^{-1}\)). The CO\(_2\)eq was based on the 100-year global warming potentials, i.e., 34 for \(\text{CH}_4\) and 298 for \(\text{N}_2\text{O}\) (IPCC, 2013). The NIP was calculated using Eq. (2) presented in the text.
Figure 1: Observed and simulated daily mean soil (5 cm) temperature, soil (0–6 cm) moisture, nitrous oxide ($N_2O$) and nitric oxide (NO) fluxes, net ecosystem exchanges of carbon dioxide (NEE), and methane ($CH_4$) emissions. The solid- and dashed-line arrows indicate the dates of fertilization and irrigation, respectively. The measurement errors were not shown in panels a, b and e. The vertical bar for each observation in panels c, d and f indicates two times standard deviations to represent the uncertain range at the 95% confidence interval. The legend in panel a applies for all subfigures.
Figure 2: Comparison between observations and simulations of annual nitrous oxide (N₂O) (a) and nitric oxide (NO) (b) emissions, seasonal net ecosystem exchanges of carbon dioxide (NEE) (c), and annual methane (CH₄) uptake (d). The black solid lines are the zero-intercept linear regression lines. The vertical bars indicate the standard error of four spatial replicates.
Figure 3: Simulated crop yields, cumulative changes in soil organic carbon (ΔSOC), methane (CH₄) and, nitrous oxide (N₂O) release, net ecosystem greenhouse gases emission (NEGE), ammonia (NH₃) volatilization, nitric oxide (NO) emission and nitrate leaching (NL) over a 18-year period (spanning three 6-year rotation cycles) for each rotation pattern scenario. For the definitions of the rotation pattern options, i.e., R₀, R₁, ..., R₅, refer to the text in section 2.3. The legend in panel e applies for all subfigures.
Figure 4: Simulated effects of rotation options under the baseline management practices on decision variables and negative impact potential (NIP). For the definitions of the rotation pattern options, i.e., R0, R1, ..., R5, refer to the text in section 2.3. The y-axis units are Mg C ha$^{-1}$ yr$^{-1}$ for the opposite of mean annual increase in soil organic carbon stock ($-\Delta$SOC), kg C ha$^{-1}$ yr$^{-1}$ for methane (CH$_4$) emission, kg N ha$^{-1}$ yr$^{-1}$ for emissions of nitrous oxide (N$_2$O), ammonia (NH$_3$) and nitrous oxide (NO), and nitrate leaching (NL), Mg CO$_2$eq ha$^{-1}$ yr$^{-1}$ for net ecosystem greenhouse gas emission (NEGE), and USD ha$^{-1}$ yr$^{-1}$ for NIP. The CO$_2$eq was based on the 100-year global warming potentials, i.e., 34 for CH$_4$ and 298 for N$_2$O (IPCC, 2013). The NIP was calculated using Eq. (2) presented in the text.