Computers and Electronics in Agriculture 191 (2021) 106486

Contents lists available at ScienceDirect

Computers and Electronics in Agriculture

journal homepage: www.elsevier.com/locate/compag

Original papers

Examining the perspectives of using manure from livestock farms as fertilizer to crop fields based on a realistic simulation

Andreas Kamilaris[a,b,*], Francesc X. Prenafeta-Boldú[c]

[a] Department of Computer Science, University of Twente, Enschede, the Netherlands
[b] CYENS Center of Excellence, Nicosia, Cyprus
[c] GIRO Program, Institute of Agrifood Research and Technology (IRTA), Barcelona, Spain

ARTICLE INFO

Keywords:
Animal Manure
Livestock farming
Environmental Impact
Logistic Problem
Optimization

ABSTRACT

Intensive livestock production has a negative environmental impact by producing large amounts of animal dejections, which, if not properly managed, can contaminate nearby water bodies with nutrient excess. However, if the animal manure could be transferred efficiently to nearby crops and used as a fertilizer for the plants, pollution/contamination would be mitigated, transforming manure from a waste to a resource. This valorization of manure from waste to a resource falls within the circular economy principles, but the transportation of manure also comes at an environmental and economic cost. It is a single-objective optimization problem regarding finding the best solution for the logistics process of satisfying nutrient crops needs through livestock manure. This paper uses a centralized optimal algorithm (COA) to solve the problem, based on a realistic simulator that considers numerous real-world constraints that related work has not yet addressed. Implementation and evaluation of this method have been carried out based on extensive geolocalized data from Catalonia (Spain), one of the densest European farming regions, as a case study. The findings show that the use of treatment units in pig farms is not profitable, while applying treatment units on selected cow farms for composting manure has its merits, under an intelligent choice of cow farms. Finally, a comparison of our findings with those of two similar studies in Hangzhou, China and Minnesota, USA, are performed.

1. Introduction

The central role of the agricultural sector is to provide adequate and high-quality food to an increasing human population, which is expected to be increased by more than 30% by 2050 Food and Agriculture of the United Nations (2009). This means that a significant increase in food production must be achieved. Because of its importance and relevance, agriculture is a primary focus of policy agendas worldwide. The agricultural sector is considered as an essential contributor to the deterioration of soil, water contamination, as well as air pollution. and climate change Bruinsma (2003, ?). Intensive agriculture has been linked to excessive accumulation of soil contaminants Teira-Esmatges and Flotats (2003), and significant groundwater pollution with nitrates Stoate et al. (2009), Garnier et al. (1998).

In particular, livestock farming has severe adverse environmental effects (Heinrich-Böll-Stiftung and Becheva, 2014). Farms produce large amounts of animal manure, which, if not properly managed, can contaminate nearby underground and aboveground water bodies (Cheng et al., 2007; Infascelli et al., 2010; Vu et al., 2007), as well as release nitrous oxide into the atmosphere (Davidson, 2009). If handled and distributed correctly, manure can be applied as organic fertilizer in crop fields that produce different types of fruits and cereals, nuts and vegetables, thus saving substantial amounts of chemical fertilizers that come at a high economic and environmental cost (Sanford et al., 2009; Bayu et al., 2005). In this way, the potential contamination of air, soil and water created by animal manure could be mitigated (He and Shi, 1998; Teira-Esmatges and Flotats, 2003; Paudel et al., 2009), while a positive effect on soil organic matter and microbiota is possible (Whalen et al., 2000; Almeida et al., 2019).

Hence, if the animal manure is efficiently exported at specific seasons of the year to nearby or distant crop fields, manure can eventually become a valuable resource rather than waste (Keplinger and Hauck, 2006; Teenstra et al., 2014; Oenema et al., 2007; Bayu et al., 2005). To consider this possibility, the financial and environmental costs of transporting large quantities of manure must be taken into account as limiting factors in the process of nutrients' transfer from livestock farms

---

* Corresponding author at: Department of Computer Science, University of Twente, Enschede, the Netherlands
E-mail address: a.kamilaris@cyens.org.cy (A. Kamilaris).

https://doi.org/10.1016/j.compag.2021.106486
Received 1 February 2021; Received in revised form 26 September 2021; Accepted 27 September 2021

to agricultural fields. Transportation should be minimized and optimized to reduce the pollution and monetary costs associated with it as much as possible. Also, manure pre-treatment, which allows nutrient concentration to reduce transport costs, needs to be taken into account.

This paper uses an optimal centralized method to solve the issue of transporting manure from livestock farms to crop fields, to be used as organic fertilizer, using the area of Catalonia (Spain) as a case study. This centralized approach is based on an adapted version of Dijkstra's algorithm for finding shortest paths Jianya (1999), together with origin–destination cost matrices.

Our contribution in this paper is twofold: on the one hand, we have developed a regional data-based methodology for finding solutions to transferring animal manure to be used as organic fertilizer in crop fields in an optimal way, taking into account current policy restrictions. On the other hand, we have addressed essential limitations of related work (see Section 2), proposing a more realistic solution to the problem.

