Modeling the contribution of agriculture towards soil nitrogen surplus in Iowa

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Abstract. The Midwest state of Iowa in the US is one of the major producers of corn, soybean, ethanol, and animal products, and has long been known as a significant contributor of nitrogen loads to the Mississippi river basin, supplying the nutrient-rich water to the Gulf of Mexico. Nitrogen is the principal contributor to the formation of the hypoxic zone in the northern Gulf of Mexico with a significant detrimental environmental impact. Agriculture, animal agriculture, and ethanol production are deeply connected to Iowa's economy. Thus, with increasing ethanol production, high yield agriculture practices, growing animal agriculture, and the related economy, there is a need to understand the interrelationship of Iowa's food-energy-water system to alleviate its impact on the environment and economy through improved policy and decision making. In this work, the Iowa food-energy-water (IFEW) system model is proposed that describes its interrelationship. Further, a macro-scale nitrogen export model of the agriculture and animal agriculture systems is developed. Global sensitivity analysis of the nitrogen export model reveals that the commercial nitrogen-based fertilizer application rate for corn production and corn yield are the two most influential factors affecting the surplus nitrogen in the soil.

Keywords: food-energy-water nexus · nitrogen export · sensitivity analysis · hypoxic zone · interrelationship · system modeling.

1 Introduction

The Gulf of Mexico dead zone is a hypoxic region of the water body that is caused by the nutrient-enriched water it receives from the Mississippi River. Nitrogen (N) is the principal nutrient that contributes to the formation of the hypoxic zone in the Gulf of Mexico [10], with obvious detrimental environmental, societal, and economic impacts. The Midwest agriculture region is a significant contributor of nitrogen loading in the form of nitrates (NO3) to the Mississippi river basin [4].

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The state of Iowa, a Midwest state in the US, is the country's foremost producer of corn, soybean, ethanol, animal products and is known for disproportionately contributing nitrogen loads to the Mississippi river basin [8]. Iowa has significantly invested in developing a subsurface drainage system to handle a unique situation of too much water for improving the agriculture productivity of its abundant farmland that produces most corn in the US. Almost 57% of Iowa's produced corn is used for ethanol production [16]. The increased demand for food production and ethanol could increase the use of nitrogen-based fertilizers by farmers for maximizing crop yield. Additionally, there is a possibility that the increased demands of ethanol production could drive corn production by converting soybean areas to corn [5]. Such a situation could increase the rate of Nitrogen (a highly water-soluble nutrient) export from Iowa watersheds through the subsurface drainage system, ultimately exiting into the Mississippi River. Further, the rising demands in animal protein have increased and concentrated Iowa's animal agriculture industry. Animal manure, a rich source of nitrogen, is also used as fertilizer along with commercial nitrogen fertilizers, making animal agriculture one of the contributors of nitrogen export from Iowa [7].

Agriculture, animal agriculture, and ethanol production are integral to Iowa's economy. However, their combined operation increases the rate of Nitrogen carried through the water system, contaminating Iowa's drinking municipal water [7] and adversely impacting the ecosystem of the Gulf of Mexico. Thus, it is important to understand the interrelationship of the Iowa food-water-energy (IFEW) system for the generation of appropriate policies that could mitigate the adverse impacts on the environment and economy.

In this work, an IFEW system model is proposed that describes the interconnections of agriculture, animal agriculture, water, energy, and the weather system along with the exported Nitrogen. Further, a macro-scale nitrogen export computational model of the agriculture and animal agriculture systems is developed and a global sensitivity analysis of this model is conducted. The Sobol' indices [15] a global sensitivity analysis method is used that reveals the important parameters contributing to the nitrogen export from Iowa.

The remainder of this paper is structured as follows. The next section presents IFEW system interrelationship, nitrogen export computational model, and global sensitivity analysis with Sobol' indices. The following section presents the results of the sensitivity analysis of the macro-scale computational model. Finally, conclusions and suggestions for future work are described.

2 Methods

This section describes the proposed IFEW system model and involved interrelationship and the formulation of the macro-scale nitrogen export model of the agriculture system. Further, the global sensitivity analysis based on Sobol' indices is described.

