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Improved manure management moves trade-off and synergy relationships among environmental indicators in desirable directions

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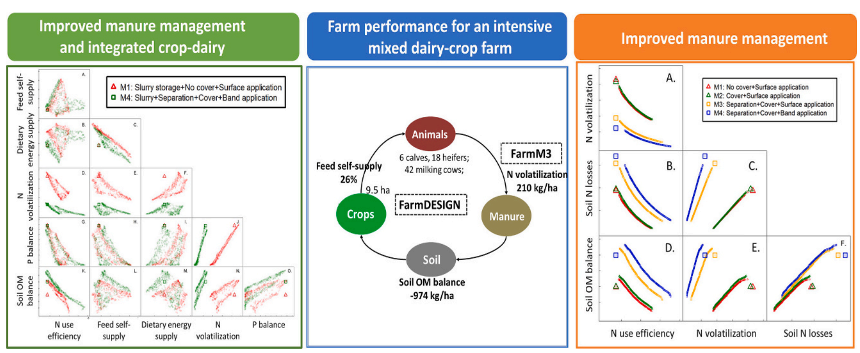
HIGHLIGHTS

- Improved manure management and crop-dairy integration enhance nutrient circularity in intensive dairy farms.
- Combining manure technologies greatly reduces N losses.
- Manure management optimizes N volatilization, soil N losses, and soil organic matter balance.
- Improved manure practices alone are insufficient to address N surplus in high-density dairies.

GRAPHICAL ABSTRACT



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ABSTRACT

CONTEXT: Dairy production systems with a high stocking density are strongly dependent on external feed resources and concentrate nutrients in manure on a small surface area, thus causing environmental challenges. Both improved manure management and integration of crop-dairy production have been proposed as ways to reduce nutrient losses and improve sustainability of intensive dairy production. However, the potential interactive relationships between these two options are rarely investigated.

OBJECTIVE: This study aimed to investigate how different manure management technologies influence nutrient losses at manure management and farm levels and how manure management impacts farm multi-objective optimization results for more integrated crop-dairy production.

METHODS: A whole farm model (FarmDESIGN) extended with a manure management module (FarmM3) was used to simulate an intensive mixed crop-dairy farm with a herd of 66 cows and 9.6 ha of crop area. The optimization aimed to improve farm environmental performance, increase feed self-sufficiency and food production.

RESULTS AND CONCLUSIONS: The results showed that individual manure management technologies were insufficient to reduce nitrogen (N) losses from manure management chains due to compensatory losses, whereas

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combinations of slurry solid-liquid separation, covered storage of solid and liquid fractions, and improved manure application could remarkably reduce N losses by 46 to 58 % and increase manure N use efficiencies by more than 30 %. Improved manure management did not influence total N losses at farm level without decreasing livestock density. Multi-objective optimization showed that improved manure management did not eliminate trade-offs or synergies among objectives but did affect the positions and the slopes of the solution frontiers between objectives. Differences between solution frontiers of alternative farm configurations in terms of N volatilization, soil N losses and soil organic matter (OM) balance indicated that manure management chains (MMCs) could be designed effectively to optimize these objectives.

SIGNIFICANCE: This study confirmed the value of improved manure management and integrated crop-dairy production in reducing N losses and improving farm nutrient use efficiency. For intensive dairy farms with limited land availability, future studies should focus on recoupling crop and dairy production at regional scales to create more sustainable and resilient food production systems.

1. Introduction

1.1. Intensive dairy production

Dairy farming has intensified and specialized over the past few decades (FAO, 2018). With high stocking rates and large external feed inputs, intensive dairy farming systems are typically characterized by high productivity and profitability but also negative site-specific environmental impacts (Clay et al., 2020). Environmental problems, such as greenhouse gas and ammonia emissions, nutrient surpluses and eutrophication of ecosystems, have gained worldwide attention (Rotz et al., 2006; Oenema et al., 2007). Poor on-farm manure management and the spatial decoupling of crop and dairy farms were perceived as the major causes of nutrient losses from intensive confinement dairy farms (Bai et al., 2013; Chadwick et al., 2020; Zou et al., 2023). With a large amount of excreted manure but limited available grassland or cropland to utilize the produced manure, manure has become a burden for intensive confinement dairy farms. Additionally, due to the high livestock density, the strong reliance on external feeds of these intensive confinement dairy farms has resulted in very low levels of nutrient circularity and use efficiency. Strategies to reduce nutrient losses and to improve nutrient use efficiency have been pointed out to involve improving manure management and by recoupling crop and dairy production (Oenema and Tamminga, 2005; Chadwick et al., 2020).

1.2. Improved manure management

Emission mitigation measures and manure treatment technologies have been developed to reduce nutrient losses from manure management facilities. For instance, covering of manure storages, slurry acidification and dilution, and injection of liquid manure were used to reduce ammonia emissions. Anaerobic digestion, solid-liquid separation and composting could contribute to mitigation of greenhouse gas emissions and facilitate manure nutrient management by producing alternative manure products such as anaerobic digestate, separated liquid and solid fractions, and compost (Foged et al., 2011; Sommer et al., 2013). However, devising a single mitigation measure on a single loss pathway has led to pollution swapping by increased losses of other compounds (De Vries et al., 2015a). It was reported that the reduced ammonia emissions by covering slurry storage and by injection of liquid manure resulted in an increased nitrous oxide emission (Sommer and Hutchings, 2001; Berg et al., 2006). Moreover, the reduced gas emission at previous stages might lead to increased losses at later manure management stages (Shah et al., 2013). Considering the pollution swapping among nutrient loss pathways and compensatory losses among manure management technologies and different stages in the manure management chain, a combination of different manure management technologies has been proven more efficient to reduce nutrient losses from the whole manure management chains (Rotz et al., 2006; Hou et al., 2015; Sajeev et al., 2018). However, the quantitative effects of improved manure management on nutrient use efficiency at farm level are rarely investigated. With more conserved nutrients in manure products, fewer nutrient inputs from synthetic fertilizers and a larger area of crop- or grassland might be needed to utilize these nutrients. Thus, for intensive confinement dairy farms, the recoupling of crop and dairy production could be a promising solution to reduce nutrient surplus and to increase nutrient circularity and use efficiency (Peyraud et al., 2014; Schut et al., 2021).

1.3. Reintegration of crop and dairy production

In integrated or recoupled crop and dairy systems, the manure produced by cows is used as a source of fertilizer for the crops, which in turn provide feeds for the livestock. These closed-loop systems allow for the efficient use of nutrients, reducing the need for synthetic fertilizers and limiting the demand for imported feeds (Ryschawy et al., 2012; Marton et al., 2016). Although the value of integrated crop-livestock systems in terms of reducing detrimental environmental impacts has been confirmed, studies have highlighted the necessity to consider food production of these systems (Lemaire et al., 2014; Puech et al., 2023), especially at farm scale, since the issue of increasing nutrient recycling by crop-livestock integration raises questions about the use of agricultural land and resource allocation between food crops, feed and animal products, particularly the role of intermediate resources such as fodder for animal feed (Barbieri et al., 2022). Thus, a strategic plan and design for integrated crop-livestock systems is highly vital to improve nutrient use efficiency and circularity, to increase feed self-sufficiency without compromising food production.

1.4. Whole farm models

Given the strong interactions among different farm components (i.e., animals, manure, soils and crops) of integrated crop and dairy farms, whole farm models can be powerful means to redesign crop and dairy systems to balance supply and demand of feedstuff and manure, and to provide ex-ante assessments of performance of integrated crop-dairy systems. In this study, we will apply a whole farm model, the FarmDESIGN model, developed by Groot et al. (2012) to redesign farming systems by balancing crop-livestock interactions. This model can identify complicated interactions among farm components, support the exploration of alternative farm configurations using a Pareto-based multi-objective optimization algorithm, and provide redesign plans for improving farm nutrient use efficiency, increasing self-sufficiency of feed and guarantee food production. With a linked external manure management module (Qu et al., 2023), it also allows the investigation of the effects of improved manure management practices on nutrient losses and farm nutrient use efficiency.