The rest of the paper is organized as follows: Section 2 describes related work on manure management based on geospatial analysis, while Section 3 presents our methodology regarding the use of a centralized optimal algorithm (COA). Section 4 analyzes the overall findings after applying the proposed method in the Catalonian context, and Section 5 discusses the results, commenting on the perspectives of this research. Finally, Section 6 concludes the paper and lists future work.

2. Related Work

Related work involves the research area of manure management based on geospatial analysis, facilitated by Geographical Information Systems (GIS) (Kamilaris and Ostermann, 2018). Less relevant work is about network flow solutions applied to other agricultural problems, such as dealing with transportation of live animals to slaughterhouses (Oppen and Løkketangen, 2008), the routing of vehicles for optimized livestock feed distribution (Kandiller et al., 2017) or biomass transportation (Gracia et al., 2014).

The idea of transporting surplus manure beyond individual farms for nutrient utilization was proposed in (He and Shi, 1998), focusing on animal manure distribution in Michigan, USA. The distribution of nitrogen and phosphorus in six counties located in the Magic Valley, Idaho, USA, to be in balance with crop nutrient demands was investigated in (Leytem et al., 2021). Analysis suggested that crop needs in nitrogen could not be met solely by dairy cattle manure, and synthetic fertilizer needs to be applied. However, to balance phosphorus with crop production, manure would need to be transported a minimum of 12.9 km from dairies and would have to replace synthetic fertilizer on 91% of regional croplands.

Teira-Esmatges and Flotats (Teira-Esmatges and Flotats, 2003) proposed a methodology to apply manure at a regional and municipal scale in an agronomically correct way, i.e. by balancing manure distribution to specific crops based on territorial nitrogen needs and predictions of future needs and availability considering changes in land use. Further, the analysis in (Ghimire et al., 2021) highlights the multi-scale spatial dimensions of the manure problem, using New Mexico, USA, as a case study: manure is concentrated at relatively small spatial scales, while available crop and grass land for manure application is distributed at larger scales. Worth mentioning is also ValorE (Acutis et al., 2014), a GIS-based decision support system for livestock manure management, where a small case study using ValorE, performed at a municipality level in the Lombardy region, northern Italy, indicated the feasibility of manure transfer.

Other researchers proposed approaches to select sites for the safe application of animal manure as fertilizer to agricultural land (Van Lanen and Wopereis, 1992; Basnet et al., 2001). Site suitability maps have been created using a GIS-based model in the Netherlands and in Queensland, Australia, respectively. In (Van Lanen and Wopereis, 1992), 40% to 60% of the total Dutch land declares as rural was found suitable for slurry injection. In (Basnet et al., 2001), 16% of the area under study (Westbrook sub-catchment within the Murray Darling Basin, Queensland, Australia) was found suitable for animal manure application. A minimum cost spatial GIS-based model for the transportation of dairy manure was proposed in (Paudel et al., 2009). The model incorporated land-use types, locations of dairy farms and farmlands, road networks, and distances from each dairy farm to receiving farmlands to identify dairy manure transportation routes that minimize costs relative to environmental and economic constraints.

The aforementioned related work has adopted various assumptions:

- aggregating geographical areas at county-level (He and Shi, 1998; Leytem et al., 2021);
- selecting generally suitable sites (i.e. crop and pasture areas) to apply animal dejections (Van Lanen and Wopereis, 1992; Basnet et al., 2001; Leytem et al., 2021);
- not considering transportation distances between livestock and crop farms (He and Shi, 1998; Teira-Esmatges and Flotats, 2003);
- not calculating the particular needs of crop fields in nitrogen that depend on the land area and the type of the crop (Basnet et al., 2001; Paudel et al., 2009);
- not including actual costs involved with the proposed solution (He and Shi, 1998; Paudel et al., 2009; Teira-Esmatges and Flotats, 2003; Basnet et al., 2001; Leytem et al., 2021);

In previous publications (Kamilaris et al., 2020; Kamilaris et al., 2020), we addressed the limitations of related work as mentioned above, proposing two different approaches to solve the problem: COA vs a decentralized nature-inspired cooperative technique, based on the foraging behavior of ants (AIA). Since COA was 8.5% more efficient than AIA, it was chosen as the technique to be used in this paper during experimentation (see Section 3).

Most of the previous related work and our previous publications made some additional assumptions, not taking into account the following assumptions, which are instead effectively addressed in the present study:

- Crop fields located inside vulnerable zones, for which limitations exist for the application of manure as fertilizer.
- Variation in availability of manure in different periods of the year.
- Assumed that manure could be transferred in one single move of the transport vehicle, without considering the vehicle's capacity limitations. The possibility of a larger quantity of manure than the vehicle's capacity to carry, depending on manure's type, was not considered. In this case, multiple routes would have been needed for the transfer. In addition to this, the transportation cost for returning the vehicle back to its basis was not considered in our previous publication.
- Varying crop demands in manure at different seasons.
- The estimation of the reduction of the percentage of nitrogen in the manure through time (i.e. during manure storage, handling and application) was very general, based on a fixed 3-month average of 40%.
- Manure could undergo some *concentration treatment* (e.g. mechanical separation) (Teira-Esmatges and Flotats, 2003) in order to reduce the volume transported.
- Different possible scenarios for the management and transfer of manure, depending on popular existing policies that could be applied in some territory.