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2.1 IFEW system interrelationship

The current IFEW system modeling approach is inspired from the Water, Energy, and Food security nexus Optimization model (WEFO) developed by Zhang et al. [20], which employs an integrated modeling approach for providing critical information to decision-makers and stakeholders for optimal management of food-energy-water (FEW) systems. In the current study, state-of-the-art multidisciplinary design optimization (MDO) [11] methodology is employed for the development of the IFEW system model to better understand FEW system interrelationship with the goal of providing critical information for efficient policy generation to mitigate the environmental and economic impact of the nitrogen export from Iowa.

The proposed IFEW model is developed such that it represents the major socioeconomic systems of Iowa that affect nitrogen export related to agricultural activity. Figure 1 shows the proposed IFEW system model, showing individual systems and their interrelationship. Further, the IFEW system is subjected to socioeconomic and environmental constraints. In particular, the IFEW system involves five distinct systems: weather, water, agriculture, animal agriculture, and energy. The weather system significantly impacts agriculture and water systems through different environmental parameters, such as temperature, precipitation, vapor pressure, and solar radiation. The weather system strongly influences agricultural output by directly affecting corn and soybean yields [19] whereas the amount of precipitation and snowfall affects surface and groundwater availability under the water system as well as the concurrent transport of excess nitrogen downstream. The water is consumed in the animal agriculture and energy systems. In the animal agriculture system, water is consumed as drinking and service water. In the energy system, water is consumed for ethanol and fertilizer production. The byproduct of ethanol production is the dried distillers grains with solubles (DDGS), which is a rich protein source used as animal feed. The commercially produced fertilizers and animal manure from animal agriculture are applied to crop fields under the agriculture system in Iowa to maximize crop yield, mainly for corn production, where a major portion of corn is used for ethanol production. Except for the weather, all other systems are responsible for meeting socioeconomic demands for corn, soybean, ethanol, water, and animal protein. Lastly, the water flowing through Iowa watersheds carries the surplus nitrogen from the soil in the form of nitrates that drains into the Mississippi river basin and further into the Gulf of Mexico.

2.2 Agriculture nitrogen export computational model

Almost 70% of Iowa's land is under high yield agriculture practices where nitrogen-based fertilizers are primarily used to enhance crop yield, especially for the corn production [7]. Further, the increasing demands of animal protein have increased animal agriculture operations in Iowa. The manure produced from animal agriculture is rich in nitrogen and have been used for soil fertilization [1]. Thus, animal agriculture mostly contributes to Iowa's nitrogen export through the

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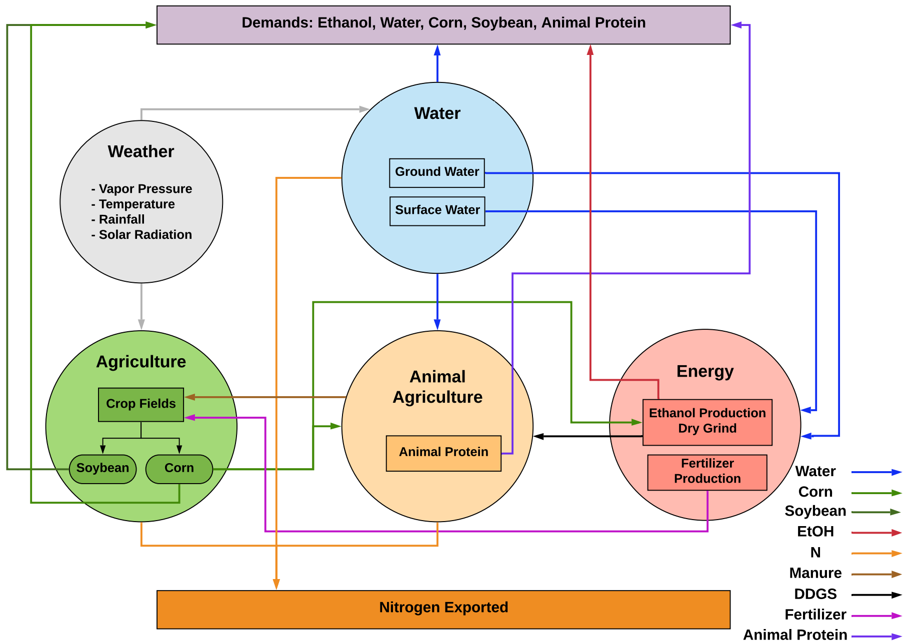

