

Development of ReturN, a manure redistribution optimisation tool: Description and application context

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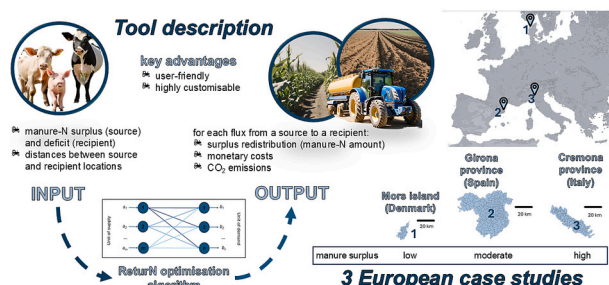
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HIGHLIGHTS

- Development of a software tool to assess the opportunity of transporting manure-N.
- N fluxes optimisation from source (N surplus) to recipient (N deficit) locations.
- Monetary costs and CO₂ emissions linked to each N flux as tool's outputs.
- The tool is applied to 3 case studies, showing its usefulness and user-friendliness.
- It helps reducing: CO₂ emissions due to transport and N-fertilisers purchase costs.

GRAPHICAL ABSTRACT

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ABSTRACT

CONTEXT: Collaborative agreements for manure management would enable intensive and specialized livestock farms to expand the agricultural area available for manure distribution by transporting manure to arable farms, thus increasing nitrogen and carbon recycling, reducing environmental pollution and decreasing farms' dependence on external inputs. The economic and environmental viability of such collaborative arrangements depends on the balance between the manure transport costs and emissions (and thus the distances between farms) and the saving in mineral fertiliser purchase costs and production emissions.

OBJECTIVE: The objective of this study is to present a software tool (ReturN) designed to assess the opportunities for moving the nitrogen (N) in manure from locations where the amount exceeds the utilization capacity of the crops to locations with spare utilization capacity. ReturN allows the optimisation of manure fluxes at a local or regional scale, on the basis of a multi-criteria balance that considers both economic and environmental criteria. The tool is applied in three European case studies thus showcasing the tool applicability options.

METHODS: The ReturN multi-criteria balance considers manure transport costs and emissions (and thus the distances between source and recipient locations) and the saving in mineral N fertiliser purchase costs and

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production emissions. The locations among which manure-N fluxes are optimised can be farms or municipalities, based on the aggregation level of the manure data. The tool outputs, linked to each flux of manure from a source to a recipient location, are the amount of transported N, the monetary costs, and the associated fossil carbon dioxide (CO₂) emissions. The ReturN tool was applied to the optimisation of manure fluxes in 3 real European case studies, and the sensitivity of its outputs to parameters was assessed using the modified Morris sensitivity analysis method.

RESULTS AND CONCLUSIONS: The application of the ReturN tool successfully optimised manure-N redistribution under varying conditions of deficits and surpluses and for different geographical areas shapes. The reduction in costs associated with the purchase of mineral N fertilisers and the decrease in fossil CO₂ emissions (due to the transportation of manure and the production of mineral N fertilisers) achieved through the optimisation of manure-N fluxes were found to be primarily dependent on the initial manure surplus condition and secondly on mineral N fertiliser price and manure characteristics (density and N concentration).

SIGNIFICANCE: The flexibility of the ReturN tool's settings, along with its limited input requirements, ensures its suitability for direct application by end users in practical contexts thus enabling both the economic and environmental assessment of the cost-effectiveness of manure transport.

1. Introduction

Traditionally, the excreta from European livestock farms was managed, manually or with basic farm machinery, as a solid (usually mixed with bedding), or as two fractions: a solid mixture of dung and bedding, and a liquid mainly consisting of urine. With increasing farm size and their specialisation, which began following the Second Agricultural Revolution that started around 1850 in the United Kingdom (Schut et al., 2021; Thompson, 1968), the amount of manure increased and it became uneconomic or impractical to manage it in the traditional ways. Large amounts of manure are more efficiently managed in a liquid form (slurry), through mechanization and automation.

The N in slurry is present as ammonium, which can be immediately taken up by crops, and organic N, which must be mineralised to ammonium by soil microorganisms, before it is crop-available. Both the concentration of N in slurry and the distribution of N between ammonium and organic N are very variable (Webb et al., 2013). It is therefore difficult for farmers to assess the value of slurry as a N fertiliser. Furthermore, the concentration of N in slurry is often <1 % by weight (Webb et al., 2013), so it is expensive to transport from the animal housing to the fields. Conversely, the N in synthetic fertilisers is present in a known concentration, it is immediately available for crop uptake, and easy to apply to fields and it is relatively accessible and cheap on market. Consequently, there is a strong incentive for farmers to rely on synthetic N fertilisers for crop production and treat slurry as a waste product, unless forced to do otherwise by environmental legislation and despite the price volatility of synthetic N fertilisers, as during the energy crisis of 2022. Although the reasons for price variation can be many, the risk of exposure to market prices is particularly high in fertiliser-importing countries.

In the past 50 years, farms have become larger and more specialized into arable and livestock enterprises (Abson, 2019) leading to a decline in mixed crop-livestock farm model (Regan et al., 2017). Furthermore, livestock production in some parts of Europe has tended to become concentrated in particular regions, leading to a regional imbalance between the production of manure and the availability of cropland on which its nutrients can be effectively utilized (Schut et al., 2021), this imbalance results in direct and indirect effects on land use change and N cycling (Oenema et al., 2007). In the absence of regulatory constraints, this can lead to an overapplication of slurry to land in livestock farms, resulting in excessive losses to the aquatic and atmospheric environment (Bijay-Singh, 2021; Sommer and Knudsen, 2021; van der Weerden et al., 2023). On the other hand, most arable farms face nutrient deficiencies that are fulfilled through the purchase of mineral N fertiliser.

The European nitrate directive (91/676/EEC) was issued in 1991 to protect water quality from agricultural nitrate pollution. Nevertheless, nitrate contamination has not shown a significant overall reduction over time and there are increasing trends reported in some areas (Børgesen et al., 2022; Musacchio et al., 2020; Serra et al., 2024). Farmers often

face financial challenges in implementing the required measures, due to the cost of infrastructure improvements (e.g., manure storage facilities), and the changes in farming practices (Glavan et al., 2019) that are required by the Nitrate Action Programmes (e.g. limitations on N fertilisers amount, regulations concerning fertilization timings and conditions for N fertilisers applications). Practical challenges in managing and transporting manure, especially in regions with high livestock density and limited arable land, complicate efforts to reduce nitrate pollution (Asai et al., 2014; Regan et al., 2017). The factors that have driven the historical specialisation in agriculture are still present today, so recoupling crop and livestock production at the farm level will often not be viable, due to resource and infrastructural constraints. However, crop-livestock integration at a local scale, beyond individual farms, could be a promising tool for increasing N and C (Soussana and Lemaire, 2014) recycling, reducing environmental pollution (Martin et al., 2016; Peyraud et al., 2014; Regan et al., 2017; Ryschawy et al., 2017; Schut et al., 2021) and decreasing farms dependence on external inputs (Bonaudo et al., 2014; Martin et al., 2016).

Collaborative agreements for manure management enable large livestock farms to expand the agricultural area available for manure distribution by transporting manure to arable farms. These recipient farms rarely pay for the full nutrient value of the manure, as the exporting farms often cover the costs of transporting and applying the manure (Asai et al., 2014). The economic viability of such collaborative arrangements depends on the balance between the manure transport costs (and thus the distances between farms) and the saving in mineral N fertiliser purchase. However, some cases show limited environmental benefits, due to the tendency of livestock farms to intensify their production in response to the increased land availability for manure distribution (Regan et al., 2017; Ryschawy et al., 2017; Schut et al., 2021). From a societal viewpoint, the environmental benefits gained by geographically distributing slurry to achieve a more effective utilization of manure nutrients involve a trade-off against the emissions of fossil CO₂ from the consumption of fuels needed to transport the large volume of water in livestock slurry. The potential economic and environmental benefits for farmers and society of agreements to exchange slurry are thus dependent on the quantity and quality of slurry produced, the locations of the producer and recipient, the utilization potential of the crops on the recipient farm and the extent to which the slurry nutrients can offset the cost of synthetic N fertilisers. The aim of this paper is to present a software tool for the optimisation of manure fluxes at a local or regional scale, on the basis of a multi-criteria balance that considers both economic and environmental criteria, and to demonstrate case studies of the tool's application context on a European gradient thus showcasing the tool applicability options.

2. Material and methods

2.1. Tool description

2.1.1. Theoretical background, inputs and outputs

The algorithm employed in ReturN draws from extensive literature on solutions for linear programming problems in operational research. In particular, the optimisation of manure fluxes pertains to Transportation Problems. In these problems, there are “sources,” each with a specified supply, and “recipients,” each with a demand. Every pair comprising a source and a recipient is associated with an effort to transport the supplies from the source to the recipient. The objective is to satisfy the demand, while minimizing user defined criteria, that will be explained later.

