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Evidence of a rebound effect in agriculture: Crop-livestock reconnection beyond the farm gate does not always lead to more sustainable nitrogen management

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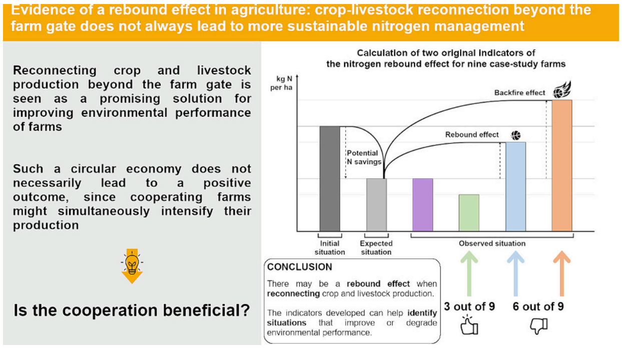
HIGHLIGHTS

- Reconnecting crops and livestock between farms is promising, but a rebound effect may offset the environmental gains.
- The study aimed to quantify a potential nitrogen (N) rebound effect due to reconnection between crop and livestock farms.
- A rebound effect appeared for three cooperating crop farms receiving manure without reducing use of inorganic fertilizers.
- A rebound effect was also observed for three cooperating dairy farms that intensified their milk production.
- The rebound effect indicator complements N-use efficiency and N balance for farm N performance evaluation.

GRAPHICAL ABSTRACT


Evidence of a rebound effect in agriculture: crop-livestock reconnection beyond the farm gate does not always lead to more sustainable nitrogen management

Reconnecting crop and livestock production beyond the farm gate is seen as a promising solution for improving environmental performance of farms

Such a circular economy does not necessarily lead to a positive outcome, since cooperating farms might simultaneously intensify their production

Is the cooperation beneficial?

Calculation of two original indicators of the nitrogen rebound effect for nine case-study farms

CONCLUSION

There may be a **rebound effect** when **reconnecting** crop and livestock production.

The indicators developed can help **identify situations** that improve or degrade environmental performance.

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ABSTRACT

CONTEXT: Reconnecting crop and livestock production beyond the farm gate by exchanging raw materials (e.g., feed, manure) between farms is seen as a promising solution for improving the environmental performance of farms, since it should reduce the use of imported nitrogen (N) inputs. However, such a circular economy does not necessarily lead to a positive outcome, since cooperating farms might simultaneously intensify their production, which could cancel out the benefits of reconnecting crops and livestock: this is known as a rebound effect.
OBJECTIVE: The aim of our study was to identify and analyze a potential rebound effect due to reconnection of crop and livestock farms.
METHODS: We collected data on 18 case-study farms in a small territory in Spain. We then calculated two indicators of the N rebound effect: one based on potential savings of inorganic N fertilizer for cooperating crop farms and another based on potential savings of N losses to the environment for cooperating livestock farms.
RESULTS AND CONCLUSIONS: On cooperating crop farms, importing manure did not lead to replacement of inorganic N fertilizer and could lead more inorganic N fertilizer being used. Thus, their mean N rebound effect

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was 520 %, which constituted a backfire effect. This mean, however, covered large differences among farms. On cooperating dairy farms, exporting manure resulted in a mean negative rebound effect of −17 %, meaning that they achieved higher savings in the N balance than expected compared to non-cooperating dairy farms.

SIGNIFICANCE: Our main contribution is to show that there may be a rebound effect when reconnecting crop and livestock production beyond the farm gate due to the intensification of farms. The indicators of the N rebound effect developed can thus help identify situations that improve or degrade environmental performance. They should be used to complement existing indicators, such as N-use efficiency and the N balance, to design efficient farming systems while avoiding a rebound effect.

1. Introduction

Nitrogen (N) is a limiting nutrient for agricultural production. The Haber-Bosch process has allowed humans to produce reactive N, which has helped greatly to meet the food needs of an increasing population (Erisman et al., 2008). However, much of the reactive N used in agriculture is lost to the environment, where it often has major impacts on environmental and human health (Sutton et al., 2013). One of the most complex challenges facing agriculture is thus to reconcile the objectives of feeding the world while reducing its N emissions (Rockström et al., 2009). The most promising ways to reach this goal are to increase N-use efficiency (NUE) in crop and livestock production, and to close the N cycle in agriculture further (Godinot et al., 2022). Closing the N cycle is usually based on closely integrating crop and livestock production in mixed farming systems: animals are fed locally produced crops, while their manure is used to fertilize the crops, thus reducing the need for inorganic fertilizers, and purchased feed (Herrero et al., 2010; Ryschawy et al., 2012).