1.5. Objectives

This study aims to investigate alternative farm management practices to improve nutrient use efficiency of intensive confinement dairy farms. Using the extended FarmDESIGN model, we first evaluate the impacts of various improved manure management practices on nutrient losses and farm nutrient use efficiency. Then we explore alternative farm configurations to further increase nutrient circularity by integrating crop and dairy production based on Pareto-based multi-objective optimization. Lastly, the potential impacts of improved manure management chains on designing and optimizing plans for integrated crop and dairy farms is investigated.

2. Materials and methods

2.1. Case study farm

A mixed dairy-crop farm in an agri-environmental scientific observation experimental station in Dali, in the province of Yunnan, China was selected as a case study. The region has experienced significant environmental challenges, particularly the degradation of Erhai Lake's water quality, primarily due to nutrient runoff from chemical fertilizers and the expansion of intensive dairy farming. To counter these issues, local policies have increasingly advocated for the use of organic fertilizers and the integration of crop and dairy farming systems, aiming to promote sustainable agricultural practices.

At this farm, the dairy herd consisted of 66 animals, including 6 calves, 18 heifers and 42 milking cows. Heifers were kept on the grazed pasture for 245 days during spring, summer and part of autumn. Milking cows and calves were kept in an open barn throughout the whole year. Dung and urine excreted on the pastures were kept on the pasture without collection. Excreta produced in the barn were collected separately with solid manure being sold off-farm and liquid manure being stored in an underground tank for a period of two months before being applied to fields.

The total cultivated farm area was 9.5 ha, with 3.5 ha for fava-bean and rice rotation, 1.5 ha for annual ryegrass, 1.5 ha for barley and maize rotation, and 3 ha for alfalfa and rape rotation. The harvested rice and rapeseed were sold and other crop products were used as animal feed or bedding. Additionally, large amounts of bedding materials and feeds were imported into the farm. Table 1 presents the annual amounts of imported feeds and bedding materials in the original farm, which were estimated based on the data provided by the farmer.

Given the limited grazing area and the high potential for nutrient losses through leaching and runoff, we revised the farm configuration with no grazing by heifers and keeping all of the animals in the open barn throughout the whole year. We also improved the herd structure by replacing dairy cows at a rate of 25 %. Correspondingly, we revised the amount of feed intake to meet animal requirements (Table 1). To increase nutrient use efficiency and circularity within the farm, we assumed that all produced manure is applied within the farm. The modified farm was taken as the baseline farm and as the starting point for farm optimization.

2.2. FarmDESIGN model

To evaluate the farm's performance comprehensively in terms of agronomic and environmental indicators, we utilized the FarmDESIGN model. This model is a bio-economic whole farm model that supports evaluation of mixed crop-livestock farm performance comprehensively with various agronomic, environmental and economic indicators (Groot et al., 2012). It can be used to simulate flows of organic matter (OM), carbon (C), nitrogen (N), phosphorus (P) and potassium (K) to, through and from farm components (crop-animal-manure-soil) on an annual basis. Based on a Pareto-based multi-objective optimization algorithm, this model also enables redesigning more sustainable farming systems by exploring alternative farm configurations of balancing different farm components interactions. We used an extended version of the model with a flexible modular manure management model (FarmM3) as detailed by Qu et al. (2023).

The FarmDESIGN model estimates the amount of manure dry matter produced (DM_{Manure}; kg) based on the amount of feed dry matter supplied to animals ($DM_{AnimalFeed}$ for each feed p; kg), corrected for feed loss

Table 1
Overview of variables in the original farm, baseline farm, farm scenario A (aiming to optimize livestock number on a 9.5 ha crop area), and farm scenario B (aiming to increase nutrient circularity by integrating more crop area) of the case study farm. The columns labeled Minimum and Maximum indicate the allowed range of variation in the optimization procedure for variables used as decision variables. The term 'External' refers to feeds or bedding materials that are imported from outside the farm.

Description		Original	Baseline	Scenario A		Scenario B	
				Minimum	Maximum	Minimum	Maximum
Number of animals kept on the farm	Dairy cows	42	42	12	42	–	–
	Replacement Rate	–	0.25	0.15	0.35	–	–
	Heifers	18	10	–	–	–	–
	Calves	6	10	–	–	–	–
	Bean-Rice	3.5	3.5	3	9.5	3	45
	Ryegrass	1.5	1.5	0.5	1.5	0.5	1.5
	Barley-Maize	1.5	1.5	0	3.0	0	3
Areas of crop in rotation, ha	Alfalfa-Rape	3	3	0	9.5	0	10
	Alfalfa-Rice	0	0	0	0	0	45
	Bean-Maize	0	0	0	0	0	45
	Chinese cabbage-Maize	0	0	0	0	0	45
	Asparagus lettuc-Rice	0	0	0	0	0	45
Amount of external feeds, kg DM per year	Alfalfa silage	134,558	134,558	0	134,558	0	134,558
	Bean Straw	10,000	10,000	0	10,000	0	10,000
	Concentrate	80,942	80,942	0	80,942	0	80,942
	Concentrate2	20,000	10,000	0	10,000	0	10,000
	Maize straw silage	0	0	0	15,000	0	15,000
Amount of bedding supplied to animals, kg per day							
	Calves	2.5	2.5	2	4	2	4
	Heifers	2.5	2.5	2	5	2	5
	Dairy Cows	4.5	4.5	2.5	6	2.5	6
Amount of bedding supplied to animals, kg DM per year							
External	Rice straw	64,000	60,000	0	90,000	0	90,000
Percentage of crop products used as feed or bedding							
Bean-Rice rotation	Rice straw (as feed)	0	0	0	100	0	100
Alfalfa-Rice rotation	Rice straw (as bedding)	0	0	0	0	0	100
Bean-Maize rotation	Bean straw (as bedding)	0	0	0	0	0	100
Milk proudction and use	Milk Production, kg per cow per day	24	24	24	30	24	30
	Amount fed to animals, kg per year	3000	5000	1000	7500	–	–

rate ($F_{L,p}$; kg/kg) and the apparent dry matter digestibility (DMD; kg/kg) of each feed, and the amount of dry matter from bedding material ($DM_{Bedding}$; kg) collected in the barn and mixed with produced faces and urine.

$$DM_{Manure} = \sum_{p=1} DM_{AnimalFeed,p} \times \left(1 - F_{L,p}\right) \times DMD_p + DM_{Bedding}$$

The amounts of OM and C in manure are determined based on the ash content of the crop and animal products and assuming a C content in organic matter of 50 %. The total amounts of N, P and K in manure (in both urine and feces) are derived from the difference between intake and products of the animals, as demonstrated bellow for N only.

$$N_{Manure} = \sum_{p=1} \left(DM_{AnimalFeed,p} \times F_{N,p} \times \left(1 - F_{L,p}\right)\right) - N_{AnimalProducts}$$

The amounts of produced manure DM, OM, C and nutrients estimated by FarmDESIGN model serve as inputs of FarmM3 model. The FarmM3 model quantifies the degradation of OM and C, losses of N, P and K along the whole manure management chain using specific loss coefficients. The detailed calculation procedure of FarmM3 can be found in Qu et al. (2023). The amounts and characteristics of manure available for application are fed back from the FarmM3 module to FarmDESIGN model. Adding FarmM3 as an external manure module improves the flexibility of the FarmDESIGN model in estimating nutrient losses from manure management chains with different manure treatment technologies.

The farm evaluation results revealed that the original farm had a high livestock density of 6.5 LU/ha (LU refers to Livestock Unit equaling 500 kg live weight), and a low feed self-reliance, with more than 70 % of feeds imported from outside the farm. Due to the large number of cows but a limited crop area, the farm exhibited a high farm N balance around 272 kg/ha, with 77 % of N losses attributed to N volatilization from manure management. The N cycling rate, defined as the fraction of excreted manure N recycled into soil, was about 37 %, while over 30 % of manure N was exported off the farm.

2.3. Manure management scenarios

To investigate how different levels of technology and management practices can enhance manure management outcomes, reduce environmental impacts, and improve nutrient use efficiency on farms, four manure management scenarios with different manure treatment technologies were developed and modelled in FarmM3 (Table 2). The manure management scenario M1 reflected the original farm practice, where manure was collected and stored without cover, resulting in significant nutrient losses through volatilization and runoff. The manure management scenario M2 introduced a concrete cover to the storage tank, which helped mitigate nutrient losses by reducing exposure to the elements, thereby enhancing overall nutrient retention. The manure management scenario M3 employed a more advanced approach by implementing solid-liquid separation, a technology that has been demonstrated to be both cost-effective and environmentally friendly (Aguirre-Villegas et al., 2019; Holly et al., 2017). In this scenario, the solid fraction was covered during storage, minimizing nutrient loss, while the liquid fraction was stored in a covered tank, further reducing potential nutrient emissions. The manure management scenario M4 built on the advancements of M3 by incorporating best practices for land application. The solid manure was applied through incorporation, which significantly reduced nutrient runoff, while the liquid fraction was delivered using a trailing hose, optimizing nutrient uptake by crops and minimizing losses.