The solution is computed using the well-known Two-Phase Simplex algorithm. ReturN utilizes the Apache Commons Math library implementation (The Apache Software Foundation, 2003, 2024). In the current context, the sources (manure-N sources) are the livestock farms that produce more manure N than the amount that can be used to fertilize the crops on the farm. This amount of manure N (manure N quota; N_{quota} , kg N, Eq. (1)) is calculated for all crops on the farm, by summing the amount of manure-N (kg N ha⁻¹) that can be applied to each crop multiplied by the area of that crop grown (area, ha). The amount of manure N that can be applied to a specific crop can either be set by environmental legislation (e.g. the EU Nitrates Directive) or following an estimate of the amount of manure N necessary to achieve the economically optimum crop yield. In the case of the latter, a yield response function is used to estimate the optimum application rate of synthetic N fertiliser ($N_{\text{requirement}}$, kg N ha⁻¹) and then this is converted to an application rate of manure N by dividing by an assumed fertiliser equivalent value for the manure (equivalent_{value}, unitless).

$$N_{\text{quota}} = \sum \left(\frac{N_{\text{requirement}}}{\text{equivalent}_{\text{value}}} \cdot \text{area} \right) \quad (1)$$

The tool needs relatively few inputs data to run: the manure-N balance of each location (kg N), calculated as its manure-N production minus its manure-N quota, and the relative distances (d_{sr} , km) between the locations. The manure-N balance of a location will be positive if there is a manure surplus (potential manure source) and negative if there is a manure deficit (potential manure-N recipient). The potential manure-N recipients are farms that have crops but no livestock, or farms with a manure production that is less than their manure-N quota. The possibility for a recipient farm to acquire mineral N fertiliser is modelled as another N-surplus source (N-mineral source) with infinite production capacity. Consequently, a recipient farm deficit is ultimately fulfilled through the purchase of mineral N fertiliser if (i) manure-N is unavailable, (ii) manure-N transport is deemed unfeasible based on the tool's multicriteria optimisation or (iii) the manure N application limit imposed by the Nitrates Directive is insufficient to satisfy the crop N requirement.

The tool returns as outputs the amount of N, the monetary costs, and the fossil CO₂ emissions linked to each flux of manure from a source to a recipient. Furthermore, for each N-deficit recipient, the tool also presents a comparison between the monetary costs and fossil CO₂ emissions before and after the redistribution.

For the current version of the tool, the following additional assumptions were made:

(i) the manure is acquired at no cost for potential recipient locations; (ii) mineral N fertiliser transport costs and transport emissions are not considered; (iii) manure transport costs are borne by the manure-importing farms (recipients); (vi) the implicit costs associated with mineral N fertiliser or manure distribution in the field were not considered, since they are significantly correlated with the recipient farm equipment and management practices and they cannot be estimated beyond the farm level.

2.1.2. Multicriteria balance description

The functional unit for our analysis is a kilogram of N. The tool tries to satisfy the total manure-N demand of recipient locations within a given geographic scope (local or regional), while minimizing the total effort for manure redistribution between source and recipient locations. The user-defined criteria were formalized through two effort functions (parameters and variables are summarized in Table 1S, Supplementary Materials).

The effort function for transporting manure from an N-surplus source to an N-deficit recipient (f_{manure} , € kg N⁻¹ km⁻¹, Eq. (2)) is a linear combination of monetary costs of transport and the associated CO₂ emissions. Both depend on the distance (km) between the source and the recipient. The transport cost is calculated using a unit transport cost (M_{km} , € kg N⁻¹ km⁻¹) whereas the cost of the fossil CO₂ emissions is calculated as the product of a unit emission rate (E_{km} , kg CO₂ kg N⁻¹ km⁻¹) and the current carbon credit value (c_{credit} , € kg CO₂⁻¹) of the European Emissions Trading System.

$$f_{\text{manure}} = (M_{\text{km}} \cdot w_m + E_{\text{km}} \cdot c_{\text{credit}} \cdot (1 - w_m)) \quad (2)$$

A unitless weighting factor (w_m) is introduced, to allow the user to set the relative weights of the transport and CO₂ emission costs, choosing a value that vary between 0 and 1. The weighting factor allows for optimization based solely on the economic aspect ($w_m = 1$), solely on the environmental aspect ($w_m = 0$), or a mixed approach with a variable balance between the two ($0 < w_m < 1$).

The effort function for acquiring from the N-mineral source (f_{mineral} , € kg N⁻¹, Eq. (3)) is a linear combination of unit cost of purchase (M_i , € kg N⁻¹) and of the fossil CO₂ emissions associated with the production of one kilogram of mineral N. The latter is calculated as the product of the unit fossil CO₂ emission resulting from production (E_i , kg CO₂ kg N⁻¹) and c_{credit} .

$$f_{\text{mineral}} = M_i \cdot w_m + E_i \cdot c_{\text{credit}} \cdot (1 - w_m) \quad (3)$$

The tool provides a distance trade-off threshold (d , km, Eq. (4)) for each set of parameter values: the distance threshold represents the distance for which the two effort functions have the same value, thus it corresponds to the ratio between the two functions. Each distance between sources and recipients is compared with the trade-off threshold to assess whether manure transport is convenient.

$$f_{\text{manure}} \cdot d = f_{\text{mineral}} \Rightarrow d = f_{\text{mineral}} / f_{\text{manure}} \quad (4)$$

The transport cost per kilometre for a given slurry tank consists of a fixed cost associated with the driver's wage and other overhead costs (c_{km} , € km⁻¹) and the cost of fuel. The latter is the product of the diesel consumption (L_{km} , L diesel km⁻¹) and the diesel cost (c_L , € L⁻¹). The unit cost of transport (M_{km}) is estimated by dividing the transport cost by the mass of slurry N in the tank (Eq. (5)). The mass of slurry N in the tank is calculated as the product of the volume of the tank (V ; m³), the manure density (ρ , t m⁻³) and the manure N concentration (N_{conc} , kg N (kg manure)⁻¹).

$$M_{\text{km}} = \frac{(L_{\text{km}} \cdot c_L) + c_{\text{km}}}{V \cdot 1000 \cdot \rho \cdot N_{\text{conc}}} \quad (5)$$

The unit emission rate for transport (E_{km} , kg CO₂ kg N⁻¹ km⁻¹, Eq. (6)) is calculated as the product of the diesel emission factor (EF_d , kg CO₂ L diesel⁻¹) and the diesel consumption per kilometre (L_{km} , L km⁻¹), divided by the mass of manure N in the tanker. The diesel emission factor can be obtained from the IPCC emission factor database (IPCC, 2006) by multiplying this value (kg CO₂ kg diesel⁻¹) by diesel density (kg (L diesel)⁻¹).

$$E_{\text{km}} = \frac{(L_{\text{km}} \cdot EF_d)}{V \cdot 1000 \cdot \rho \cdot N_{\text{conc}}} \quad (6)$$

Table 1
Optimisation tool parameters values sources, unit of measures and values employed in the tool application case studies scenarios (S1, S2, S3, S4 and S5). The distance tradeoff threshold (d), calculated by the tool for each parameters set, is also reported.

Parameter	Definition	Unit	Cremona (North Italy)					Girona (Catalonia-Spain)					Mors (Denmark)				
M_{km}	monetary cost to transport 1 kg N	€ kg N ⁻¹ km ⁻¹	0.03261					0.0205					0.02898				
L_{km}	absolute diesel consumption	L diesel km ⁻¹	1.1					0.55					0.93				
C_L	diesel cost	€ (L diesel) ⁻¹	1.008					1					0.88				
E_{km}	CO ₂ emitted to transport 1 NU	kg CO ₂ kg N ⁻¹ km ⁻¹	0.0363					0.01452					0.03069				
V	manure transport tank volume	m ³	20					25					20				
E_i	CO ₂ emitted to produce 1 kg N of mineral fertiliser	kg CO ₂ kg N ⁻¹	3.41(Hoxha and Christensen, 2019)					2.79 (Anton, 2017)					3.7 (Yara, 2025.)				
C_{km}	overhead costs for manure transport	€ km ⁻¹	1.5														
N_{conc}	manure N concentration	kg N (kg manure) ⁻¹	0.004 (Webb et al., 2013)														
ρ	manure density	t m ⁻³	1 (Webb et al., 2013)														
EF_d	emission factor diesel	kg CO ₂ (L diesel) ⁻¹	2.64 (IPCC, 2006)														
C_{credit}	C credit cost	€ kg CO ₂ ⁻¹	0.1														
Scenario			S1	S2	S3	S4	S5	S1	S2	S3	S4	S5	S1	S2	S3	S4	S5
M_i	monetary costs to purchase 1 NU	€ kg N ⁻¹	0.331	0.185	0.923	0.331	0.331	0.331	0.185	0.923	0.331	0.331	0.331	0.331	0.923	0.331	0.331
W_m	costs weight in the multicriteria balance	unitless	1	1	1	0	0.75	1	1	1	0	0.75	1	1	1	0	0.75
$1 - W_m$	emissions weight in the multicriteria balance	unitless	0	0	0	1	0.25	0	0	0	1	0.25	0	0	0	1	0.25
d	distance tradeoff threshold for manure transport	km	10.15	5.67	28.3	94.02	13.15	16.15	9.02	45.02	192.32	20.21	11.42	6.38	31.85	120.67	15.14