However, such technical complementarities are weaker in current farming systems due to the specialization of farms and agricultural regions, which has disconnected and spatially segregated crop and livestock production in the European Union (EU) and elsewhere (Naylor et al., 2005; Peyraud et al., 2014). This trend breaks the N cycle: livestock farms and regions lack protein to feed animals, while crop farms and regions lack N to fertilize crops (Nesme et al., 2015; Senthilkumar et al., 2012). To overcome these problems, the EU imports huge quantities of feed, mostly soybean and soybean meal, representing more than 33 Mt. in 2020 (IDH, 2022), some contributing to “imported deforestation” (Escobar et al., 2020). In parallel, crop production relies massively on inorganic fertilizers, which have high environmental impacts (Ma et al., 2021). It is thus essential to reduce the use of these inputs to reduce N losses.

One solution is therefore to redevelop mixed farming systems to close the N cycle further. However, specialized agriculture relies on strong economic drivers such as economies of scale and of agglomeration, which makes such a change difficult (Chavas, 2008; Gaigné et al., 2012). To overcome this issue, it could be interesting to reconnect crop and livestock production beyond the farm gate, such as through exchanging materials (e.g., feed, manure) between specialized farms within a region (Nowak et al., 2015; Regan et al., 2017; Ryschawy et al., 2017). Crop farms can import manure from livestock farms, while livestock farms can import feed from crop farms. The underlying assumption is that the use of inorganic fertilizers would decrease on the crop farms, while feed imports from overseas and N surplus would decrease on the livestock farms. This cooperation would thus represent an example of a circular economy that would benefit from the economic advantages of specialization, while limiting their negative environmental impacts (Korhonen et al., 2018; Martin et al., 2016). Such benefits are highlighted in the literature because it is generally assumed that farming systems remain unchanged during cooperation, all other things being equal (Fernandez-Mena et al., 2020). However, this kind of circular economy does not necessarily decrease environmental impacts because the cooperating farms might use the increase in efficiency to intensify their production, which could decrease the benefits of reconnecting crop and livestock production (Jouan et al., 2020a; Zhang and Lassaletta, 2022); this can be likened to a rebound effect.

The rebound effect is related to the concepts of efficiency and economic rationality: it describes the trend in which increased efficiency makes the production of some good (e.g., energy) relatively less expensive, leading to increased consumption of the good, which cancels out some of the initial savings (Zink and Geyer, 2017). Ultimately, the rebound effect may result in a “backfire effect” when the increased consumption completely offsets the environmental benefits of higher efficiency (Brookes, 2000; Sorrell, 2009a).

The rebound effect was first described as the “Jevons paradox” during the Industrial Revolution (Alcott, 2005) and was then seldom used until energy economists used it frequently at the end of the 20th century (Brookes, 1990; Khazzoom, 1980). Since then, it has been applied to environmental assessment, related, for example, to water management (Berbel and Mateos, 2014; Sears et al., 2018) or land-use management (García et al., 2020; Valin et al., 2013). The review of Paul et al. (2019) also revealed evidence of a rebound effect related to an increase in land productivity and irrigation. Regarding nutrient-use efficiency, Scholz and Wellmer (2015) investigated a rebound effect for the phosphorus cycle. Recently, Rodríguez et al. (2023) showed a rebound effect in Spain: pig production systems became more efficient, while total production increased dramatically to meet demand, leading to an overall increase in feed consumption. Finally, several studies have highlighted a rebound effect following crop-livestock reconnection, either by modelling farm exchanges within a region (Jouan et al., 2020b) or by analyzing case studies (Leterme et al., 2019; Regan et al., 2017).

However, no study has quantified the rebound effect related to the N that farms may be able to save when they cooperate on N management. The aim of our study was thus to quantify N flows and calculate and analyze the potential rebound effect due to crop and livestock reconnection between farms. To this end, we collected data on 18 case-study farms, half of which cooperated, in a small territory in Spain. We then calculated two indicators of the N rebound effect: one based on potential savings of inorganic N fertilizer for cooperating crop farms and another based on potential savings of N losses to the environment for cooperating livestock farms.