2.4. Farm scenarios and objective

To address the challenges of high nutrient losses and low farm nutrient use efficiency, two scenarios were developed. The first scenario (Scenario A) aimed to optimize the number of livestock units based on the amount of feed produced within the farm. The objective of this scenario was to maximize whole farm N use efficiency (%) and soil organic matter (OM) balance (kg/ha), and to minimize N volatilization (kg/ha) and soil N losses (kg/ha). In Scenario B, the focus was on increasing nutrient circularity, improving feed self-sufficiency for the herd, and expanding food production by integrating more crop area. Since P surplus can also pose significant challenges for dairy operations, we included whole farm P balance as a critical objective. By optimizing both N and P balance, the scenario aimed to achieve a more holistic approach to farm nutrient management. It intended to maximize whole farm N use efficiency (%), self-supply of total feed DM (%), dietary energy production (persons fed/ha), and soil OM balance (kg/ha/year), while minimizing N volatilization (kg/ha) and whole farm P balance (kg/ha/year). The calculations for these objectives were as follows:

- Whole farm N use efficiency (%) is calculated by comparing the amount of N output to the amount of N input. Nitrogen can enter the farm through imported crop products, imported fertilizer or manure, symbiotic fixation, non-symbiotic fixation and deposition. The output of N includes exported N from crop product, animal product and exported animal manure.
- N volatilization (kg/ha) estimates the total cumulative N losses via ammonia emissions, nitrous oxide emissions and nitrogen (N_2) emissions through the entire manure management process, including manure excretion, storage, treatment (such as solid-liquid separation, composting, anaerobic digestion etc.) and application.
- Soil N losses (kg/ha) quantifies the total N losses by denitrification, leaching and runoff from soil.
- Soil OM balance (kg/ha/year) is quantified as the difference between inputs of OM into the soil and losses by degradation, erosion, decomposition of active soil OM and added manure. Inputs of OM include crop roots and residues, mulch, and farm-produced and imported manures.
- Whole farm P balance (kg/ha/year) is calculated as the difference between P inputs, which include imported feed, bedding materials, imported fertilizers, and atmospheric deposition, and P outputs, which consist of P in animal and crop products as well as exported manure.

Table 2
Description of modelled manure management chains.

Manure management chains (MMCs)	Description
M1	All of the manure excreted in the barn was collected and stored in a tank without cover. After being stored for two months, the slurry was applied to fields without incorporation.
M2	All of the manure excreted in the barn was collected and stored in an underground tank with a concrete cover. After being stored for two months, the slurry was applied to fields without incorporation.
M3	All of the manure excreted in the barn was collected and stored in an underground tank before being separated into solid and liquid fractions. The separated solid fraction was stored and covered during storage. The liquid fraction was stored in an underground tank with a concrete cover. After being stored for two months, the liquid and solid fractions were applied to fields without incorporation.
M4	All of the manure excreted in the barn were collected and stored in an underground tank before being separated into solid and liquid fractions. The separated solid fraction was stored and covered during storage. The liquid fraction was stored in an underground tank with a concrete cover. After storage, the solid manure was applied to fields by broadcast application with incorporation and the liquid was applied to fields by a trailing hose.

- Self-supply of total feed DM (%) is a key indicator used to determine the proportion of feed produced on a farm. This calculation involves dividing the amount of feed produced on the farm by the total amount of feed consumed by the animals.
- Dietary energy production (persons fed/ha) is a crucial metric used to measure the efficiency and sustainability of food production systems. It quantifies the number of individuals that can meet their daily dietary needs based on the complete daily dietary reference intake from various sources such as field crops, animal breeding and other production systems.

For each farm scenario, we explored alternative farm configurations to meet the target objectives and investigated the impacts of MMCs with different manure treatment technologies on alternative farm configurations.

2.5. Decision variables and constraints

For each scenario, the decision variables included management variables of the size of the livestock herd, allocation of crop areas, the destination of crop products, and the amounts of external feeds and bedding materials supplied to animals (Table 1). Constraints (see Table 3) were set for the total crop areas that should not be more than 9.5 ha in Scenario A and should be less than 45 ha in Scenario B. The extended farm areas in Scenario B were determined based on the availability of surrounding crop areas. The number of livestock units should be less than the baseline farm's 56.2 LU in Scenario A and be kept the same as for the baseline farm in Scenario B. The availability of energy, protein and fibrous material ('structure') in feed should match animal requirements, whereas intake capacity (corrected for saturation units) should not be exceeded. The soil N losses comprising leaching, runoff and denitrification should not be less than 20 kg N/ha/year, to make sure that enough N is in the system to support crop and grassland production while acknowledging unavoidable losses, and the soil P and K losses should not be less than 0 kg/ha/year to avoid mining. The supplied bedding material should be sufficient given requirements per animal (i.e., the bedding balance) with an allowed deviation of less than 5 % for animal welfare (Table 3).

Table 3
Overview of constraints on different farm scenarios of the case study farm.

		Scenario A		Scenario B	
Description	Baseline	Minimum	Maximum	Minimum	Maximum
Deviation in feed balance intake (%)	−6.9	-∞	0	-∞	0
Deviation in feed balance energy (%)	2.2	−5	5	−5	5
Deviation in feed balance protein (%)	5.2	0	30	0	30
Deviation in feed balance structure (%)	159.1	0	∞	0	∞
Rotation Area (ha)	9.5	9	9.5	9	45
Livestock Units (LU)	56.2	15	57	–	–
Deviation bedding balance (%)	1.3	−5	5	−5	5
Soil nitrogen (N) losses (kg/ha)	197	20	197–352 [a]	20	197–352 [a]
Phosphorus (P) balance (kg/ha)	37	0	∞	0	∞
Potassium (K) balance (kg/ha)	664	0	∞	0	∞

[a] The soil N losses varied with manure management chains.

2.6. Model exploration

For model exploration, we ran the Pareto-based multi-objective optimization for 3000 iterations to get 500 alternative farm configurations for each scenario. The complete mathematical explanation of the algorithm with the corresponding formulae is described by Groot et al. (2012). Here we briefly summarize the optimization process. The DE algorithm generates two populations of solutions which represent the decision variables. The opportunity space created by these populations is diverse; the variety in the decision variables (genotypes) creates diversity in farm performance that is measured by the indicators (phenotypes). The first population of 'parents' serves as the result-set that is iteratively improved, while the second population consists of 'competitors' that are generated by uniform cross-over of three selected 'parent' solutions in each iteration.

The solutions in both populations are ranked using the principle of Pareto-optimality (Groot et al., 2012) and the Euclidean distance between the solutions in the opportunity space is calculated from the normalized indicator values, which serves to quantify a crowding metric. After ranking a selection process is conducted by pairwise comparison: a solution in the 'parent' population is replaced by the paired individual from the 'competitor' population if the latter has a better Pareto rank or if the ranks are equal it is positioned in a less crowded part of the opportunity space. The rank-based selection results in movement of the 'parent' population in the direction of the trade-off frontier (or surface), while the crowd-based selection ensures spread along the frontier (or surface).

The final set of alternative farm configurations produced by the model represents a solution space (Groot and Rossing, 2011). The solution frontier, defined as the boundary of solution space, illustrates the best possible trade-offs among the objectives, highlighting the optimal configurations that balance competing goals. We repeated each optimization for 3 times to get stable outcomes. The parameter settings of uniform cross-over in the Differential Evolution algorithm of the optimization was 0.85 for mutation probability and 0.15 for amplitude of mutations (Groot et al., 2007).