2.2. Tool application case studies

The tool was applied to three different areas in Europe, to evaluate the effect of its practical application within three production districts with different geographical characteristics and livestock densities, and to assess the sensitivity of the tool outputs to its input parameters. In the case studies, tool inputs data were derived from the relative regional databases, managed by the public authorities in compliance with the European Nitrates Action Programme. The databases contain farm level data about livestock load (e.g. number and type of livestock), manure-N (e.g. type and produced amount), and crop N requirements (e.g. farm's crop rotations, percentage of farm area dedicated to each crop). Each database was employed to derive the annual manure-N balances aggregated at the municipality level. The spatial units employed to estimate the manure-N balances thus correspond to the municipalities of the selected areas, as this scale was previously employed to identify hotspots having a high manure-N load (Serra et al., 2019). Municipality refers to the area that is comprised within the administrative borders of this geographical administrative division, that includes both urbanized and agricultural land (the employed spatial unit type for the Danish case study is denoted as parish due to the limited dimensions of the case study area). For the tool application, the estimate of manure-N balances considered the Utilized Agricultural Area (UAA) located within the boundaries of the spatial unit. The annual location manure-N balance was therefore estimated at the farm level (as the difference between the manure-N input and the total N quota) and then the farms were aggregated, by sum, into municipalities. By summing, the manure-N deficit of farms with negative balance inside a municipality are automatically fulfilled by the manure-N surplus of farms with positive balance within the same municipality. A fertiliser equivalent value for the manure (equivalent_{value}) of 0.5 (Italian and Spanish case studies) and 0.75 (Danish case study) was employed to obtain the N quota of the location. The distances between source and recipient locations correspond to the straight-line distances between the centroids of the polygons of each municipality, and were computed with Q-GIS 3.16. The tool was applied by employing 5 combinations of the tools parameters values, that are reported in Table 1 (S1, S2, S3, S4 and S5). In the scenarios S1, S2 and S3 the multicriteria balance was performed by considering only the weight of the financial cost (w_m equal to 1) and by varying the monetary cost (M_i , € kg N⁻¹) to purchase one NU in each combination. The monetary costs were derived from a European database (Directorate-General for Agriculture and Rural Development, 2024) of fertiliser prices for the time span 2019–2024, by removing periods with unusual market fluctuations that led to prices unrepresentative of situation (2020 and 2021 due to the COVID-19 pandemic and 2022 due to the war in Ukraine) to ensure that the examples presented in the case studies better reflect the current context. The average price of nitrogen fertiliser obtained (0.331 € kg N⁻¹) was used in S1. In scenario S2, the lowest price (0.185 € kg N⁻¹) was used. In scenario S3, the highest price (0.923 € kg N⁻¹) was used. In the scenarios S4 and S5, the multicriteria balance considers also emissions weight, by assigning a value lower than one to w_m . The carbon credit cost (C_{credit} , € kg CO₂⁻¹) selected corresponds to the highest value of the time span 2019–2024 from the European Emissions Trading System. In the case study (Table 1), the total N content (kg N) of the tank was estimated by assuming a density, ρ , equal to 1 t m⁻³ and a N concentration, N_{conc} , of 0.004 kg N (kg manure)⁻¹. The emission associated with the transport of one NU (E_{km} , kg CO₂ kg N⁻¹ km⁻¹) was calculated from the fuel consumption per kilometre of a tanker having a specified volume (V , m³). It is calculated by multiplying the diesel emission factor (2.64 kg CO₂ L diesel⁻¹) for the absolute diesel consumption per kilometre of the tanker (L_{km} , L km⁻¹), divided by its N content (kg N) for the considered manure type. The diesel emission factor was derived from the IPCC diesel emission factor for European Diesel Heavy-Duty Vehicles (3.140 kg CO₂ kg diesel⁻¹, IPCC, 2006) by considering a diesel density equal to 0.84 kg diesel⁻¹ L diesel⁻¹ thus obtaining a value of 2.64 kg CO₂ L diesel⁻¹.

2.2.1. Cremona (North Italy)

The province of Cremona (Lombardia region) has an elongated shape, extending in a north-south direction for about 75–80 km and in an east-west direction for about 45–50 km (depending on the specific point where these distances are measured). The average distance between two municipalities is 31.21 km (median distance 27.06 km), but there is a higher frequency of distances between municipalities that are smaller than the average (Fig. 5S, Supplementary materials). This province was chosen for the tool application case study due to the following characteristics: (i) high manure surplus due to high livestock density: the province is located in a region where the stocking rate (number of livestock per utilized agricultural area) exceeds the national average (Table 2S, Supplementary Materials) and where pig farming is predominant, but there is also a significant presence of cattle farming; (ii) nitrogen deficit due to significant crop production areas; (iii) since the shape and layout of the province can significantly impact the feasibility and efficiency of optimising manure fluxes, this province was chosen due to its narrow and compact shape that allows highlighting the tool application effect on the manure balance of the locations. The N requirement of each crop was derived from the Nitrate Action Program (Regional Directive DGR n.3634/2024), which defines the maximum field-applicable efficient-N amount per crop needed to achieve the average yield attainable under typical field conditions in a specific agricultural area.

2.2.2. Girona (Catalonia-Spain)

The province of Girona (Catalonia region) presents a rounded and compact shape, extending in a north-south direction for about 100–110 km and in an east-west direction for about 70–80 km (depending on the specific point where these distances are measured). The average distance between two municipalities is 31.32 km (median distance 29.74 km), and as for the Italian case study, there is a higher frequency of distances between municipalities that are smaller than the average (Fig. 5S, Supplementary materials) with the cases of relative distances higher than the average less frequent. This province was selected for the tool application case study due to: (i) a moderate manure surplus: the province is located in a region where pig farming is predominant (Table 3S, Supplementary Materials) and where, in comparison with Lombardia region, the utilized agricultural area is lower; (ii) a N deficit due to of large crop production areas; (iii) a geographic shape that is compact and relatively cohesive, unlike Cremona province, that allows for a clear demonstration of the tool's impact on local manure-N balance across various geographical shapes. The N requirement of each crop was derived from potential crop yield, according to expert knowledge by following recommendations from the Fertilization Office of the Generalitat de Catalunya (Generalitat de Catalunya, 2019).

2.2.3. Mors (Denmark)

The area of Mors is an island with an irregular shape, narrower in the northern part and wider in the southern part. It extends in a north-south direction for about 20 km and in an east-west direction for about 10–15 km. In fact, the average distance between two parishes is 11.45 km while the median distance corresponds to 10.50 km (Fig. 5S, Supplementary materials). Mors Island was selected for the tool application case study due to several key characteristics: (i) a low manure surplus: Mors island is located in a region where the stocking rate is in line with the national value (Table 4S, Supplementary Materials) and where pig farming is predominant; (ii) a limited N deficit due to substantial agricultural activities; (iii) its compact and irregular shape enhances the feasibility of optimising manure flows, allowing for a clear demonstration of the tool's optimization capability in small and isolated geographical areas. Indeed, this region is different from the latter two provinces, since the farms are located on an island, which is connected with two bridges to the mainland. The assumption that we made is that the transport of manure from the island to the main land is negligible due to high transport costs. The N requirement of each crop was derived from the maximum allowed amount of N per crop and per soil type, as annually set by the by the Danish Agency for Green Transition and Aquatic Environment.

2.3. Sensitivity of tool outputs to input parameters

Tool sensitivity was estimated by tuning key input parameters (Table 2) related to manure characteristics (density, depending on manure maturation stage, and N concentration, depending on livestock type and housing type), slurry transport conditions (tank volume) and the cost of mineral N fertiliser to display parameters influence on outputs variation. The outputs considered were the distance trade-off threshold for manure transport, the difference between the cost before and after the manure redistribution and between the emissions before and after manure redistribution. The sensitivity analysis was run by using the three case studies as site replicates. Since the distance trade-off threshold only depends on the input parameter values, its sensitivity to parameters did not vary between site replicates. Conversely, the cost and the emissions differences, depending both on input parameters and on the relative distances between recipients and sources farms of the three case studies, presented a specific variable sensitivity to the input parameters in the three site replicates. Thus, for these outputs the sensitivity test was presented separately for each case study. The diesel emission factor derived from the IPCC database was considered constant and therefore it was not included in the sensitivity analysis.