2. Materials and methods

2.1. Presentation of the dataset

We used data from the EU project CANTOGETHER. Nine cooperating farms (five crop farms, four dairy farms) and nine non-cooperating farms (four crop farms, five dairy farms) were chosen as representative of the study area, a part of the Ebro River basin in Zaragoza Province, northeastern Spain (Regan et al., 2017). Farms were surveyed to collect data on their structure, farming practices and N flows for 2013 (Table 1). The study area has a Mediterranean semi-arid climate, with rainfall of about 290–400 mm/year. Most crops were therefore irrigated. Crop farms produced mainly winter cereals, grain maize and oilseeds. Dairy farms produced mainly silage maize, Italian ryegrass and alfalfa; double cropping of Italian ryegrass and silage maize was common. Cooperating and non-cooperating farms had a similar milk yield per cow, but cooperating farms produced nearly twice as much milk per ha because they

Table 1
Mean ± 1 standard deviation of main characteristics of the farm groups surveyed in the Ebro River basin, Spain.

Characteristic	Non-cooperating crop farm (n = 5)	Cooperating crop farm (*n* = 4)	Non-cooperating dairy farm (n = 4)	Cooperating dairy farm (*n* = 5)
Utilized agricultural area (ha)	155 ± 127	159 ± 171	35 ± 7	30 ± 23
Forage area (%)	25 ± 19	29 ± 12	94 ± 7	75 ± 35
Cereal and oilseed area (%)	73 ± 19	70 ± 11	6 ± 7	22 ± 32
Stocking rate (cows ha^{-1})	NA	NA	2.4 ± 0.2	4.4 ± 3.3
Milk yield (L cow^{-1} yr^{-1})	NA	NA	10,510 ± 1033	10,405 ± 2484
Milk production (1000 L ha^{-1})	NA	NA	25 ± 4	46 ± 31

All land-use areas are expressed as a percentage of the utilized agricultural area (not including double-cropping area) of the farm; NA: not applicable.

had a much higher mean stocking rate (+94 %) than non-cooperating farms.

2.2. *Characterization of the cooperation strategy*

Since cooperating dairy farms in the study area produced few cereals, they obtained the straw they needed for bedding and animal feed by exchanging dairy manure for straw with cooperating crop farms. Hereafter, "cooperation" is restricted to this material exchange between these specialized farms. Cooperating dairy and crop farms were heavily invested in the partnership, exchanging ca. 61 % and 81 % of their total manure and straw production, respectively. Cooperation was very local, with an average road distance of 5 km between farms.

2.3. *Quantification of N flows*

Calculating indicators of the N rebound effect, as well of N management and its potential environmental impacts, requires knowing the N flows of each farm surveyed. N inputs included inorganic N fertilizers, N in received manure, N in purchased feed and forage, biological N fixation by legume crops, N from irrigation and atmospheric N deposition. N outputs included N in sold grain, forage, straw, animals and milk, as well as exported organic N fertilizer (i.e., manure). All N flows were calculated as the quantities of raw material input and output recorded in the surveys multiplied by reference data on N content (Regan et al., 2017) and expressed per ha of utilized agricultural area (see Supplementary material).

Quantifying N flows allowed two additional indicators to be calculated: farm-gate N balance (hereafter, "N balance") and NUE. N balance (kg N ha^{-1}) was calculated as total N inputs minus total N outputs (Watson and Atkinson, 1999). NUE (unitless) was calculated following guidelines of the EU Nitrogen Expert Panel (2016):

$$NUE = \frac{crop\ N\ output + milk\ N\ output + meat\ N\ ouptut}{total\ N\ inputs - manure\ N\ ouput} \tag{1}$$

where all output and input variables are expressed in kg N ha^{-1}.

2.4. *Calculation of indicators of the N rebound effect*

Based on the definition of the rebound effect, the N rebound effect of farm cooperation could be calculated only for cooperating farms, since they were those that implemented a supposedly more efficient practice. To quantify this N rebound effect, we compared actual and potential N savings differently for cooperating crop farms and cooperating dairy farms (Fig. 1).

2.4.1. *Indicator of the N rebound effect for cooperating crop farms*

For each cooperating crop farm, actual N savings equaled its total N inputs before it cooperated with a dairy farm (hereafter, "initial N input") minus its N inputs at the time of data collection, when it was cooperating (hereafter, "observed N input"). Potential N savings are the theoretical decrease in N input due to cooperation (i.e., N input not purchased because cooperation replaces it completely). Expected N input thus equaled initial N input minus potential N savings.