3. Results

3.1. Impacts of manure management on N losses from manure management chains (MMCs)

As shown in Fig. 1, although there were no obvious differences in N losses and N use efficiencies between MMCs M1 and M2, MMC configurations M3 and M4 could reduce N losses by 46 to 58 % and increase

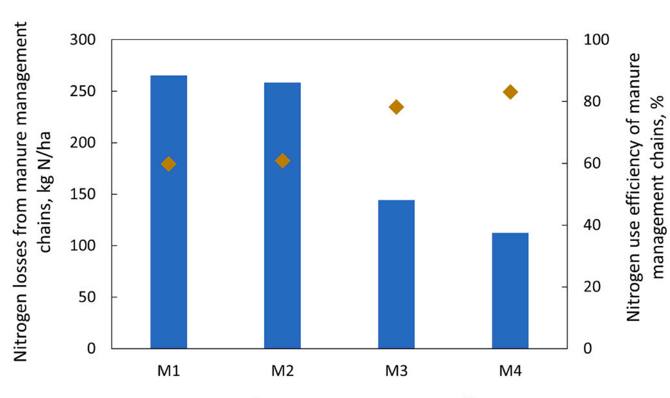

Fig. 1. Nitrogen losses and N use efficiency under different manure management chains (M1-M4, described in Table 2). The blue bars represent N losses, and the diamond dots indicate N use efficiency of various manure management chains. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

manure N use efficiencies by more than 30 %, compared to M1. This implied that applying a single emission mitigation measure (i.e., slurry cover) had limited influence on N losses from MMCs and manure N use efficiencies, while combinations of slurry solid-liquid separation, covered solid and liquid fractions storage and improved manure application could remarkably reduce N losses and improve N use efficiencies of manure management.

3.2. Impacts of manure management on N losses from the whole farm

Differences among the MMC configurations M1-M4 combined with the baseline farm configuration would not result in reduction of total N losses from the whole farm or improvement of farm N use efficiency. Due to the high livestock density and heavy reliance on imported feeds in baseline farm configuration, the N excreted by animals exceeded the N requirements of crop production, resulting in a high N surplus. Without changing the number of cows and crop areas, the conserved N from improved manure management would be lost after being applied to soil. Therefore, for this intensive mixed crop-dairy farm, improvements in manure management did not affect farm N use efficiency which is calculated as the ratio of N output (i.e., crop and animal products) from the farm to total N inputs (i.e., imported feeds, fixation and deposition) to the farm.

3.3. Effects of manure management on farm environmental performance

The results of multi-objective optimization in farm Scenario A revealed distinct synergies (1) between improving whole farm N use efficiency and reducing N volatilization (Fig. 2A), (2) between improving whole farm N use efficiency and decreasing soil N losses (Fig. 2B), (3) between reductions of soil N losses and N volatilization (Fig. 2C). On the other hand, trade-offs were found (4) between improvements of whole farm N use efficiency and soil OM balance (Fig. 2D), (5) between reducing N volatilization and increasing the soil OM balance (Fig. 2E), and (6) between reducing soil N losses and improving the soil OM balance (Fig. 2F). The main factor explaining the synergies and trade-offs between objectives was the number of cows on the farm. With the same farm area, a greater whole farm N use efficiency

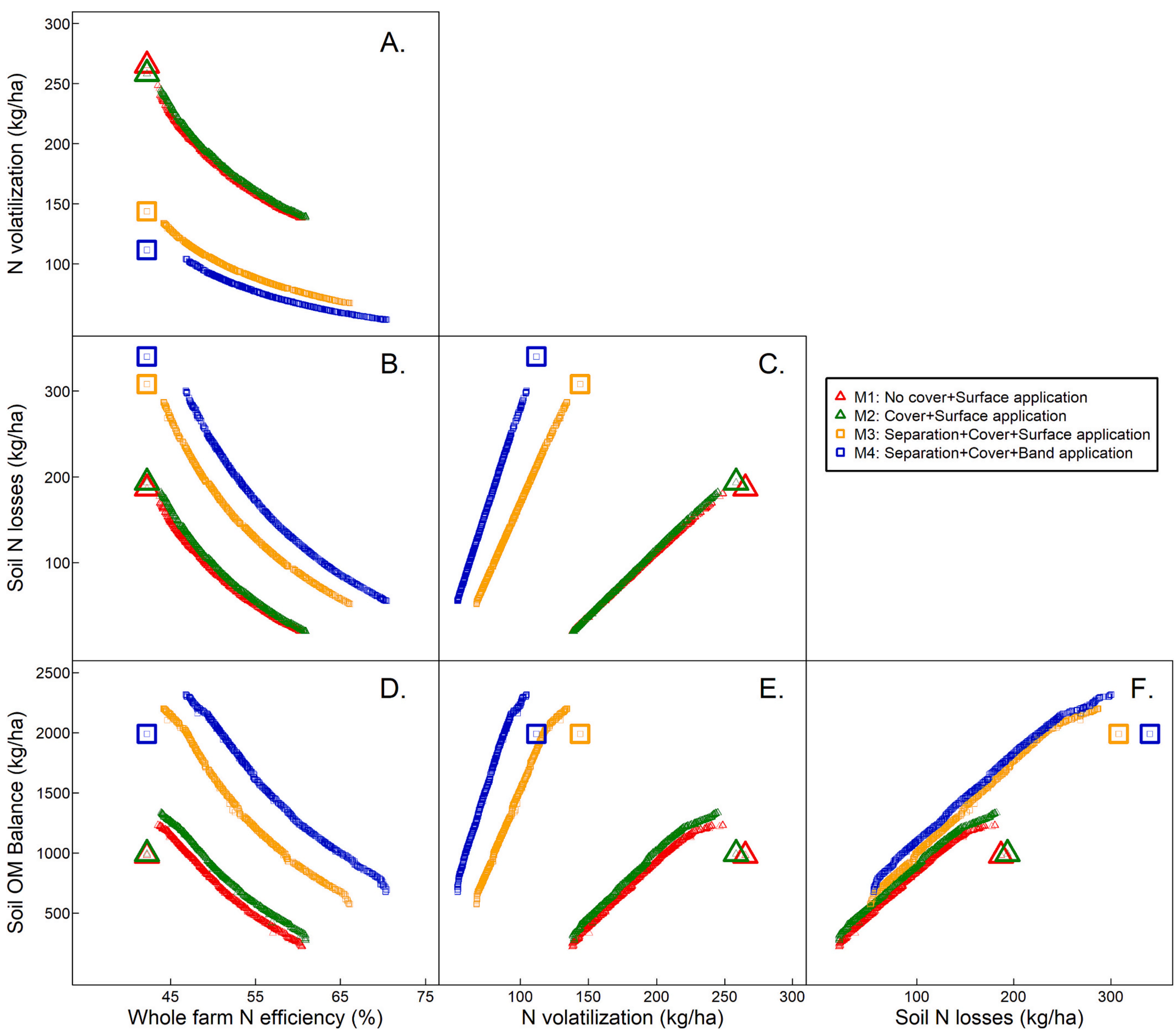

Fig. 2. Relationships between the objectives whole farm N use efficiency, N volatilization, soil N loss and soil OM balance in the farm scenario A with different manure management chains (i.e., M1, M2, M3 and M4). The larger symbols mark the performance of the baseline farm configuration.

could be achieved by reducing the number of cows. Reducing the number of cows reduced N volatilization and soil N losses but also lowered the soil OM balance.

Although the trade-off or synergy relationships among objectives were present under different MMCs, considerable differences in positions and slopes of solution frontiers in terms of N volatilization, soil N losses and soil OM balance among MMCs were observed (Fig. 2). These differences could primarily be explained by the impacts of manure management technologies on N volatilization, soil N losses and soil OM balance. As shown in Fig. 2, the apparent distance between the solution frontiers of MMCs M1, M2 and M3, M4 in terms of N volatilization and whole farm N use efficiency (Fig. 2A) showed lower N volatilization in MMCs M3 and M4 due to multiple N mitigation measures (i.e., solid-liquid separation, cover and improved application methods). Similar results were also found in solution frontiers of N volatilization and soil N losses (Fig. 2C) and N volatilization and soil OM balance (Fig. 2E). But higher soil N losses and soil OM balance were observed in MMCs M3 and M4 than in MMCs M1 and M2 with the same whole farm N use efficiency (Fig. 2B and D). Higher soil N losses in MMCs M3 and M4 demonstrated the compensatory N losses from manure management and soil, with less N volatilization from MMCs M3 and M4 (Fig. 2A) leading to higher N losses from soil (Fig. 2B). Higher soil OM balance in MMCs M3 and M4 could be as a result of the larger contribution of solid manure to soil OM than the contribution of slurry manure in MMCs M1 and M2.