Therefore, the screening method of Morris modified by (Campolongo et al., 2007) was employed to qualitatively rank a set of 11 parameters on the base of the importance of their mean effect μ^* . The Morris method (Morris, 1991), also known as the Elementary Effects (EE) method, uses

Table 2
Tool parameters considered in the sensitivity analysis: definition, unit of measure and ranges.

Function	Parameter	Definition	Unit	Equation	Lower limit	Upper limit
Effort function for transporting manure, effort function for acquiring mineral fertiliser	C_{credit}	C credit cost	€ kg CO ₂ ⁻¹	2 and 3	0.01	0.10
	w_m	costs weight in the multicriteria balance	unitless	2 and 3	0.00	1.00
Effort function for acquiring mineral fertiliser	M_i	monetary costs to purchase 1 kg N	€ kg N ⁻¹	3	0.15	1.00
	E_i	CO ₂ emitted to produce 1 kg N	kg CO ₂ kg N ⁻¹	3	2.70	3.80
	V	manure transport tank volume	m ⁻³	5 and 6	15.00	40.00
Unit cost of manure transport, unit emission rate for manure transport	ρ	manure density	t m ⁻³	5 and 6	0.35	1.00
	N_{conc}	manure N concentration	kg N (kg manure) ⁻¹	5 and 6	0.0019	0.0047
	L_{km}	absolute diesel consumption	L (diesel km) ⁻¹	5 and 6	0.50	1.40
Unit emission rate for manure transport	c_{km}	overhead costs for manure transport	€ km ⁻¹	6	1.00	3.00
	c_L	diesel cost	€ (L diesel) ⁻¹	6	0.70	1.20

a one-at-a-time (OAT) design employed to assess the impact of varying one input parameter at a time on a specific output. The modified Morris method provides three sensitivity metrics for each input parameter: μ and μ^* reflect the overall significance of the parameter in influencing the variability of the model's output, while σ identifies the presence of non-linear effects and/or interactions between parameters. The Morris' sensitivity metrics (μ , μ^* and σ) are obtained as statistics of the distributions of the Elementary Effects EE_i of the parameter i (with $i = 1, \dots, k$) defined in Eq. (5), where x and $x + \Delta e_i$ represent two of the $r(k + 1)$ selected points in the input parameter space, where e_i is a k -dimensional vector with the i -th component equal to 1 and all other components equal to 0. The distance between x and $x + \Delta e_i$ is denoted by Δ , and $Y(x)$ refers to the output variable's value when the parameter setting x is applied. For any input parameter j , μ is the mean, μ^* is the mean of the

absolute values, and σ is the standard deviation of the Elementary Effects (EE_i , Eq. (7)) distribution. In the approach, these metrics classify input parameters into three categories: (i) those with negligible effects (low μ^* and σ); (ii) those with significant linear effects without interaction effects (high μ^* and low σ); and (iii) those with substantial non-linear and/or interaction effects (high μ^* and high σ).

$$EE_i(x) = \frac{Y(x + \Delta e_i) - Y(x)}{\Delta} \quad (7)$$

In this work, the sampling within the space of parameters is performed by setting $k = 10$ (parameters), $M = 100$ (total trajectories), $p = 4$ (levels) and $r = 10$ (selected trajectories). Each of the forthcoming experiments thus consists in $r(k + 1) = 110$ different settings of the input parameters (each corresponding to one of the selected points in the k -

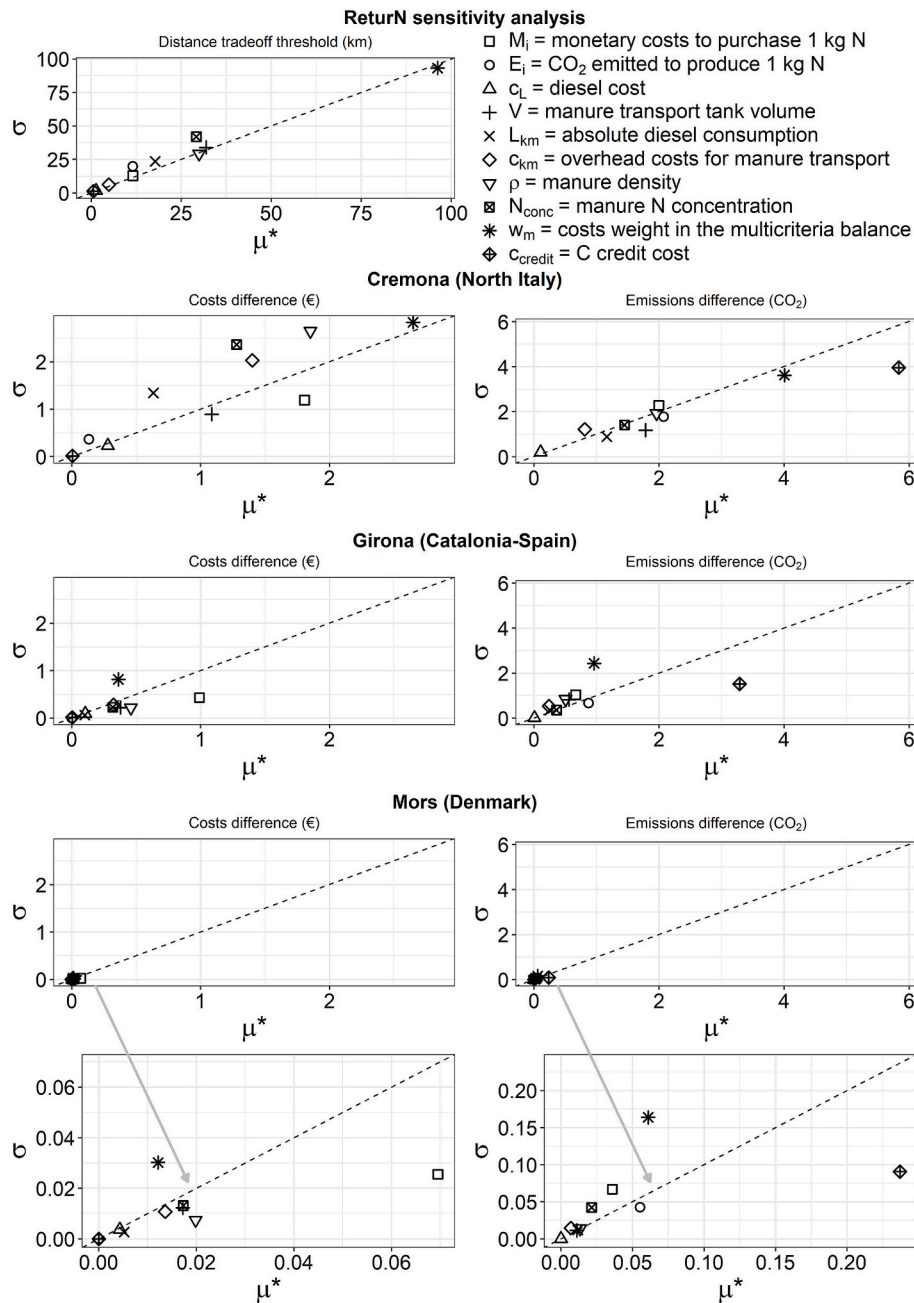


Fig. 1. Plot of the Morris' sensitivity measures indicating how the input parameters (M_i , E_i , c_L , V , L_{km} , c_{km} , ρ , N_{conc} , w_M , c_{credit}) affect the variability of the three tool outputs considered (distance trade-off threshold, costs and emissions before and after manure transport), in the (μ^*, σ) -plane. In each panel, the dashed line denotes the threshold $\sigma = \mu^*$. For the costs difference, μ^* and σ values are reported after division by 10^6 , while for the emissions difference they are divided by 10^5 .

dimensional hypercube) and the same number of realizations of the ReturN tool: i.e., for each one of the selected $r(k + 1)$ points, the three above-mentioned tool outputs were calculated. For the generation of parameter samples, the 10 parameters that were considered in this study had a defined uniform range of values as shown in Table 2. The sensitivity analysis was performed by using the SALIB Python library (Herman and Usher, 2017).

3. Results

3.1. Tool outputs sensitivity to input parameters

On the basis of the results of the Morris sensitivity analysis, parameters were ranked according to the value of μ^* for each of the considered tool output. As reported in Fig. 1, the parameter that showed high μ^* and high σ , and therefore exhibited the largest non-linear and/or interaction effects on the distance trade-off threshold output, is the costs weight (w_m). While the following parameters, in order of decreasing relevance, presented intermediate μ^* values associated with intermediate σ values: the manure N concentration (N_{conc}), the tank volume (V) and the manure density (ρ). Manure density and N concentration interact with each other in determining the N amount that can be transported by a specified tank volume, thus influencing the convenience of manure transport and the associated distance trade-off threshold. Higher density and N concentration mean that more N is transported per trip, which affects both transport costs and the balance between transport and fertiliser costs. Furthermore, since the N concentration of manure affects its nutrient value, a higher N concentration can reduce the amount of mineral fertiliser required by a destination location, influencing the distance trade-off threshold significantly. For this particular output, none of the parameters highlighted large linear effects with negligible interaction effects (high μ^* and low σ).