For crop farms, cooperation with dairy farms was the exchange of straw for manure to reduce the need for inorganic N fertilizer, all other things being equal: only N input from manure and inorganic N fertilizer was considered when calculating the indicator of the N rebound effect. Since the data were collected for only one year (2013), no information was available on the cooperating crop farms before they cooperated; therefore, we assumed that the initial N input per unit area (kg N ha^{-1}) of each cooperating crop farm equaled the average N input from inorganic N fertilizer of non-cooperating crop farms. This is a purely theoretical state that has been established for the purpose of providing a suitable proxy for calculation needs in the absence of historical data. Observed N input of each cooperating crop farm represented the actual inorganic N fertilizer purchased. To calculate the potential N savings, one major assumption was that the manure that replaced purchased inorganic N fertilizer had a direct N effect of 50 % during the year of application. This direct effect reflects the fact that, unlike inorganic fertilizers, only a percentage of the N content of manure (20–60 %; 50 % as an assumption in this study) is available to crops during the year that it is applied (Quemada et al., 2020; Schröder, 2005). Finally, the indicator of the N rebound effect for cooperating crop farms was calculated as follows:

$$\begin{aligned} N\ rebound\ effect_{arable} &= \left(1 - \frac{Actual\ N\ savings}{Potential\ N\ savings}\right) \times 100 \\ &= \left(1 - \frac{Initial\ N\ input - Observed\ N\ input}{Potential\ N\ savings}\right) \times 100 \end{aligned} \tag{2}$$

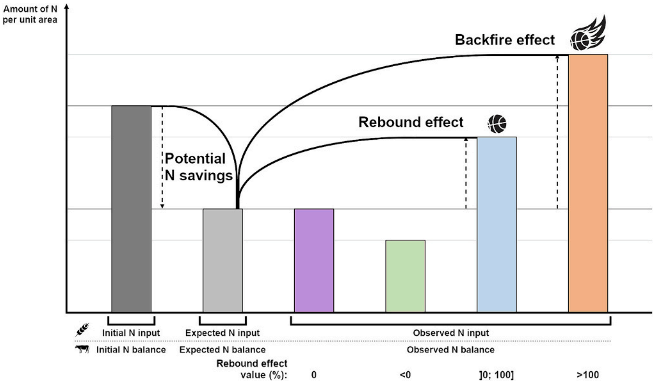

Fig. 1. Interpretation of the indicator of the nitrogen (N) rebound effect calculated based on N input for cooperating crop farms (wheat symbol) or N balance for cooperating dairy farms (cow symbol). It equals 0 % when the potential N savings have been achieved (i.e., observed N input or balance (purple) equals expected N input or balance (light grey)), is less than 0 %, when potential N savings are higher than expected (green) (i.e., super conservation effect), ranges from 0 to 100 % when the potential N savings are partially decreased (blue) (i.e., rebound effect) and greater than 100 % when the potential N savings are completely offset and N input increases (orange) (i.e., backfire effect) compared to the initial situation (dark grey). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2.4.2. Indicator of the N rebound effect for cooperating dairy farms

For dairy farms, straw represented only a small N flow, which was not a major effect of the cooperation. We therefore calculated the indicator of the N rebound effect based on N balance, as a proxy of N losses to the environment. We hypothesized that, due to the large quantity of manure produced per ha of utilized agricultural area on the dairy farms studied, much of it would be lost to the environment when applied on the farm. Therefore, manure export from cooperating dairy farms reduced their N balance, and likely their environmental impacts. Indeed, finding an outlet for manure was the main reason why the dairy farms cooperated with crop farms. Actual N savings thus equaled the N balance of each dairy farm before it cooperated with a crop farm (hereafter, “initial N balance”) minus its N balance at the time of data collection, when it was cooperating (hereafter, “observed N balance”). Finally, the indicator of the N rebound effect for cooperating dairy farms was calculated as follows:

$$N\ rebound\ effect_{dairy} = \left(1 - \frac{Actual\ N\ savings}{Potential\ N\ savings}\right) \times 100$$

$$= \left(1 - \frac{Initial\ N\ balance - Observed\ N\ balance}{Potential\ N\ savings}\right) \times 100 \qquad (3)$$

2.4.3. Interpretation of the indicator of the N rebound effect

When the indicator of the N rebound effect equals 0 %, there is no rebound effect: the potential N savings have been achieved (Fig. 1). When it is less than 0 %, potential N savings are higher than expected (i.e., “super conservation”). When it ranges from 0 to 100 %, the potential N savings are partially decreased due to the rebound effect. When it is greater than 100 %, the potential N savings are completely offset, and N input increases compared to that of the initial situation (i.e., “backfire effect”).