The steeper slope of the synergy frontier between N volatilization and whole farm N use efficiency in MMCs M1 and M2 than in MMCs M3 and M4 indicated a stronger reduction in N volatilization in MMCs M1 and M2 needed to reach the same increase in whole farm N use efficiency (Fig. 2A). On the contrary, the steeper slope of the synergy frontiers between N volatilization and soil N losses in MMCs M3 and M4 showed that with the same decrease in N volatilization, more reduction in soil N losses could be obtained in MMCs M3 and M4 than M1 and M2 (Fig. 2C). Similar slopes but larger ranges of the frontiers were observed between whole farm N use efficiency and soil N losses, between whole farm N use efficiency and soil OM balance, and between soil N losses and soil OM balance in MMCs M3 and M4 than M1 and M2 (Fig. 2B and C). Compared to the baseline farm N use efficiency, a larger improvement in whole farm N use efficiency could be achieved in MMCs M3 and M4 than in MMCs M1 and M2.

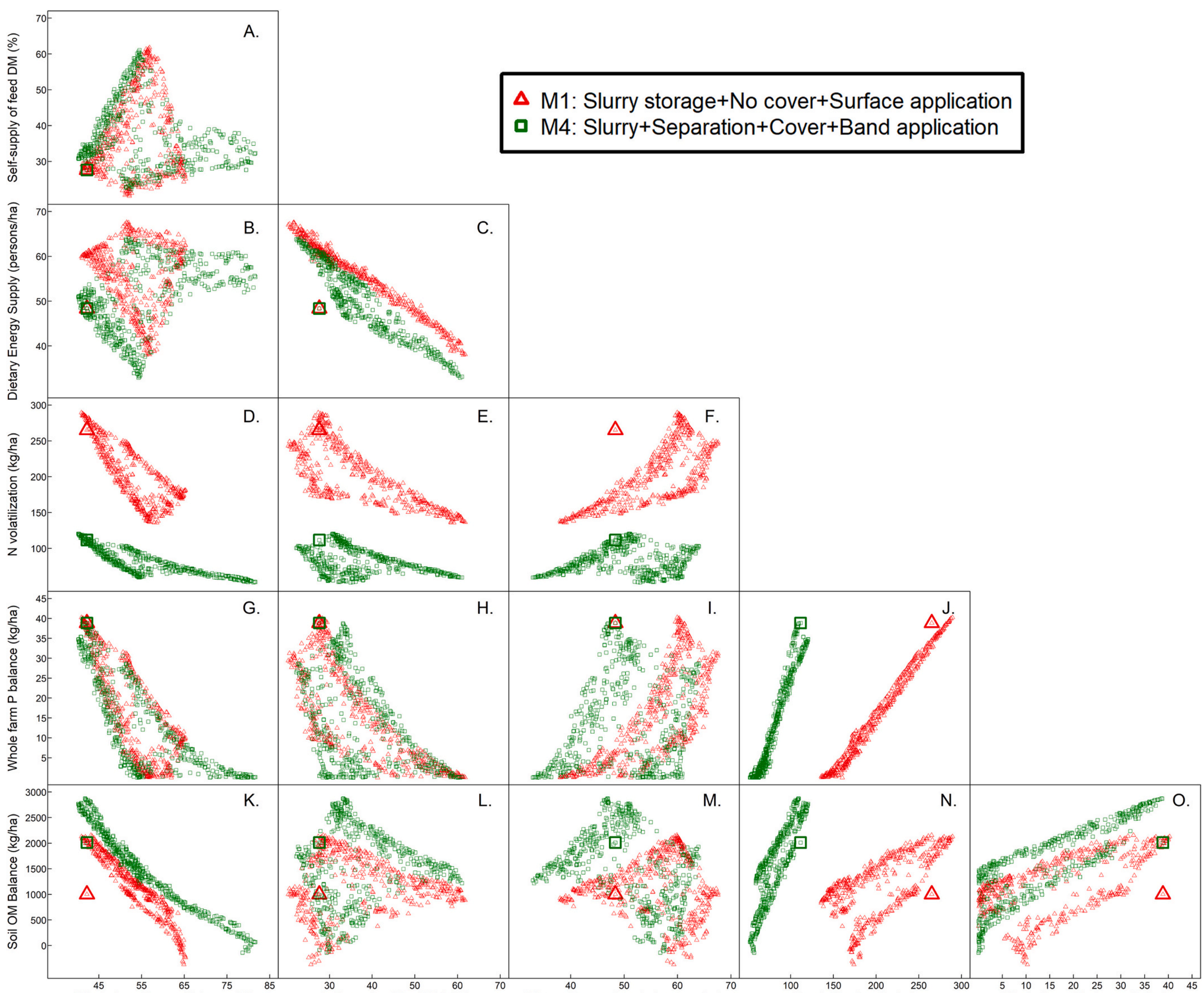

Fig. 3. Relationships between the objectives whole farm N use efficiency, self-supply of feed DM, dietary energy supply, N volatilization, whole farm P balance and soil OM balance in the farm scenario B with two different manure management chains. The larger symbols mark the performance of the baseline farm configuration.

3.4. Effects of manure management on optimization results for more integrated crop-dairy production

Since there was no clear difference in optimization results of objectives between MMCs M1 and M2, and between MMCs M3 and M4, we only performed farm explorations for the two most contrasting MMCs (M1 and M4) in farm Scenario B. Compared to exploration results of farm Scenario A, similar but more curvilinear trade-offs and synergies among objectives of whole farm N use efficiency, N volatilization and soil OM balance were observed in farm Scenario B due to more complicated interactions with added objectives of feed self-sufficiency, dietary energy supply and whole farm P balance. Exploration results of integration of crop and dairy production with multi-objective optimization indicated that changing farm configurations could also substantially improve whole farm N use efficiency, reduce N volatilization and improve soil OM balance (Fig. 3). With MMC M1, a maximum whole farm N use efficiency of 65 % could be reached, while MMC M4 could obtain values up to 85 %.

An obvious synergy relationship between reducing N volatilization and reducing P balance was observed (Fig. 3J). The steeper slope of the synergy frontier between N volatilization and whole farm P balance in MMC M4 compared to MMC M1 indicated that MMC M4 can achieve a greater reduction in P balance with the same decrease in N volatilization (Fig. 3J). Improved manure management MMC M4 also contributed to larger solution spaces for relationships between improving whole farm N use efficiency and reducing whole farm P balance (Fig. 3G), between increasing self-supply of feed DM and reducing whole farm P balance (Fig. 3H), and between improving dietary energy supply and reducing whole farm P balance (Fig. 3I). Improved manure management moves the synergy frontiers between reducing whole farm P balance and improving self-supply of feed DM (Fig. 3H), and between reducing whole farm P balance and improving soil OM balance in a more desirable direction (Fig. 3O).

The improved MMC M4 also moved the trade-off frontiers between whole farm N use efficiency and self-supply rate of feed DM (Fig. 3A) and between whole farm N use efficiency and dietary energy supply