The carbon credit cost parameter (C_{credit}), that is employed to assign a monetary value to CO₂ emissions, has the highest elementary effect on the emissions difference output in two case studies: this effect is characterized by a high variability (suggesting that this parameter has high interaction effects) for the Italian case study (where the amount of transported manure-N is the highest), while its variability is low in the Spanish case study (where the amount of transported manure-N is moderate). C_{credit} is not relevant for this output in the Danish case study (where the least manure-N transport occurs). Given that the costs associated with carbon credits are relatively low compared to other costs considered in the multicriteria balance, the effect of this parameter on the cost difference output is negligible. In the Italian case study, the costs weight parameter (w_m) is highlighted as relevant (high μ^* and high σ) both for the emissions difference and for the costs difference outputs. This underlines how, in situations of high N surplus, the user's initial choice regarding the importance given to costs—and consequently to emissions—in the multi-criteria balance is crucial in determining the distance trade-off threshold, and subsequently, the difference in costs and emissions that can be achieved through the redistribution of flows. In this case study, the cost weight parameter is followed by influence on the costs difference output by the manure density parameter (high μ^* and high σ), the mineral fertiliser cost (M_i), as it presents a high μ^* and low σ and therefore has large linear effects with negligible interaction effects, and by two parameters having low μ^* and high σ (manure N concentration and overhead costs for manure transport). In the Italian case study, the two output variables related to the differences from the baseline in costs and emissions were found to be much more sensitive to changes in the values of all the tool's parameters in general, and more specifically to the variation of the above-mentioned parameters (C_{credit} , w_m and ρ having high μ^*), compared to what was observed in the other two case studies. For these variables, the sensitivity to these parameters (and thus μ^*) increases as the surplus of manure-N increases that determines, consequently, the amount of fluxes between sources and recipients evaluated by the tool, whose economic-environmental

feasibility is determined by the values of these parameters. Therefore, the sensitivity to these parameters is highest in the Italian case study, decreases in the Spanish case study, and is minimal in the Danish case study (due to the lower manure-N surplus).

3.2. Italian case study

In this and subsequent case studies, the results from the scenarios are shown as the percentage change from the baseline scenario (situation before the optimised redistribution of the fluxes). In the province of Cremona, in the baseline scenario, the high manure-N surplus is mainly concentrated in the municipalities located in the northern part of the province (Fig. 2). In the three scenarios (S1, S2, and S3) where the multicriteria balance was optimised considering only economic criteria, the most advantageous redistribution for the group of locations is obtained in the scenario where the cost of mineral N fertiliser is the highest (S3, d equal to 28.3 km). In this scenario, the municipalities with manure-N deficit before the redistribution of flows that are located near the concentration of manure-N surplus municipalities manage to fully meet their N demand after the redistribution (manure balance close to zero t N year⁻¹). Thus, as expected, the higher cost of mineral N fertiliser makes it economically viable to transport manure over longer distances compared to the scenario with the average fertiliser price (S1, d equal to 10.15 km) and the scenario with the lowest price (S2, d equal to 5.67 km). The scenario (S4) in which the multicriteria balance was optimised without considering economic criteria turns out to be the most advantageous scenario in terms of eliminating manure-N surpluses. In fact, following the redistribution of flows, all municipalities manage to transport their manure-N surplus to deficit municipalities within a threshold distance of 94.02 km. In the scenario S4, a complete depletion of manure-N surpluses is achieved, while a deficit situation remains concentrated in the southern part of the province. This is not due to the distance between these municipalities and those with a surplus (ranging between 50 and 75 km, which does not exceed the distance trade-off threshold) but it is caused by the exhaustion of the amount of manure N that could be redistributed (the province presents a total deficit, estimated as the sum of manure-N surplus minus the sum of manure-N deficit, of $-5.3 \cdot 10^3$ t N year⁻¹). The scenario (S5, d equal to 13.15 km) that considers both economic and environmental criteria leads to an optimisation of fluxes similar to that of the scenario that considers only the economic criteria and uses the same average mineral fertiliser price (S1). The only scenario where the costs after fluxes optimisation are higher than those before the optimisation is the one that does not consider economic criteria (S4). The cost reduction in the other scenarios is linked to the decrease in the amount of mineral N fertiliser purchased. As with cost reduction, the reduction in emissions following redistribution is also directly proportional to the distance trade-off threshold: the decrease in emissions is greatest in scenario S4 and smallest in scenario S2.

3.3. Spanish case study

In the province of Girona, under the baseline scenario, the moderate manure-N surplus does not show any particular clustering and is mainly distributed along a band of municipalities that crosses the upper part of the province (Fig. 3). The scenarios (S1, S2, and S3, d comprised between 9.02 and 45.02 km) where the multicriteria balance was optimised by considering only economic criteria show almost no differences in terms of manure-N balance from the scenario in which only emissions were considered (S4, d equal to 192.32 km) and from the mixed scenario (S5, d equal to 20.21 km). Following the fluxes optimisation, in all the analysed scenarios, the municipalities that initially had a surplus achieved a manure-N balance close to zero due to the transport of all available manure-N to municipalities that had a deficit (except for one municipality in the S2 scenario). However, the deficit situation remains moderate after fluxes redistribution: only some of the deficit

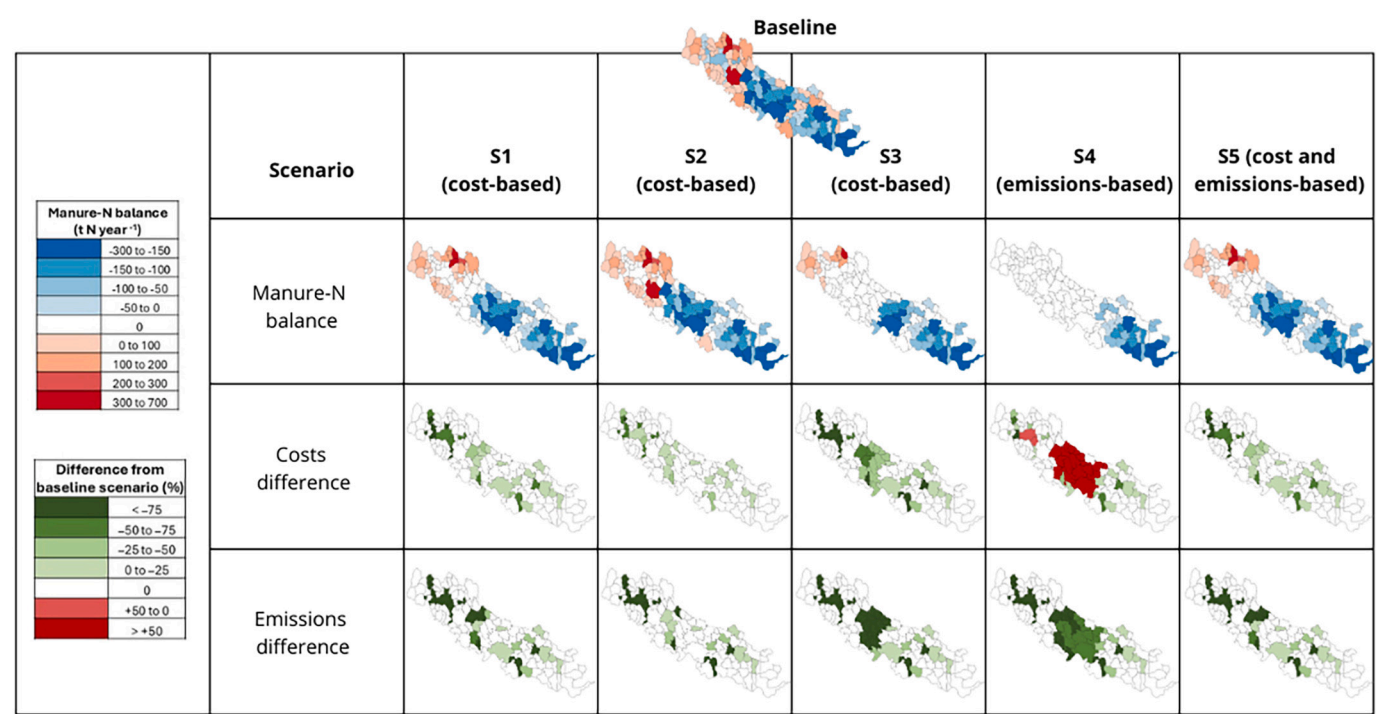


Fig. 2. Manure-N balances (t N year⁻¹), costs (€) and emissions (kg CO₂) percentual difference from the baseline scenario after tool application employing different parameters set up (S1, S2, S3, S4 and S5) in the Italian case study. The scenarios S1, S2 and S3 are cost-based, the scenario S4 is emissions-based and the scenario S5 is both costs and emissions-based. N-deficit locations (recipients) are coloured from blue to light blue, while N-surplus locations (sources) from light red to red. Costs and emissions difference from the baseline are coloured from green to light green (negative difference, savings) and from red to light red (positive difference, costs or emissions increase). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