3. Results

3.1. Assessment of N management and potential N losses of cooperating and non-cooperating farms

Cooperating crop farms imported a mean of 30 kg N ha^{-1} as manure from cooperating dairy farms, while non-cooperating crop farms did not use manure (Table 2). This manure represented, on average, 19 % of the total N fertilizer input. However, contrary to expectations, cooperating crop farms did not reduce their inorganic N fertilizer use proportionally to manure inputs, and even increased it: on average, they even used 31 kg N ha^{-1} more inorganic N fertilizer than non-cooperating crop farms. On average, cooperating crop farms had 27 % more N input and 16 % more N outputs than non-cooperating ones. Thus, increased outputs did not fully compensate for increased inputs, which led cooperating crop farms to have a higher mean N balance and lower mean NUE.

Similarly, on average, cooperating dairy farms exported large quantities of N as manure (366 kg N ha^{-1}) and purchased some inorganic N fertilizers (71 kg N ha^{-1}), while non-cooperating dairy farms were nearly self-sufficient in N fertilization (Table 2). Cooperating dairy farms also had lower mean N inputs from symbiotic fixation (−30 %), which reflected the lower percentage of forage, including alfalfa, in their utilized agricultural area. Regarding animal production, cooperating dairy farms had substantially higher mean feed inputs than non-cooperating dairy farms (+156 %). Their mean N outputs were also higher: N from milk production was 81 % higher than that of non-cooperating dairy farms, due to the nearly double stocking density. This substantial increase in inputs led them to have to a higher mean N balance than non-cooperating farms (+36 %). However, their mean NUE was also higher than those of non-cooperating dairy farms.

3.2. Assessment of the indicators of the N rebound effect of cooperating farms

In this sample of cooperating crop farms, importing manure did not lead to replacement of inorganic N fertilizer and could even lead to more inorganic N fertilizer being used. Thus, their mean N rebound effect was 520 %, which constituted a backfire effect (Fig. 2). This mean, however, covered large differences among farms. Three of the four cooperating crop farms used more inorganic N fertilizers than the non-cooperating farms did despite using manure (backfire effect), but the other one used less inorganic N fertilizer than expected given its manure use, which led to a negative rebound effect of −102 % (super conservation) (Fig. 1).

On cooperating dairy farms, exporting manure resulted in a mean negative rebound effect of −17 %, meaning that they achieved higher savings in the N balance than expected compared to non-cooperating

Table 2
Mean ± 1 standard deviation of nitrogen (N) inputs, N outputs, N balance and N-use efficiency (NUE) of farm groups surveyed in the Ebro Basin, Spain. All values are expressed in kg N ha^{-1} except NUE (unitless).

Category	Subcategory	Non-cooperating crop farm (n = 5)	Cooperating crop farm (n = 4)	Non-cooperating dairy farm (n = 4)	Cooperating dairy farm (n = 5)
Fertilizer N input					
	Inorg. fertilizer	105 ± 21	136 ± 65	2 ± 3	71 ± 49
	Manure	0 ± 0	30 ± 22	0 ± 0	0 ± 0
Feed N input					
	Straw and forage	NA	NA	58 ± 54	409 ± 417
	Concentrate	NA	NA	315 ± 55	546 ± 370
Biological N fixation		114 ± 104	115 ± 109	190 ± 135	133 ± 238
Atm. N deposition		8 ± 0	8 ± 0	8 ± 0	8 ± 0
Irrigation N input		6 ± 7	8 ± 10	18 ± 13	15 ± 11
Total N input		**233 ± 116**	**296 ± 131**	**590 ± 74**	**1182 ± 936**
Crop N output					
	Forage	100 ± 84	110 ± 82	0 ± 0	0 ± 0
	Grain	79 ± 15	95 ± 36	4 ± 8	11 ± 22
	Straw	3 ± 3	6 ± 2	0 ± 0	0 ± 0
Livestock N output					
	Milk	NA	NA	139 ± 23	250 ± 172
	Animals	NA	NA	15 ± 7	18 ± 17
	Manure	NA	NA	7 ± 15	366 ± 403
Total N output		**182 ± 89**	**212 ± 100**	**165 ± 31**	**646 ± 563**
N balance		**51 ± 28**	**84 ± 31**	**425 ± 63**	**536 ± 453**
NUE		**0.78 ± 0.04**	**0.71 ± 0.03**	**0.27 ± 0.05**	**0.39 ± 0.13**

Atm.: atmospheric; Inorg.: inorganic; NA: not applicable.