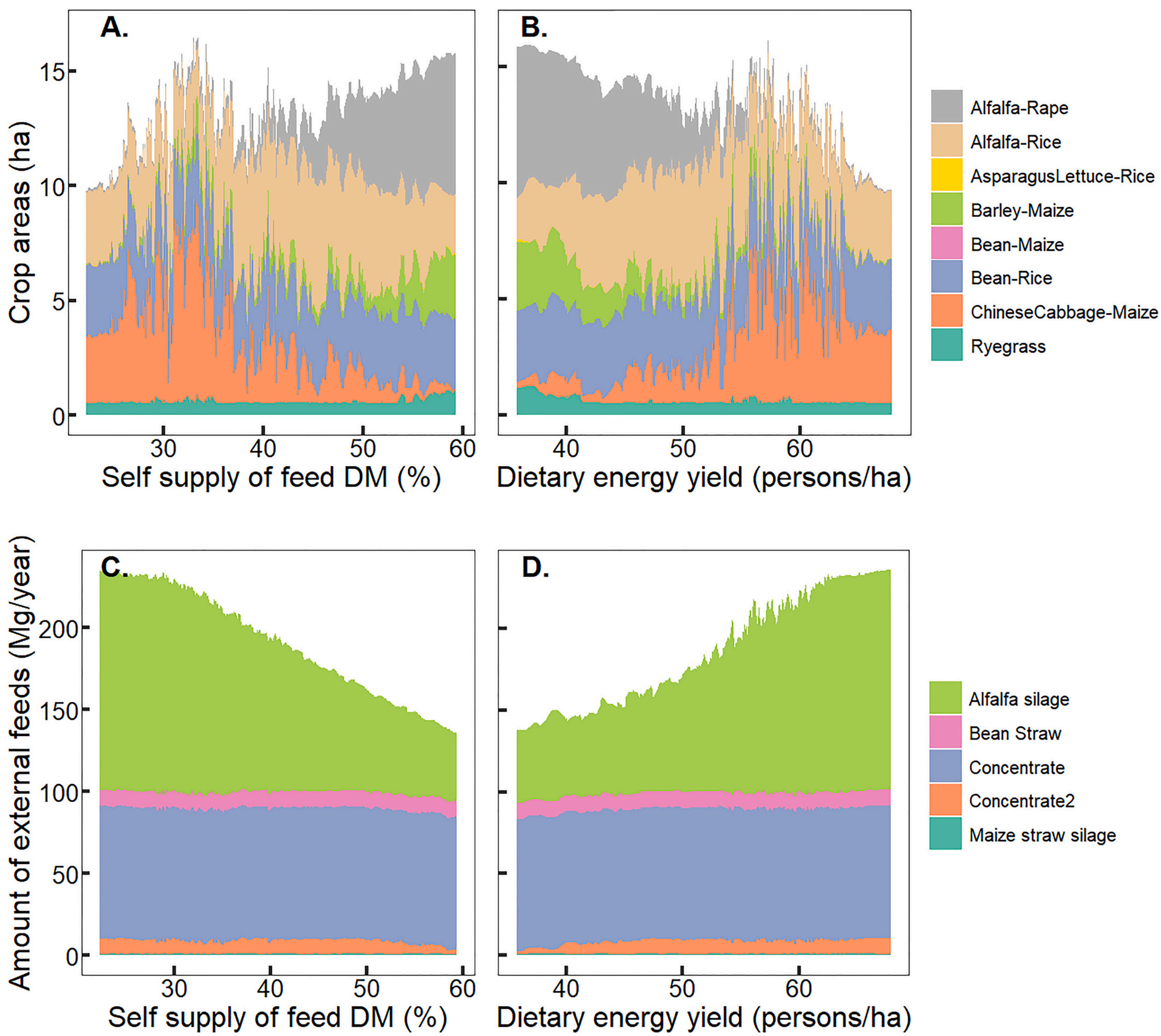

Fig. 4. Modelled allocation of crop areas and quantities of imported feeds in each alternative farm configuration generated to meet the objectives of maximizing self-supply rate of feed DM and dietary energy yield in farm Scenario B. The x-axis values were ordered from minimum to maximum for each objective.

(Fig. 3B) towards more desirable directions. But a clear trade-off between increasing self-supply rate of feed DM and improving dietary energy supply was observed (Fig. 3C), indicating food-feed competition at the case study farm. Fig. 4 shows how the shift in cropping patterns and changes in the amount of external feed inputs define the relationship between feed self-supply and dietary energy production. In farm Scenario B, to approach the objective of increasing feed self-sufficiency, the model shifted the feed production from external importation to on-farm production, subsequently causing the increase of areas to feed crops, such as alfalfa (Fig. 4A and B). Conversely, in the alternative configurations with greater dietary energy supply, the model allocated larger areas to food crops (i.e., Chinese cabbage and maize) and smaller areas to alfalfa. The reduced on-farm alfalfa silage production was compensated by an increased external alfalfa silage input (Fig. 4C and D).

4. Discussion

In this study we compared N losses under various manure management chains with different manure management technologies, and explored the effects of improved manure management chains on farm environmental performance optimization. The results demonstrated that an individual emission mitigation measure was insufficient to reduce N losses at manure management chain level. However, implementing a combination of solid-liquid separation, covered solid or liquid manure storage and improved manure application (M4) resulted in substantial reductions in N losses from the whole manure management chains.

The importance of an integrated approach with combined manure management technologies along the manure management chain has been pointed out (De Vries et al., 2015a, 2015b), given the compensatory losses among manure management facilities. Previous study reported that the reduced N loss by covered solid manure storage resulted in larger N loss after manure field application, and highlighted that combined manure management practices were more effective to reduce total N losses (Shah et al., 2013). In a study by Rotz et al. (2006) for a farm with 100 cows on 100 ha cropland and a farm with 1000 cows on 600 ha cropland, implementing nutrient conservation technologies, including a barn floor for feces and urine separation, covered six-month manure storage, and manure injection, reduced ammonia emission by 54 % to 77 % and reduced total farm N losses by 24 % to 29 %.

Although multiple mitigation measures showed potential for reducing N loss from manure management, we found no decrease in total N loss from the farm. This could be explained by the high livestock density and large quantity of imported feed N on the case study farm. The imported feed N led to excessive amounts of N cycled through the farm system. Although improved manure management practices conserved more N in manure, the limited croplands could not assimilate the conserved N, leading to larger losses from soil. This implied that for intensive dairy farms with limited land availability, it probably is not enough to reduce N losses only by improving manure management chain with multiple mitigation practices, and exporting manure outside the farm or integrating more croplands to the farm is likely needed.

We also found no substantial decrease in whole farm P balance from improved manure management practices. This was primarily because manure P was mainly lost by runoff and leaching after application. As noted by Spears et al. (2003), around 96 % of manure P can be conserved during manure storage and accumulated in the soil after manure application. Additionally, feed imports significantly contribute to the whole farm P balance (Ros et al., 2023). By enhancing feed self-reliance through the integration of more crop areas for on-farm feed production, we could see substantial reductions in whole farm P balance. This is in consistent with the finding from Harrison et al. (2021), which indicate that farming systems with a higher inclusion rate of home-grown feed in their herds' diet exhibited greater P use efficiency and lower P surplus.

The results of the multi-objective optimization on environmental performance in the case study farm demonstrated that improved manure management with multiple mitigation measures could move trade-off and synergy relationships among N volatilization, soil N losses, soil OM balance and whole farm N use efficiency in desirable directions. Integrated crop-dairy systems offered further possibilities for minimizing environmental impacts. Larger reductions in N volatilization and greater whole farm N use efficiencies were achieved through integrating crop and dairy production.

Integrated crop–livestock systems have been identified as a viable strategy to increase nutrient circularity and limit the negative environmental impacts (Lemaire et al., 2014; Moraine et al., 2014; Peyraud et al., 2014).For intensive dairy farming systems with heavy reliance on off-farm feeds and with substantial manure nutrient surpluses, closing the loop in nutrient and energy cycles by recoupling crop systems at farm and regional scales can help reduce the environmental externalities of intensive farms and increase their resilience (Garrett et al., 2020; Chen et al., 2023). This study showed that combined with improved manure management, crop-dairy integration reduced N volatilization, soil N losses, whole farm P balance and achieved high farm nutrient use efficiency.

Although the obvious trade-off between feed self-sufficiency and dietary energy supply at the case study farm was identified, it is important to note that this is not the case for other integrated crop-livestock systems. With a high stocking density, this case study farm allocated the majority of crop area to produce feeds, creating a trade-off between food and feed production. Integrating crop areas to produce feed created a shift on the trade-off, but did not change the trade-off relationship. The issue of crop-dairy integration has raised the question about resource allocation for food and feed production, especially for intensive dairy farms with high stocking densities (Muscat et al., 2020; Puech and Stark, 2023). The food-feed competition in our study was mainly generated from the use of cropland, with more cropland used to produce livestock feeds (e.g., alfalfa and whole maize silage) leading to a smaller area for food production. Potential ways to alleviate the food-feed competition on integrated crop-dairy farm might include increasing nutrient use efficiency in cropping systems through optimizing crop rotations and increasing crop yields per area (Barbieri et al., 2021). Increasing animal feed use efficiency at the animal and herd level is also an important lever to save feed resources (Barbieri et al., 2022). Additionally, collaboration between local crop and dairy farms for direct exchange of manure and crop by-products could further close nutrient loops at larger scales, promoting resource utilization efficiency and contributing to a circular food system (Martin et al., 2016; De Boer and Van Ittersum, 2018; Ghimire et al., 2021).