Fig. 1: A model of the interrelationship of the Iowa food-energy-water system.

agriculture system. With large agriculture operations, widespread availability of manure from animal agriculture, and high commercial nitrogen-based fertilizer application rates could create surplus nitrogen in the soil, which is then carried by the water through the subsurface drainage system. In this work, a nitrogen export model is developed for the state of Iowa based only on the agriculture and animal agriculture systems. The other systems are not accounted for in this simplified computational model. Figure 2 shows an extended design structure matrix of diagram [9] of the proposed nitrogen export model with the definitions of the parameters given in Tables 1 and 2.

The model yields a computation of the nitrogen surplus (N_s) based on the construction of a rough agronomic annual nitrogen budget [3] given as

$$N_s = CN + FN + MN - GN, \tag{1}$$

where CN represents the commercial nitrogen that the soil receives from the application of commercial nitrogen-based fertilizers, FN represents the nitrogen fixed in the soil by soybean crop, GN represents the nitrogen that is taken out from soil through the harvested grain, and MN represents the nitrogen generated from animal manure that is applied to the soil. Such nitrogen budgeting provides an insight into nitrate sources of Iowa.

The agriculture system receives four input parameters, which are the corn yield (x_1), soybean yield (x_2), rate of commercial nitrogen for corn (x_3), and

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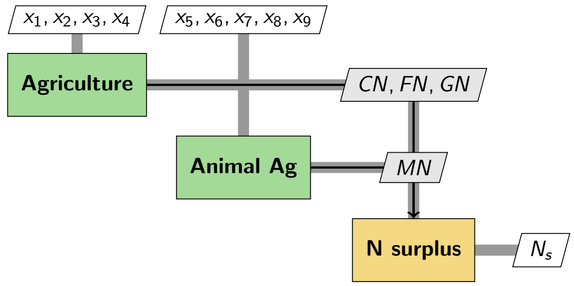

Fig. 2: An extended design structure matrix diagram of nitrogen export model considering only the agriculture and animal agriculture systems (Tables 1 and 2 give the parameter descriptions).

Table 1: Macro-level nitrogen export model input parameters.

Input parameters	Description
x_1	Corn yield
x_2	Soybean yield
x_3	Rate of commercial nitrogen for corn
x_4	Rate of commercial nitrogen for soybean
x_5	Hog/pigs population
x_6	Beef cattle population
x_7	Milk cows population
x_8	Other cattle population (heifers + slaughter cattle)
x_9	Chicken/hens population

the rate of commercial nitrogen for soybean (x_4). The output parameters of the agriculture system are CN, FN, and GN, respectively. The commercial nitrogen (CN) is computed as

$$CN = \frac{(x_3 A_{corn} + x_4 A_{soy})}{A}, \tag{2}$$

where A_{corn} and A_{soy} are Iowa corn and soybean acreage, and $A = A_{corn} + A_{soy}$ represents cumulative area under corn and soybean. In the current study, the corn and soybean acreages are obtained from USDA [18]. The biological fixation nitrogen by the soybean crop is computed using the relationship between soybean yield and FN provided by Barry et al. [2] given as

$$FN = \frac{(81.1x_2 - 98.5)A_{soy}}{A}, \tag{3}$$

where the soybean yield (x_2) is in tons per hectare to provide FN in kg per hectare. The nitrogen exported in the harvested grain from corn and soybean harvest is computed assuming 6.4% nitrogen in the soybean seed and 1.18%

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Table 2: Macro-level nitrogen export model output parameters.

Output parameters	Description
CN	Commercial nitrogen (nitrogen in commercial fertilizers)
FN	Biological fixation nitrogen of soybean crop
GN	Grain nitrogen (Nitrogen harvested in grain)
MN	Manure nitrogen (Nitrogen in animal manure)
N_s	Surplus nitrogen in soil

nitrogen in corn seed [3] given as

$$GN = \frac{x_1 \frac{1.18}{100} A_{corn} + x_2 \frac{6.4}{100} A_{soy}}{A}. \quad (4)$$

In (2), (3), and (4), CN, FN and GN have the unit kg/ha.