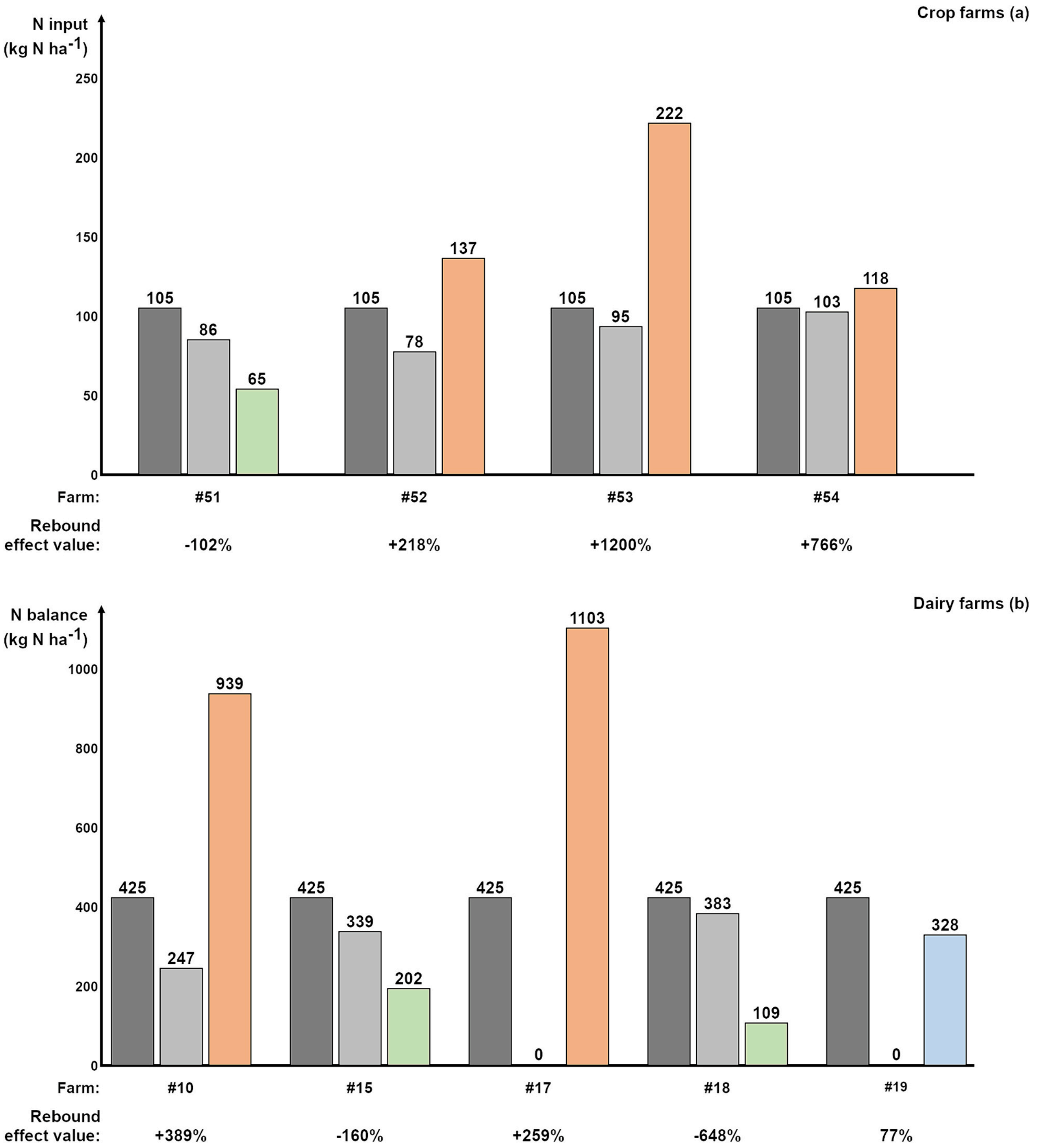

Fig. 2. The quantity of nitrogen (N) used to calculate indicators of the N rebound effect (below the x-axis) for (a) four cooperating crop farms (based on N input) and (b) five cooperating dairy farms (based on N balance). The dark grey columns represent the initial N input or N balance before cooperation started; the light grey columns represent the expected N input or N balance allowed through cooperation. Observed N input or N balance could be lower than expected (green), higher than expected but lower than the initial value (blue) or higher than the initial value (orange). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

dairy farms. Like for the cooperating crop farms, the indicator varied greatly among farms. Two farms had a much smaller N balance than expected (negative rebound effect): they used more inorganic N fertilizer but purchased less feed and forage than non-cooperating dairy farms did, while exporting less milk and more crops. The other three farms had a much higher N balance than expected (rebound effect): exporting manure did not decrease their N balance, since they had much higher stocking rates and an associated increase in feed and forage inputs as well as milk outputs than the non-cooperating dairy farms.