Some limitations of this study were identified based on current results. First, we explored alternative farm configurations with a focus on optimizing environmental and nutritional indicators and without considering economic indicators. Although some studies have proven that crop-livestock integration could limit the negative environmental impacts without compromising farm economics (Martin et al., 2016), in practice, the cost for manure management varies with types of treatment technologies (Hansen, 2019; Sefeedpari et al., 2019). A more comprehensive evaluation that considers environmental, economic and nutritional indicators would contribute to a better understanding of the role of manure management in farm management, and would help farmers to adopt cost-effective manure management technologies. Second, our study might underestimate the contribution of manure management on farm nutrient management as the model calculated nutrient flows based on mass balance without considering the nutrient availability of different manure types as fertilizer which highly depends on methods of manure handling, storage and treatment (Rufino et al., 2007; Risbery et al., 2017). In addition, the impacts of manure management technologies on manure quality are crucial for maintaining soil biodiversity, and are worthwhile to investigate (Köninger et al., 2021).

The combined FarmDESIGN and FarmM3 models offer a useful tool to explore how improved manure management influence nutrient flows and use efficiency at the whole farm. The generated alternative solutions based on Pareto-based multi-objective optimization algorithm can support farmers to have their autonomous choice from a broad portfolio of alternatives and can serve as entry points for future participatory process with multiple stakeholders (Groot and Rossing, 2011). As integration of crop and dairy production within farms requires greater workload and increased skills and knowledge in animal, manure, soil and crop management, future research on integrating crop and dairy production beyond the farm scale by exchanging manure and feedstuff between dairy and crop farms are necessary, especially for intensive and specialized farms. Nutrient "sharing" between crop and dairy farms within a region can provide complementary interactions and benefits, reducing externalities of specialized farms and contributing to close nutrient cycles at a larger scale.

5. Conclusions

Manure management plays an important role in farm nutrient management of intensive mixed crop-dairy farms. Due to substantial nutrient losses from a large amount of produced manure, as well as complicated interactions of manure management and soil and crops, the effects of improved manure management on farm nutrient management should also be considered when seeking to optimize farm configurations. Our study integrated an external manure management model (FarmM3) to a whole farm model (FarmDESIGN), which enables (i) to evaluate the effects of diverse improved manure management technologies on nutrient losses from manure management and from the whole farm system; (ii) to identify potential influence of improved manure management on multi-objective optimization of farm configurations.

To reduce nutrient losses from the whole manure management chain, a single manure management technology was insufficient, highlighting the importance of integrated approaches to reduce N losses from manure management. At a high livestock density, total N losses from the whole farm were not influenced by improved manure management, since conserved N from manure management could be lost after being applied to cropland. A greater reduction of N losses from both manure management and soil could be achieved by reducing livestock density, resulting in an improved whole N use efficiency. Additionally, improved manure management did not lead to a decrease in whole farm P balance, primarily because manure P was mainly lost through runoff and leaching after application. However, integrating crop and dairy production to increase on-farm feed production could significantly reduce whole farm P balance.

Although trade-offs and synergies existed among objectives, improved manure management did not change relationships among objectives but did affect the positions and the slopes of the solution frontiers between objectives of N volatilization, soil N losses and soil OM balance. To move towards sustainable intensification of dairy production, increasing nutrient circularity by improving manure management with multiple mitigation measures and integrating crop and dairy production within farm or between farms are necessary. Given the trade-off of food-feed competition when integrating crop production within dairy farms with high stocking densities and heavy reliance on external feeds, food production should also be considered when optimizing farm configurations towards more sustainable agricultural production.

CRediT authorship contribution statement

Qingbo Qu: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Jeroen C.J. Groot:** Writing – review & editing, Supervision, Software, Methodology, Funding acquisition, Conceptualization. **Keqiang Zhang:** Writing – review & editing, Supervision, Resources, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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References

Aguirre-Villegas, H.A., Larson, R.A., Sharara, M.A., 2019. Anaerobic digestion, solid-liquid separation, and drying of dairy manure: measuring constituents and modeling emission. Sci. Total Environ. 696, 134059. https://doi.org/10.1016/j.scitotenv.2019.134059.

Bai, Z.H., Ma, L., Oenema, O., Chen, Q., Zhang, F.S., 2013. Nitrogen and phosphorus use efficiencies in dairy production in China. J. Environ. Qual. 42, 990–1001. https://doi.org/10.2134/jeq2012.0464.

Barbieri, P., Pellerin, S., Seufert, V., Smith, L., Ramankutty, N., Nesme, T., 2021. Global option space for organic agriculture is delimited by nitrogen availability. Nat. Food 2, 363–372. https://doi.org/10.1038/s43016-021-00276-y.

Barbieri, P., Dumont, B., Benoit, M., Nesme, T., 2022. Opinion paper: livestock is at the heart of interacting levers to reduce feed-food competition in agroecological food systems. Animal 16, 100436. https://doi.org/10.1016/j.animal.2021.100436.

Berg, W., Brunsch, R., Pazsiczki, I., 2006. Greenhouse gas emissions from covered slurry compared with uncovered during storage. Agric. Ecosyst. Environ. 112, 129–134. https://doi.org/10.1016/j.agee.2005.08.031.

Chadwick, D.R., Williams, J.R., Lu, Y.L., Ma, L., Bai, Z.H., Hou, Y., Chen, X.P., Misselbrook, T.H., 2020. Strategies to reduce nutrient pollution from manure management in China. Front. Agric. Sci. Eng. 7, 45–55. https://doi.org/10.15302/j-fase-2019293.

Chen, X., Lin, J., Tan, K., Pei, Y., Wang, X., 2023. Cooperation between specialized cropping and livestock farms at local level reduces carbon footprint of agricultural system: a case study of recoupling maize-cow system in South China. Agric. Ecosyst. Environ. 348, 108406. https://doi.org/10.1016/j.agee.2023.108406.

Clay, N., Garnett, T., Lorimer, J., 2020. Dairy intensification: drivers, impacts and alternatives. Ambio 49, 35–48. https://doi.org/10.1007/s13280-019-01177-y.

De Boer, I.J.M., Van Ittersum, M.K., 2018. Circularity in Agricultural Production. Wageningen University. https://library.wur.nl/WebQuery/wurpubs/fulltext/470625 (accessed 23 July 2021).

De Vries, J.W., Groenestein, C.M., Schröder, J.J., Hoogmoed, W.B., Sukkel, W., Groot Koerkamp, P.W.G., De Boer, I.J.M., 2015a. Integrated manure management to reduce environmental impact: II. Environmental impact assessment of strategies. Agr. Syst. 138, 88–99. https://doi.org/10.1016/j.agsy.2015.05.006.

De Vries, J.W., Hoogmoed, W.B., Groenestein, C.M., Schröder, J.J., Sukkel, W., De Boer, I.J.M., Groot Koerkamp, P.W.G., 2015b. Integrated manure management to reduce environmental impact: I. Structured design of strategies. Agric. Syst. 139, 29–37. https://doi.org/10.1016/j.agsy.2015.05.010.

FAO, 2018. The State of the world's Animal Genetic Resources for Food and Agriculture - Livestock Diversity Is Essential, 2nd ed. Food and Agriculture Organization of the United Nations.

Foged, H.L., Flotats, X., Blasi, A.B., Palatsi, J., Magri, A., Schelde, K.M., 2011. Inventory of manure processing activities in Europe. Technical Report No. I concerning "Manure Processing Activities in Europe" to the European Commission, Directorate-General Environment, 138.

Garrett, R.D., Ryschawy, J., Bell, L.W., Cortner, O., Ferreira, J., Garik, A.V.N., Gil, J.D.B., Klerkx, L., Moraine, M., Peterson, C.A., dos Reis, J.C., Valentim, J.F., 2020. Drivers of decoupling and recoupling of crop and livestock systems at farm and territorial scales. Ecol. Soc. 25 (1), 24. https://doi.org/10.5751/ES-11412-250124.

Ghimire, S., Wang, J., Fleck, J.R., 2021. Integrated crop-livestock systems for nitrogen management: a multi-scale spatial analysis. Animals 11 (1), 100. https://doi.org/10.3390/ani11010100.