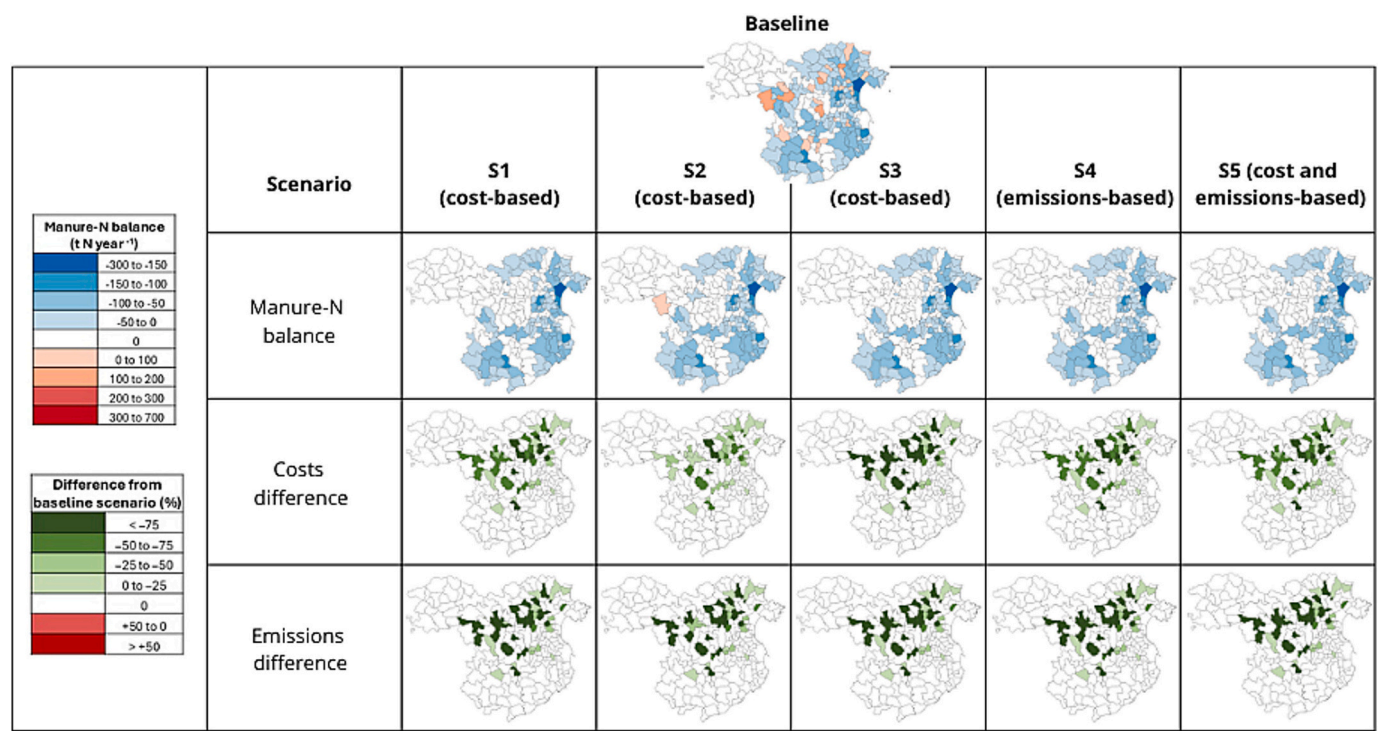


Fig. 3. Manure-N balances (t N year⁻¹), costs (€) and emissions (kg CO₂) percentual difference from the baseline scenario after tool application employing different parameters set up (S1, S2, S3, S4 and S5) in the Spanish case study. The scenarios S1, S2 and S3 are cost-based, the scenario S4 is emissions-based and the scenario S5 is both costs and emissions-based. N-deficit locations (recipients) are coloured from blue to light blue, while N-surplus locations (sources) from light red to red. Costs and emissions difference from the baseline are coloured from green to light green (negative difference, savings) and from red to light red (positive difference, costs or emissions increase). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

municipalities adjacent to surplus municipalities manage to partially close their manure-N balance. Therefore, in this province as in the Italian case study, the factor limiting the resolution of manure-N deficit situations is the availability of manure-N itself in surplus municipalities. In these scenarios, fluxes redistribution results in the complete exhaustion of the manure-N surplus, leading to an overall deficit situation of $-6.8 \cdot 10^3$ t N year⁻¹. Similarly to the results obtained for manure-N balances, all scenarios show a similar reduction in costs compared to the baseline scenario following the fluxes optimisation. This reduction is due to the decreased amount of mineral fertiliser purchased, but only in municipalities adjacent to or very close to those with a manure-N surplus (that are the first destinations to which the manure-N is sent by the fluxes optimisation tool ReturN, since the optimiser favours shorter transport distances). In all the analysed scenarios, the estimated emissions following fluxes redistribution decrease only in municipalities that were in deficit before the redistribution if the flow optimisation allows for the partial or complete satisfaction of the deficit itself (Fig. 3). As with the cost decrease, the emission decrease following redistribution is also moderate due to the disproportion between the manure-N surplus and the deficit, which limits the possibility of addressing deficits in more distant municipalities.

3.4. Danish case study

In the region of Mors, under the baseline scenario, the particularly moderate manure-N surplus is distributed between 5 parishes located on the border of the island (Fig. 4). Following the fluxes optimisation, in all the analysed scenarios, as for the Spanish case study, the parishes that initially had a surplus achieved a manure-N balance close to zero due to the transport of all available manure-N to parishes that had a deficit. However, the deficit situation remains moderate after fluxes redistribution: only some of the deficit parishes adjacent to surplus parishes manage to partially close their manure-N balance. Therefore, also in this

region, the factor limiting the resolution of manure-N deficit situations is the availability of manure-N itself in surplus parishes: fluxes redistribution results in the complete exhaustion of the manure-N surplus, leading to an overall deficit situation of $-1.66 \cdot 10^3$ t N year⁻¹. All the scenarios show a similar reduction in costs and emissions compared to the baseline scenario following the fluxes optimisation in the parishes that imported manure. The uniformity of the results obtained from applying of the tool across the 5 scenarios is attributed to the fact that the average distance between two parishes in this region is significantly lower than the distance trade-off thresholds calculated for the five scenarios (which range from 6.38 to 120.67 km). Therefore, in all 5 scenarios, the transport of manure from surplus parishes to neighbouring deficit parishes is always advantageous, both economically and environmentally.

4. Discussion

4.1. Constraints and comparison with tools available for similar purposes

Some existing GIS-based approaches, aimed at detecting manure load hotspots due to confined animal feeding operations, such as Manuresheds by Spiegel et al. (2020), highlighted the needs for identifying intra-county pathways for redistribution of manure nutrients. Indeed, existing models typically identify the least-cost transportation paths for manure application, making extensive use of spatial data and geographic information systems (GIS) to achieve cost-effective manure applications based on road networks and farm-to-field distances. As in ReturN, Paudel et al. (2009) considered one manure type only, but they by employed also off-road distances to optimise dairy manure transport from farms to farmland through the development a continuous cost surface. In this approach, several road speed limits were taken into account, while 40 km per h were the majority (while in ReturN overhead costs were estimated for a tractor pulling a slurry tank at a speed