Currently, Iowa holds the first rank in red meat, pork, and egg production in the U.S. [18]. Thus, for the manure nitrogen computation, the hogs/pigs, cattle, and chicken/hens populations are considered. The animal agriculture system model receives five input parameters representing the population of the following categories in Iowa, namely hogs/pigs (x_5), beef cattle (x_6), milk cows (x_7), total heifers and slaughter cattle (x_8), and layers chicken/hens (x_9). The annual manure nitrogen contribution from each animal category is given by [6]

$$MN_{Livestock\ group} = PN_m L_c, \quad (5)$$

where P represent livestock population, N_m represents nitrogen present in animal manure, and L_c represents life cycle in days. Table 3 gives the numerical values of the parameters used in (5) for each livestock group.

The total MN contribution from animal agriculture is

$$MN = ((MN_{Hog/Pigs} + MN_{Beef\ cattle} + MN_{Milk\ cow} + MN_{other\ cattle} + MN_{Chicken/Hens}))A^{-1}, \quad (6)$$

where the other cattle livestock group is composed of 50% heifers/steers population and 50% slaughter cattle population. In this study, the Iowa animal population data of 2012 [6] is used for the MN computation.

2.3 Global sensitivity analysis

For this study, global sensitivity analysis (GSA) of the nitrogen export model is performed to understand the contribution of each input parameter to the model output. In particular, Sobol' sensitivity analysis [15] is used in this work. Sobol' analysis provides a computation of the first-order and total-effect Sobol' sensitivity indices, which can be used to determine the sensitivities of individual parameters and their interactions with other input parameters on the model output.

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Specifically, Sobol's method uses a variance decomposition to calculate the Sobol' indices. Consider the model response $y = f(\mathbf{x})$ as a function of vector $\mathbf{x}$ with n parameters. Then, the total variance $var(Y)$ in any model response Y can be decomposed as [13]

$$var(Y) = \sum_{i}^{n} V_i + \sum_{i}^{n} \sum_{i<j}^{n} V_{ij} + ... + V_{12...\ n}, \tag{7}$$

where V_i is $var(\mathbb{E}(Y|x_i))$ is the variance contribution of i^{th} design parameter to the total variance $var(Y)$, V_{ij} is the variance contribution of i^{th} and j^{th} parameter to $var(Y)$ and so on. The Sobol' indices are obtained by dividing (7) by the total variance $var(Y)$ to obtain

$$1 = \sum_{i}^{n} S_i + \sum_{i}^{n} \sum_{i<j}^{n} S_{ij} + ... + S_{12...\ n}, \tag{8}$$

where S_i represents the first-order Sobol' index given by [13]

$$S_i = \frac{V_i}{var(Y)}. \tag{9}$$

The total-effect Sobol' index is given as [13]

$$S_{T_i} = 1 - \frac{var(\mathbb{E}(Y|\mathbf{x}_{\sim i}))}{var(Y)}, \tag{10}$$

where $\mathbf{x}_{\sim i}$ represents the set of all parameters except x_i. Sobol' total-order index S_{T_i} indicates total contribution of i^{th} parameter to total variation in Y including first-order S_i and interaction effects with other input parameters. The interaction effect is represented by difference between S_{T_i} and S_i ($S_{T_i} - S_i$). Zero interaction effect indicates that the particular parameter affects the model response only with first order-effect making $S_i = S_{T_i}$. Sobol' indices are typically computed using Monte Carlo-based numerical procedure. For this study, the numerical procedure provided by Saltelli et al. [13] is used.

Table 3: Nitrogen content in manure and life cycle for livestock groups used in manure nitrogen calculation [6]

Livestock group	Nitrogen in manure N_m (kg per animal per day)	Life cycle L_c (days per year)
Hog/pigs	0.027	365
Beef cattle	0.15	365
Milk cows	0.204	365
Heifer/steers (0.5 × other cattle)	0.1455	365
Slaughter cattle (0.5 × other cattle)	0.104	170
Chicken/Hens	0.0015	365

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Table 4: Input parameter bounds.