Groot, J.C.J., Rossing, W.A.H., 2011. Model-aided learning for adaptive management of natural resources: an evolutionary design perspective. Methods Ecol. Evol. 2, 643–650. https://doi.org/10.1111/j.2041-210X.2011.00114.x.

Groot, J.C.J., Rossing, W.A.H., Jellema, A., Stobbelaar, D.J., Renting, H., Van Ittersum, M.K., 2007. Exploring multi-scale trade-offs between nature conservation, agricultural profits and landscape quality—a methodology to support discussions on land-use perspectives. Agric. Ecosyst. Environ. 120, 58–69. https://doi.org/10.1016/j.agee.2006.03.037.

Groot, J.C.J., Oomen, G.J.M., Rossing, W.A.H., 2012. Multi-objective optimization and design of farming systems. Agr. Syst. 110, 63–77. https://doi.org/10.1016/j.agsy.2012.03.012.

Hansen, B.G., 2019. CO2–emission, costs and capacity of different manure management practices-results from an advisory project. Agr. Syst. 173, 325–334. https://doi.org/10.1016/j.agsy.2019.03.011.

Harrison, B.P., Dorigo, M., Reynolds, C.K., Sinclair, L.A., Dijkstra, J., Ray, P.P., 2021. Determinants of phosphorus balance and use efficiency in diverse dairy farming systems. Agr. Syst. 194, 103273. https://doi.org/10.1016/j.agsy.2021.103273.

Holly, M.A., Larson, R.A., Powell, J.M., Ruark, M.D., Aguirre-Villegas, H., 2017. Greenhouse gas and ammonia emissions from digested and separated dairy manure during storage and after land application. Agric. Ecosyst. Environ. 239, 410–419. https://doi.org/10.1016/j.agee.2017.02.007.

Hou, Y., Velthof, G.L., Oenema, O., 2015. Mitigation of ammonia, nitrous oxide and methane emissions from manure management chains: a meta-analysis and integrated assessment. Glob. Change Biol. 21 (3), 1293–1312. https://doi.org/10.1111/gcb.12767.

Köninger, J., Lugato, E., Panagos, P., Kochupillai, M., Orgiazzi, A., Briones, M.J.I., 2021. Manure management and soil biodiversity: towards more sustainable food systems in the EU. Agr. Syst. 194, 103251. https://doi.org/10.1016/j.agsy.2021.103251.

Lemaire, G., Franzluebbers, A., Carvalho, P.C.D.F., Dedieu, B., 2014. Integrated crop–livestock systems: strategies to achieve synergy between agricultural production and environmental quality. Agric. Ecosyst. Environ. 190, 4–8. https://doi.org/10.1016/j.agee.2013.08.009.

Martin, G., Moraine, M., Ryschawy, J., Magne, M.-A., Asai, M., Sarthou, J.-P., Duru, M., Therond, O., 2016. Crop–livestock integration beyond the farm level: a review. Agron. Sustain. Dev. 36, 53. https://doi.org/10.1007/s13593-016-0390-x.

Marton, S.M.R.R., Zimmermann, A., Kreuzer, M., Gaillard, G., 2016. Comparing the environmental performance of mixed and specialised dairy farms: the role of the system level analysed. J. Clean. Prod. 124, 73–83. https://doi.org/10.1016/j.jclepro.2016.02.074.

Moraine, M., Duru, M., Nicholas, P., Leterme, P., Therond, O., 2014. Farming system design for innovative crop-livestock integration in Europe. Animal 8, 1204–1217. https://doi.org/10.1017/S1751731114001189.

Muscat, A., de Olde, E.M., de Boer, I.J.M., Ripoll-Bosch, R., 2020. The battle for biomass: a systematic review of food-feed-fuel competition. Glob. Food Sec. 25, 100330. https://doi.org/10.1016/j.gfs.2019.100330.

Oenema, O., Tamminga, S., 2005. Nitrogen in global animal production and management options for improving nitrogen use efficiency. Sci. China. Ser. C. 48, 871–887. https://doi.org/10.1360/062005-279.

Oenema, O., Oudendag, D., Velthof, G.L., 2007. Nutrient losses from manure management in the European Union. Livest. Sci. 112, 261–272. https://doi.org/10.1016/j.livsci.2007.09.007.

Peyraud, J.-L., Taboada, M., Delaby, L., 2014. Integrated crop and livestock systems in Western Europe and South America: a review. Eur. J. Agron. 57, 31–42. https://doi.org/10.1016/j.eja.2014.02.005.

Puech, T., Stark, F., 2023. Diversification of an integrated crop-livestock system: Agroecological and food production assessment at farm scale. Agric. Ecosyst. Environ. 344, 108300. https://doi.org/10.1016/j.agee.2022.108300.

Qu, Q., Zhang, K., Groot, J.C., 2023. A model to identify entry points to curb emissions from complex manure management chains. J. Clean. Prod. 137787. https://doi.org/10.1016/j.jclepro.2023.137787.

Ros, M.B.H., Godber, O.F., Olivo, A.J., Reed, K.F., Ketterings, Q.M., 2023. Key nitrogen and phosphorus performance indicators derived from farm-gate mass balances on dairies. J. Dairy Sci. 106 (5), 3268–3286. https://doi.org/10.3168/jds.2022-22297.

Rotz, C.A., Oenema, J., van Keulen, H., 2006. Whole farm management to reduce nutrient losses from dairy farms: a simulation study. Appl. Eng. Agric. 22, 773–784.

Rufino, M.C., Tittonell, P., van Wijk, M.T., Castellanos-Navarrete, A., Delve, R.J., de Ridder, N., Giller, K.E., 2007. Manure as a key resource within smallholder farming systems: Analysing farm-scale nutrient cycling efficiencies with the NUANCES framework. Livest. Sci. 112, 273–287. https://doi.org/10.1016/j.livsci.2007.09.011.

Ryschawy, J., Choisis, N., Choisis, J.P., Joannon, A., Gibon, A., 2012. Mixed crop-livestock systems: an economic and environmental-friendly way of farming? Animal 6, 1722–1730. https://doi.org/10.1017/S1751731112000675.

Sajeev, E.P.M., Winiwarter, W., Amon, B., 2018. Greenhouse gas and ammonia emissions from different stages of liquid manure management chains: abatement options and emission interactions. J. Environ. Qual. 47, 30–41. https://doi.org/10.2134/jeq2017.05.0199.

Schut, A.G.T., Cooledge, E.C., Moraine, M., Van de Ven, G.W.J., Jones, D.L., Chadwick, D.R., 2021. Reintegration of crop-livestock systems in Europe: an overview. Front. Agric. Sci. Eng. 8, 111–129. https://doi.org/10.15302/JFASE-2020373.

Sefeedpari, P., Vellinga, T., Rafiee, S., Sharifi, M., Shine, P., Pishgar-Komleh, S.H., 2019. Technical, environmental and cost-benefit assessment of manure management chain: a case study of large scale dairy farming. J. Clean. Prod. 233, 857–868. https://doi.org/10.1016/j.jclepro.2019.06.146.

Shah, G.A., Groot, J.C., Shah, G.M., Lantinga, E.A., 2013. Simulation of long-term carbon and nitrogen dynamics in grassland-based dairy farming systems to evaluate mitigation strategies for nutrient losses. PloS One 8, e67279. https://doi.org/10.1371/journal.pone.0067279.

Sommer, S.G., Hutchings, N.J., 2001. Ammonia emission from field applied manure and its reduction - invited paper. Eur. J. Agron. 15, 1–15. https://doi.org/10.1016/S1161-0301(01)00112-5.

Sommer, S.G., Christensen, M.L., Schmidt, T., Jensen, L.S., 2013. Animal Manure Recycling Treatment and Management. John Wiley & Sons.

Spears, R.A., Young, A.J., Kohn, R.A., 2003. Whole-farm phosphorus balance on western dairy farms. J. Dairy Sci. 86 (2), 688–695.

Zou, T., Meng, F., Zhou, J., Ying, H., Liu, X., Hou, Y., Zhao, Z., Zhang, F., Xu, W., 2023. Quantifying nitrogen and phosphorus losses from crop and livestock production and mitigation potentials in Erhai Lake Basin, China. Agric. Syst. 211, 103745. https://doi.org/10.1016/j.agsy.2023.103745.