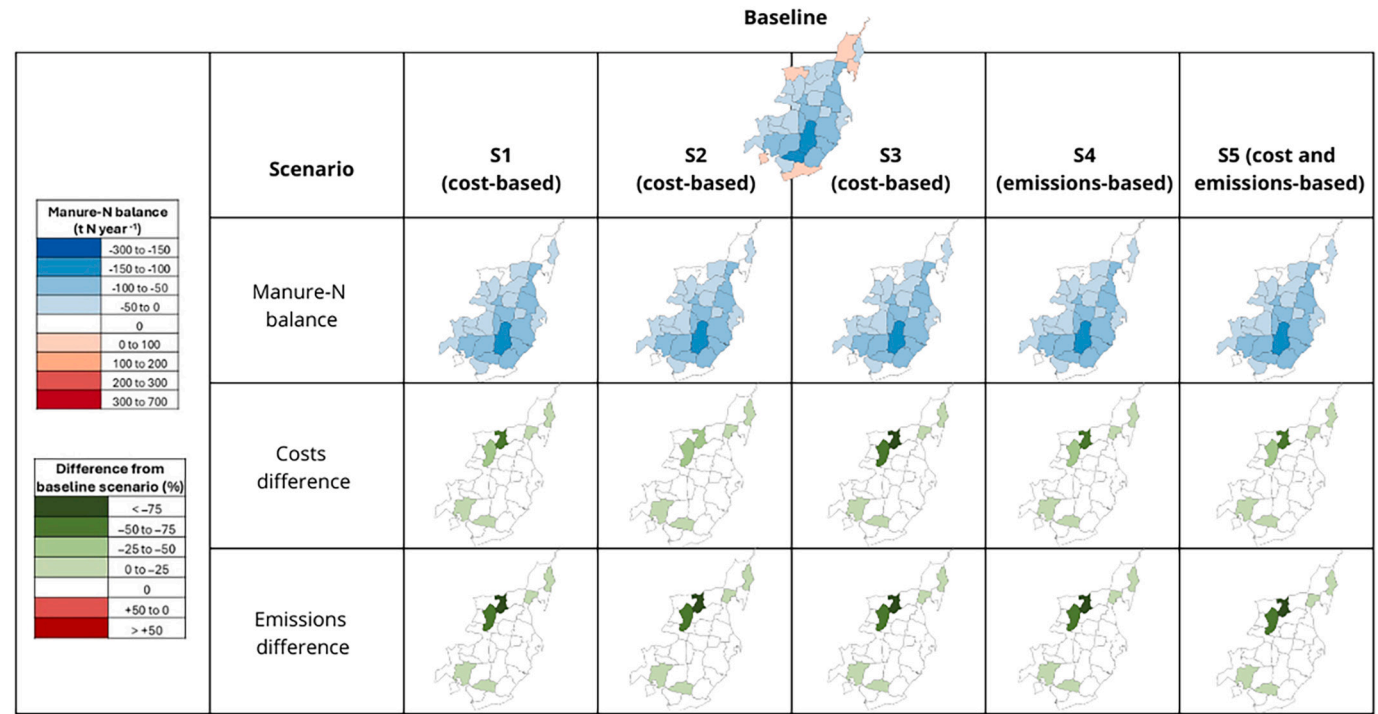


Fig. 4. Manure-N balances (t N year⁻¹), costs (€) and emissions (kg CO₂) percentual difference from the baseline scenario after tool application employing different parameters set up (S1, S2, S3, S4 and S5) in the Danish case study. The scenarios S1, S2 and S3 are costs-based, the scenario S4 is emissions-based and the scenario S5 is both costs and emissions-based. N-deficit locations (recipients) are coloured from blue to light blue, while N-surplus locations (sources) from light red to red. Costs and emissions difference from the baseline are coloured from green to light green (negative difference, savings) and from red to light red (positive difference, costs or emissions increase). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

between 25 and 30 km per h). As in ReturN, Aillery et al. (2009) estimated the manure balances at the farm-level and summed them to the county level, thus dividing farms into sources of manure (only from confined livestock) and into recipients. This GIS-based model incorporates a policy constraints to manure disposal: the model allowed to obtain a net regional cost of manure application that involves a penalty cost for surplus manure exceeding the area land application capacity, while in ReturN the user could provide the applicable quantity in compliance with regulations as inputs. Cai et al. (2023) integrates a GIS approach, with a direct measures campaign (aimed at assessing soils N and P_2O_5 content) to evaluate how much pig manure can be safely applied to land and to identify farms with N or P surplus. In comparison with the approach of Cai et al. (2023) and Paudel et al. (2009), ReturN approach proves to be effective for assessing the potential reduction of soil livestock load in compliance with the Nitrate Directive within the European legislative, pedoclimatic, and agri-livestock framework characterized by production districts with high livestock load and high N surplus, and by a European legislation regulating the use of manure-N but not manure-P. However, the same multicriteria balance logic can be applied to manure-P to evaluate the possibility of optimising manure-P fluxes in situations where the main focus is not nitrate pollution but the issue of phosphorus surplus in agricultural soils. The methodology proposed by Zeng et al. (2023) evaluated the economic factors associated with manure utilization versus chemical fertilisers, as in ReturN. Specifically, they determined the maximum economically feasible distance for transporting manure, under the assumption that farmers would not opt for manure if its cost (manure transportation costs, supplemental chemical fertiliser purchase costs, and labour costs) exceeded that of chemical fertilisers.

In contrast, multi-criteria optimisation approaches, can use spatial data of manure-N and manure-P supply and demand similarly but apply it within broader decision-making frameworks that allows the user to balance multiple objectives or prioritize one of them (such as the weights assigned to costs and emissions in ReturN). Lessmann et al. (2023) for example, aimed at optimising not only transportation costs but also nutrient recovery and environmental impacts, such as contamination from heavy metals (e.g., zinc and copper) present in manure. Tools like those developed by van der Straeten et al. (2010) employ a multi-agent system (MAS) that simulates the decision-making processes of farmers, optimising manure allocation by also factoring in the costs of manure processing, transportation, and disposal. Unlike GIS-based approaches, these multi-criteria tools are more flexible in modelling individual farm decisions and regional manure flows, allowing for the optimisation of multiple variables such as nutrient recovery, contamination, and economic trade-offs.

Thus, while GIS-based tools are strong in spatial data handling and route optimisation, multi-criteria models offer greater flexibility in integrating environmental and economic factors, making them more comprehensive for managing manure in a sustainable manner. The ReturN tool distinguishes itself by not requiring GIS for fluxes optimisation among small groups of farms, making it more user-friendly and accessible for end users, since it only requires farms manure-N balances and relative distances. The tool is still capable of benefiting from GIS for advanced spatial analysis when needed, and therefore, ReturN stands out due to its different and potentially broader stakeholder target. Coupling ReturN with GIS-software (to extract geo-referenced input data and to visualize tool's outputs on maps) could be primarily suited for territorial planning, since the coupling is constrained by the availability and updating of very specific spatial data, and thus geared towards local policymakers, serving as a tool to support strategic plans aimed at improving circularity and reducing environmental risks. Furthermore, it appears that none of the mentioned approaches explicitly take into account the CO_2 emissions associated with manure transport and the emissions related to the production of the mineral fertiliser. On the other hand, ReturN aims to evaluate the reduction of livestock load in source spatial units by also considering the balance between CO_2

emissions from manure transport and those from the production of mineral fertilisers. One of the main strengths of the ReturN tool lies in its flexibility to adjust and fine-tune the weight assigned to both economic factors and those that describe the environmental impact during the analysis. This ability allows for a more customized and balanced evaluation, ensuring that the tool can cater to different priorities and objectives, whether the focus is more on financial considerations, environmental sustainability, or a combination of both.

4.2. Results from optimal manure distribution studies in literature

The transportation cost per kilometre of one metric ton of manure obtained in the presented case studies (ranging from 0.08 to 0.13 € km^{-1}) aligns with the costs associated with transporting the same volume of manure used by Paudel et al. (2009), for slow-speed roads (0.12 € km^{-1}) and for high-speed roads (0.05 € km^{-1}). These authors identified a threshold distance beyond which transporting manure is not cost-effective compared to mineral fertilisers application, corresponding to 30 km when considering N and 15 km when considering P_2O_5 . This trade-off threshold for N reflects the results obtained in the presented case studies, considering that the cost analysis performed by Paudel et al. (2009) considered dairy manure (N_{conc} equal to 0.0026 kg N kg manure $^{-1}$) cost, its loading, transportation and application. In the case of pig manure, Cai et al. (2023) used an economic hauling distance of 8.4 km for nitrogen and 6.1 km for P_2O_5 , respectively. In agreement with these values, Aillery et al. (2009) calculated average manure hauling distances, for different type of land-applied manure in areas where excess manure nutrients often exceed the assimilative capacity of the local land base, ranging from 4.5 to 87.9 km.

4.3. What are the case study characteristics that influence the tool applicability?

The applicability of ReturN in the current context depends on several factors. First and foremost, the application of the ReturN tool must be constrained by the regulatory framework governing the group of locations among which the fluxes must be optimised since the legislative context can vary across countries. For instance, in some areas like the Netherlands, livestock farms are not required to own land for manure distribution. In contrast, in Denmark, the livestock load is regulated based on the farmland area. Such regulations inherently lead to a more balanced distribution of N across agricultural land, potentially preventing the large nutrient surpluses observed in regions like the Northern Italy. In this regard, it is the user's responsibility to provide the tool with manure-N deficits for each location, as already calculated in accordance with nitrate and other regulations.