4. Discussion

4.1. *Observed benefits and drawbacks of cooperation through material exchange*

The main contribution of this study is to show that there may be a rebound effect, or worse, a backfire effect, for farms that cooperate. Indeed, three of the four cooperating crop farms that imported manure did not reduce their use of inorganic N fertilizer and increased their total crop fertilization. The backfire effect resulting from this intensification showed that the common and simple assumption of “all other things being equal” should not be taken for granted. The farmers may have intensified crop production because they thought that their yields were still limited by N and therefore continued to use inorganic N fertilizer along with the manure.

This phenomenon was also observed for three of the five cooperating dairy farms that exported manure but had a higher N balance. We hypothesize that the dairy farmers increased milk production once they were no longer constrained by on-farm manure management. Securing an outlet for manure with nearby crop farms therefore provided the dairy farms the opportunity to increase stocking density and, in turn, milk production. This cooperation may also have been related to increased forage input since forage is rarely purchased over long distances due to transportation costs.

Expected benefits of crop-livestock cooperation included (i) an increase in NUE, due to increased N cycling between crop and animal production, and (ii) a decrease in the N balance, due to better use of manure and lower input of inorganic N fertilizers (Farias et al., 2020; Ryschawy et al., 2017). They were observed in the present study for one cooperating crop farm and two cooperating dairy farms, showing that territorial cooperation can be a way to improve N management when not used as an opportunity to intensify land use. For three of the four cooperating crop farms, increased use of N fertilizer resulted in less than proportional gains in crop N outputs, a common observation known as the law of diminishing returns (Mitscherlich, 1909). This decreased the NUE slightly and increased the N balance, while laying within the range of those of other studies (e.g., Quemada et al., 2020). Interestingly, cooperating dairy farms had higher mean NUE than non-cooperating dairy farms in spite of a higher input use, contrary to this general law. This could be explained by a slightly higher NUE at the animal level (0.25 ± 0.06 vs. 0.22 ± 0.04 for non-cooperating dairy farms), probably due to lower use of concentrate feed per cow. However, an improvement in NUE at animal level was probably not the only explanation, as it does not always translate into a better NUE at farm level (Godinot et al., 2022). Increasing the quantity of feed purchased is also known to increase NUE by externalizing N losses related to feed production (Godinot et al., 2014). In addition, the increase in the quantity of crops sold on two cooperating dairy farms also increased the NUE, since crop production is more N efficient than animal production (Godinot et al., 2015). Three cooperating dairy farms also had high N balances that exceeded the maximum balances observed in a large European dataset (Quemada et al., 2020). Increased stocking rate required more feed input and led to a higher N balance, as observed in other studies (Børsting et al., 2003). The increased N balance for the majority of cooperating farms was associated with a higher risk of N losses.

4.2. Types of rebound effect characterized

The N rebound effects highlighted in this study are not what economists refer to as direct rebound effects (also known as “price effects”), which occur when an innovation increases the efficiency with which a commodity is produced, which reduces its price, which in turn increases the demand for it and absorbs the resources saved by the increase in efficiency (Sorrell, 2009b). Here, we did not study the relation between the innovation implemented (i.e., the material exchange to decrease the N input of cooperating crop farms and N balance of cooperating dairy farms) and the innovation's price (i.e., the prices and costs of transporting the materials exchanged). In addition, the price of inorganic nitrogen fertilizers at the time of the study in Spain had not undergone any specific variation, which rules out a price effect from inorganic fertilizers themselves (Eurostat, 2024). Consequently, we consider this rebound effect a “regulatory effect” because the cooperation partially lifted a regulatory constraint (i.e., cap on the amount of manure being spread per hectare).

Likewise, the N rebound effects studied are not what economists refer to as indirect rebound effects (also known as “income effects”), which occur when the potential financial savings made possible by lower consumption of materials or energy (e.g., fuel for automobile trips) are used to consume other goods that require materials or energy (e.g., airplane trips) (Berkhout et al., 2000). By analogy, it would have been interesting to study the relation between the exchange of materials (to decrease the N input or N balance) and the consumption of other inputs such as pesticides or water. Indeed, other studies found that farms that used more inorganic N fertilizers also often used more pesticides (Pergner and Lippert, 2023).

We focused the present study of N rebound effects on N management to highlight the environmental performance of cooperation. It would have been interesting to extend the analysis to include economic performance: by cooperating, farms can purchase inputs at prices lower than those on regular markets, thereby saving money and increasing their profit. Thus, cooperation between farms could improve economic performance, but it may not always improve environmental performance, as demonstrated.