Input parameters	Upper bound	Lower bound	Units
x_1	203	137	bushels/acre
x_2	45	60	bushels/acre
x_3	215	155	kg/hectare
x_4	30	5	kg/hectare
x_5	30,661,542	20,441,028	-
x_6	1,107,555	738,370	-
x_7	474,616	316,411	-
x_8	4,205,037	2,803,358	-
x_9	30,728,227	20,485,485	-

2.4 Parameter sampling

The Latin hypercube sampling technique (LHS) [12] with uniform distributions is used for the sample generation. The input parameter ranges for the agriculture system, and animal agriculture systems are given in Table 4. The corn and soybean yield ranges are obtained from USDA report [18] and are based on the maximum and minimum yield recorded during the 2008-2019 period. The commercial nitrogen application rate for corn is obtained from the Iowa State University extension guidelines [14] considering the average nitrogen rates for corn following corn and corn following soybeans in Iowa. The commercial nitrogen rate of soybean are chosen based on the fertilizer use, and price data between 2008-2018 [17]. The acreage for corn and soybean is 13.5 and 9.2 million acres, respectively, according to USDA 2019 statistics report [18]. The animal population headcount required for animal agriculture input parameters is acquired using Iowa animal population data [6]. The lower bound shows the animal population data from the year 2012 (see Table 4), whereas the upper bound is determined by assuming a 50% increase from the lower bound for each livestock group.

3 Results

Figure 3 shows the sampling history of the Sobol' first-order and total-order indices, indicating convergence with 10^5 samples. It should be noted that the negative values of estimated Sobol' indices are due to numerical error and usually occur when indices magnitudes are close to zero [13].

The Sobol' computation is repeated 30 times to provide a statistical mean and standard deviation for the Sobol' indices. Figure 4 shows the averaged Sobol' indices of the nitrogen export model. The most influential parameters are corn commercial nitrogen rate (x_3) and corn yield (x_1) based on their total-order Sobol' index magnitudes. These two parameters chiefly affect the variation in nitrogen surplus amount of soil. The soybean commercial nitrogen rate (x_4) and soybean yield (x_2) slightly affects the nitrogen surplus amount while parameters (x_{5-9}) connected to animal agriculture has a negligible effect on soil nitrogen surplus amount. Further, it is observed that the interaction effects among input

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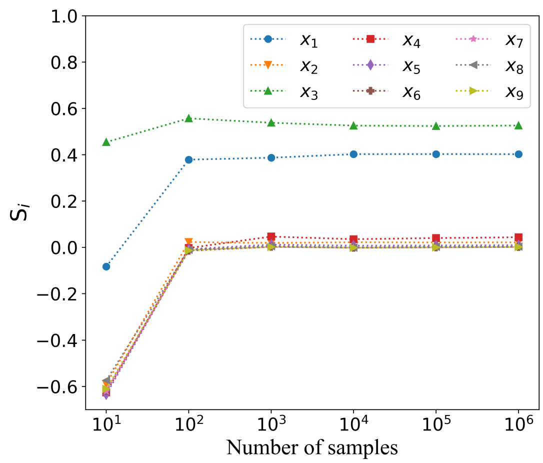
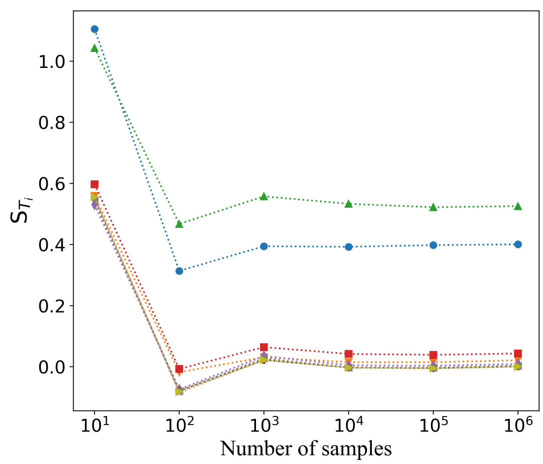


(a)



(b)

Fig. 3: Convergence of the Sobol' indices of the input parameters (cf. Table 1) in the nitrogen export model: (a) first-order indices, and (b) total-effect indices.

parameters are nonexistent. This is mainly due to the current limitation of the nitrogen export model, which employs only feed-forward design in its modeling approach.