The shape of the areas to which the tool is applied plays a significant role in determining the outcome of the fluxes optimisation, as it directly impacts the relative distances between the spatial units, that are provided as tool inputs. These, together with the spatial distribution of surplus and deficit within the area and the consistence of surplus and deficit themselves, affect the tool's output sensitivity to changes in its parameter values, as demonstrated from the comparison of the sensitivity analysis results across the three analysed areas. When the analysed area has an elongated shape with significant surplus concentrated in a specific area, the application of the tool with different parameter configurations can lead to substantial variations in costs and emissions following the redistribution as highlighted by the sensitivity analysis, which may be viewed positively or negatively by different stakeholders (e.g., arable farmers, specialist livestock farmers, lawmakers, scientists). However, when surpluses are moderate and dispersed in a compact area, the application of the tool under the explored mineral fertiliser cost scenarios does not result in significant changes in estimated costs or emissions. Indeed, the mineral fertiliser cost (M_i) has an elementary effect with a decreasing value from the Italian case study (elongated shape, high surplus) to the Danish one (compact shape, limited surplus),

passing through the Spanish case study (compact shape, moderate surplus). ReturN can provide more accurate results, to evaluate and consider the ease of nitrogen import and export across regions or provinces, if fed with more detailed spatial information about farms location and detailed routes information as in Paudel et al. (2009), that optimised manure transport conditions by considering several barriers (as water bodies, bridges and slopes). In our case studies, actual routes including physical barriers for transport, which may impose some logistical challenges affecting transport costs and CO₂ emissions, have not been employed because the farm location is GDPR sensitive. This detailed spatial information would improve the understanding of the extent to which nutrient imbalances can be mitigated by manure transport.

The current version of the tool requires assumptions to render the methodology applicable at large scale beyond the farm level (e.g. provincial or regional scale), which may in some instances limit its applicability but could be addressed through further development. The assumption that the locations receiving the manure are responsible for transport costs was included to evaluate the economic viability of transporting and using manure-N, compared to purchasing mineral fertiliser. To balance the distribution of expenses between surplus and deficit spatial units, it was assumed that the locations receiving the manure do not pay for the intrinsic value of the N it contains, as reported in the literature (Asai et al., 2014; Paudel et al., 2009). In the practical context of collaborative agreements for manure management, whether manure transport costs are covered by the exporting farms or by the importing farms depends greatly on specific factors, in particular on the proximity between farms, but also on how valuable and sought-after the manure is for specific applications (e.g., mature manure in horticultural context). It is therefore hypothesized that in the case of long-distance transport, which are more frequent for highly valuable manure, the tool's assumption that the importing farm pays for the transport costs may be consistent. However, in these specific cases, it is also likely that the importing farm will compensate the exporting farm for the monetary value of the manure-N itself. Similarly, which type of farm (source or recipient) is responsible for field application costs is also variable. If the farm receiving the manure is not a livestock farm (i.e., it does not have manure storage facilities or manure application machinery), then the application costs are likely paid by the exporting farm, as it would be directly handling the operation itself. Alternatively, the receiving farm might hire a contractor to perform field application, that is frequent in cases where less widespread machinery is required (such as in farms that employ minimum tillage techniques or direct seeding). In addition to improving nutrient distribution, the optimisation process should incorporate a more comprehensive cost-benefit analysis by including optional settings that consider the full nutrient value of imported materials, the costs associated with manure distribution, and the expenses related to transporting and applying mineral nitrogen fertilisers. The tool could be further developed to include options for determining which category of locations (sources or recipients) should bear the different expense categories associated with the manure (manure transport cost, manure application cost, cost of nitrogen contained in the manure) and with the mineral fertiliser (mineral fertiliser transport and application costs) parts of the multicriteria balance.

Furthermore, ReturN assumes a constant supply of N from manure sources, however, during periods of high demand, there is a possibility that manure sources could temporarily deplete. This temporal mismatch could result in periods where nitrogen is unavailable, which would affect the accuracy of nutrient distribution simulations. Additionally, the long-term storage of manure influences its N content, with potential losses or changes in nutrient quality over time (Chadwick et al., 2011). Our case studies, which simulate nutrient distribution over a single growing season, do not account for potential variations in N supply or the effects of manure storage. The N requirements for each farm were calculated based on crop types for the current year, but these requirements would vary in years with different crop rotations, potentially

leading to varying levels of N demand and availability.

Another practical limitation of this version of the tool, which it shares with other approaches due to model structures requirements, is its ability to manage only one type of manure at a time. The manure type is characterized by its density (ρ) and N concentration parameters (N_{conc}), which, based on the results of the sensitivity analysis conducted, are two of the most relevant parameters in determining the distance trade-off threshold for the economic feasibility of manure-N transport. Furthermore, in the Italian case study (elongated shape, high surplus) these parameters also significantly influence the costs difference of the fluxes optimisation. However, it is important to highlight the potential usefulness of optimising the distribution of multiple types of manure simultaneously, especially in cases where the production district has an abundance of different types of livestock. Future perspectives for further tool development involve enhancing the system's ability to manage manure and slurry more effectively. This can be achieved by simultaneously optimising the distribution and utilization of both manure and slurry, taking into account the unique characteristics of each type, such as their density and nitrogen concentration. It would be useful if the tool could also allocate manure deficits within each location, considering the specific crop rotations present. For example, different crops have varying nutrient requirements, and the tool would partition the necessary amounts of manure and slurry accordingly to ensure that the nutrient needs of the crops are met efficiently.

Finally, the choice of the parameter w_m , which assigns weight to the economic criteria of the optimization (from 0, minimum weight, to 1, maximum weight) and consequently to the environmental criteria ($1 - w_m$), is determined by the tool's user based on the specific objective for which the optimization of manure-N flows is applied. For deficit or surplus farms interested in joining collaborative agreements for manure transport, the focus will presumably shift completely towards economic savings (w_m equal to 1), whereas for public authorities, a combined economic-environmental assessment might be of greater interest ($w_m < 1$). Similarly, the identification of the stakeholders who benefit from the conversion of CO₂ emissions in costs (€) through carbon credits should be carefully conducted by the user, as the selection of the cost assigned to carbon credits significantly impacts the tool's results, in particular in terms of difference between the emissions before and after the fluxes optimisation as highlighted by the performed sensitivity analysis. Therefore, carbon credits cost is the major determinant of the economic viability of redistributing manure when considering emissions in the multicriteria balance. In the current scenario, where carbon credits have a relatively low value in the public market, largely because they are not incentivized by public institutions, the economic viability of manure-N transport is currently determined primarily by the cost of mineral fertiliser, while carbon credits are less relevant. Therefore, the volatility of prices for both mineral fertilisers and carbon credits in Europe (in both public and private markets) will be crucial in determining the future economic convenience of manure-N redistribution.

5. Conclusions

As demonstrated by the presented case studies, the application of the ReturN tool enables the optimisation of the manure-N redistribution under varying conditions of deficits and surpluses, different geographical areas shapes, and assorted sizes of production districts. The reduction in costs associated with the purchase of mineral N fertilisers and the decrease in fossil CO₂ emissions achieved through the optimisation of manure-N flows are found to be primarily dependent on the initial manure surplus and the spatial distribution of the source and recipient locations, and secondly on the mineral N fertiliser price and manure characteristics (density and N concentration). However, the advantage of flow optimization through ReturN, in situations with varying initial manure load (i.e., high surplus and significant deficit, moderate surplus and significant deficit, low surplus and low deficit) remains consistent even when the purchase price of mineral fertiliser is particularly

favorable. Furthermore, even in cost-based scenarios, manure transport results in CO₂ emission savings, as the emissions from optimised manure transport are lower than those from mineral fertiliser production.

The flexibility of the ReturN tool's settings, along with its limited input requirements, makes it suitable for direct application by end users in practical contexts. This enables both the economic and environmental assessment of the cost-effectiveness of manure transport, as well as the evaluation of manure management strategies on areas of varying sizes. Due to the flexibility of the software, further details will be easily integrated in the code to allow a comprehensive cost-benefit analysis that accounts for the full nutrient value of imported manure, mineral fertiliser transport, and their field application expenses, along with options to allocate these costs to sources or recipients, for a closer representation of the depicted system at the farm level.

CRediT authorship contribution statement

Mara Gabbrielli: Writing – original draft, Visualization, Investigation, Formal analysis, Conceptualization. **Johannes Wilhelmus Maria Pullens:** Writing – review & editing, Funding acquisition, Conceptualization. **Marco Botta:** Writing – review & editing, Visualization, Software. **Nicholas John Hutchings:** Writing – review & editing, Resources, Conceptualization. **Jordi Doltra:** Writing – review & editing, Investigation. **Francesc Domingo-Olivé:** Writing – review & editing, Investigation. **Marco Acutis:** Writing – review & editing, Conceptualization. **Andrea Fiorini:** Writing – review & editing, Conceptualization. **Paola Pasta:** Writing – review & editing, Investigation. **Giorgio Ragagnini:** Writing – review & editing, Investigation. **Alessia Perego:** Writing – review & editing, Supervision, Resources, Funding acquisition, Conceptualization.

Code availability

The code of the ReturN tool is available from the authors upon reasonable request.

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.agry.2025.104350>.

Data availability

The input data used for the fluxes optimisation in the case studies is GDPR sensitive and therefore not publicly available.

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