4.3. Limitations of the approach

The main limitation of the study is that, based on the available data, we had to assume that non-cooperating farms were a suitable proxy to represent the initial situation of cooperating farms before they began cooperating. Because this was a strong assumption, we performed a sensitivity analysis by modifying the initial N input of cooperating crop farms (105 kg N ha^{-1}) (Fig. 2) by plus or minus one standard deviation (± 21 kg N ha^{-1}). Its results showed that the indicator of the N rebound effect remained sensitive to the initial situation, and two of the four farms still showed large rebound effects with the initial N input plus one standard deviation (126 kg N ha^{-1}; data not shown). The relevance of this method could be further demonstrated by collecting data on farms before and after the adoption of innovation (i.e., the material exchange). However, since the main objective of the study was to highlight the evidence of a rebound effect, and thus to put the benefits of cooperation into perspective, we argue that the precise value of the rebound effect indicator was not central to this study: its mere existence supports these conclusions.

Another limitation is related to the substitution rate of inorganic fertilizer with manure. We used a value of 50 % to represent the direct effect of manure over one year, but this substitution is likely to reach 100 % over a longer period (Zhang et al., 2020). We therefore tested this alternative assumption. Three cooperating crop farms still showed a backfire effect, although attenuated (mean N rebound effect: 414 %, −43 % compared to the initial calculation). The farm with an initial N rebound effect of −101 % came much closer to the expected N savings (N rebound effect: −1 %).

4.4. Designing farming systems requires considering the rebound effect

The results provide strong evidence that N rebound effects may occur when crops and livestock are reconnected through cooperation among specialized farms at the local scale. The fact that this N rebound effect can cancel out the benefits expected from cooperation suggests that much greater attention should be paid to such systemic change. In particular, such behavioral changes need to be considered in the design of new farming systems. Empirical studies that target such changes are thus essential, especially in agriculture, in which rebound effects have rarely been studied (Paul et al., 2019).

To avoid rebound effects, the development of technical or organizational innovations to increase efficiency must be accompanied by policies that prevent consumption from increasing. For example, this has been done for more efficient irrigation technologies by associating them with water rights to limit water consumption (Grafton et al., 2018; Li and Zhao, 2018). Regarding animal production, additional regulatory constraints on N management could be implemented. For example, in nitrate vulnerable zones (European Council, 1991), fertilization in the form of manure is limited to 170 kg N ha^{-1}, and N fertilization must remain balanced (i.e., not exceed crop requirements). This encourages livestock farmers to limit the use of manure on their farms and to use excess manure on their neighbors' farms, thus decreasing N leaching (Velthof et al., 2014). Milk quotas could also be reintroduced to cap animal production per farm and thus its emissions. Nevertheless, this measure was removed from the CAP in 2015 with the objective of allowing the market to achieve equilibrium between supply and demand.

Beyond these regulatory aspects, another mechanism to avoid negative effects of cooperation between farms is for stakeholders to identify common goals and values, which goes beyond N management (Chapman et al., 2019). By highlighting the prospect of developing more sustainable agriculture at a regional scale, it would thus be possible to promote better regional allocation of manure through cooperation. Such an approach would be also help identify potential trade-offs among individual and collective performances related to crop-livestock integration among farms (Ryschawy et al., 2019).

5. Conclusion

The exchange of materials between crop farms and dairy farms at a regional level is an interesting strategy to reconnect crop and livestock production, particularly in regions with specialized farms. However, implementing this strategy may not yield all of the benefits expected. Indeed, a rebound effect may occur when cooperating farms intensify their production and thus offset the benefits of crop and livestock reconnection. In this study, three of the four cooperating crop farms experienced a rebound effect: they received manure but did not reduce their use of inorganic N fertilizer and thus intensified their crop production. In addition, three of the five cooperating dairy farms also experienced a rebound effect: they exported manure but had a higher N balance. The indicators of the N rebound effect developed can thus identify situations that improve or degrade environmental performance. They should be used to complement existing indicators, such as NUE and N balance, to design efficient farming systems while avoiding a rebound effect. This approach will be essential if agriculture is to meet the challenges of the 21st century.

Credit authorship contribution statement

Olivier Godinot: Writing – review & editing, Writing – original draft, Validation, Methodology, Conceptualization. **Julia Jouan:** Writing – review & editing, Writing – original draft, Visualization, Methodology. **Thomas Nesme:** Writing – review & editing, Resources, Conceptualization. **Matthieu Carof:** Writing – review & editing, Writing – original draft, Visualization, Methodology.

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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Appendix A. Supplementary data

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