The nitrogen export model is investigated to compute the average contribution of CN, FN, GN, and MN towards nitrogen surplus in soil. A total of 10^5 samples are used to compute average values. Figure 5 shows that CN, FN, and MN cumulatively contributes 214 kg/ha of nitrogen to the soil, whereas 171.8 kg/ha of nitrogen is removed from soil through harvested grains (corn and soy-

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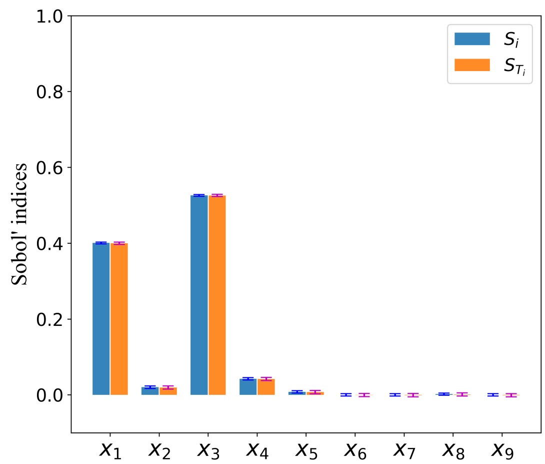

Fig. 4: Converged averages and standard deviations of the Sobol' indices for the input parameters (cf. Table 1) of the nitrogen export model.

bean), leaving on an average 42.2 kg/ha of nitrogen surplus in soil. Figure 5 also shows the contribution of corn and soybean fields in CN and GN computation. Additionally, MN contributes an average of 20.8 kg/ha of nitrogen to the soil, which is almost 9.7% of total nitrogen input to the soil ($CN + GN + MN$). The higher nitrogen surplus in soil subjected to high water flux could increase the rate of exported nitrogen to the Mississippi river basin. The current nitrogen export model could be used to reduce nitrogen surplus in the soil to mitigate nitrogen export.

4 Conclusion

In this study, an Iowa food-energy-water (IFEW) systems model is proposed for understanding its interrelationship and to provide critical information for policy making to mitigate the environmental and economic impacts of the nitrogen export from Iowa. In particular, a macro-scale nitrogen export model of the agriculture and animal agriculture system is developed and a global sensitivity analysis is conducted to understand its influential parameters. It is observed that commercial nitrogen application rate for corn and corn yield are the two most influential parameters affecting soil nitrogen surplus. The parameters connected to soybean production and animal agriculture have a minimal effect on soil surplus; however, these parameters substantially contribute to soil nitrogen input and output. In future work, the IFEW system model will be further developed to include the water, weather, and energy systems to simulate different scenarios such as drought, flooding, or increased ethanol demand to regulate nitrogen export from Iowa.

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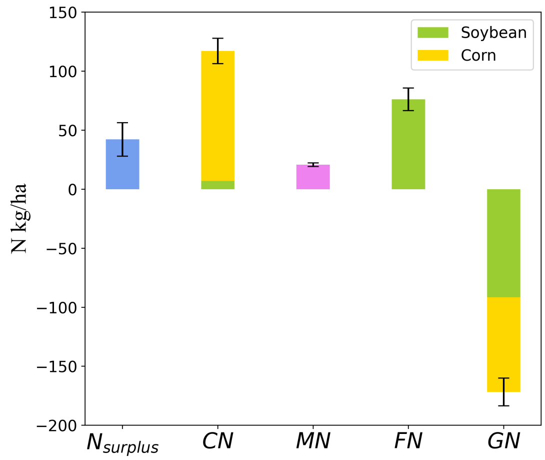

Fig. 5: Average contribution of commercial nitrogen (CN), fixation nitrogen (FN), and manure nitrogen (MN) towards the soil nitrogen surplus (N_s).

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