This paper addresses all the above limitations towards a more realistic simulation for approaching the problem of transferring manure as fertilizer from livestock farms to crop fields in the most optimized way. The problem modelling and the methodology for addressing the assumptions above are described in Section 3.

It is worth noting that two recent related works, by Akdeniz et al. Li et al. (2021), Li et al. (2021) as well as by Porter and James (Porter and James, 2020) addressed the assumptions listed above too. Akdeniz et al. considered the region of Hangzhou, China, as a case study concerning manure management. In contrast to our Catalonian pilot, the study in Hangzhou involved a mountainous topography, different crops with specific needs in fertilizer and different manure treatment operations. The authors proposed a regional manure utilization chain (RMUC) model to minimize the animal manure utilization cost by selecting the optimal decisions of manure transport between animal feeding operations, centralized manure processing facilities, and crop farms.

On the other hand, Porter and James selected the state of Minnesota, USA, which is imperative to the country's livestock production, currently ranking first in U.S. turkey production, third in hog production, seventh in dairy cow inventory, and eighth in cattle on feed inventory. Similar to our Catalonian study, the Minnesota study shares many similarities to our work in terms of livestock farms and crop fields and the physical terrain. Three different nitrogen fertilizer recommendation approaches were considered, ranging from economically optimized rates on the low end to yield goal-driven rates on the high end, modelled based on varying nitrogen application rates.

Some comparison between our work and the two studies mentioned above (Li et al. (2021), Li et al. (2021), Porter and James (2020)) is attempted in Section 5.2 (see Table 5).

3. Problem Modelling and Methods Description

The overall goal is to solve the problem of finding optimal and economically viable way to distribute animal manure to fulfil agricultural fertilization needs. The purpose of this section is to describe how the problem was modelled using the area of Catalonia as a case study (Section 3.1) and and to explain how the objective function was defined (Section 3.2). Furthermore, this section presents the method adopted to solve the problem under study. This method is the centralized optimal algorithm (COA) (Section 3.3).

3.1. Problem Modelling

The autonomous community of Catalonia, located in the north-east part of Spain near the borders with France (see Fig. 1), is facing the challenge of soil and water pollution with nutrient excess due to the application of animal manure, because of intensive livestock farming (mainly swine) during the last decades (Kamilaris et al., 2017). The high density of livestock in some areas, linked to insufficient accessible arable land, has resulted in severe groundwater pollution with nitrates (Nitrate Directive, 1991). Catalonia is one of the European regions with the highest livestock density[1], with reported numbers of around 7 M pigs, 0.7 M cattle, 0.1 M sheep and 75 M poultry in a geographical area of 32,108 km^2. Aggregated statistics of farms and animals, manure and nitrogen produced are listed in Table 1. Farms of other animal types such as horses, rabbits and goats were not included due to their insignificance.

Fig. 1. Geographical map of Catalonia, Spain.

To model the problem, the geographical area of Catalonia has been divided into a 315 × 238 two-dimensional grid, as shown in Fig. 2 (left). In this way, the distances between livestock farms (i.e. original grid cell) and crop fields (e.g. destination grid cell) are easier to compute, considering straight-line grid cell Manhattan distance as the metric to use (and not actual real distance through the existing transportation network). The centre of the crop field is used for calculations of distance. An approximation to real-world distances is attempted in Section 3.2.

Each crop field and livestock farm has been assigned to the grid cell where the farm is physically located, as depicted in Fig. 2 (right). Details about livestock farms (i.e. animal types and census, location etc.) have been provided by the Department of Agriculture of the Government of Catalonia for the year 2016, after signing a confidentiality agreement (see Table 1). Details about crop fields (i.e. crop type, hectares, irrigation method, location etc.) have been downloaded from the website of the Department[2], for the year 2015. For every livestock farm, the yearly amount of manure produced and its equivalent in nitrogen as fertilizer have been calculated, depending on the type and number of animals, based on the IPCC guidelines (TIER1) (Intergovernmental Panel on Climate Change (IPCC), 2006) and the work in (Borhan et al., 2012). Similarly, for every crop field, the yearly needs in nitrogen have been computed, depending on the crop type and total hectares of land, according to (RuralCat, 2015).

Summing up, the total area of Catalonia has been divided into 74,970 grid cells, each representing a 1 × 1 square kilometre of physical land. Every cell has a unique ID and (x, y) coordinates, ranging between $[1, 315]$ for the x coordinate and $[1, 238]$ for the y coordinate. For each grid cell, we are aware of the crop and livestock farms located inside that cell, the manure/nitrogen production (i.e. from the livestock farms), and nitrogen needs (i.e. of the crop fields).

Based on the data received by the Department of Agriculture, Government of Catalonia for the years 2015–2016, the estimated total fertilizer needs of 20.526 crop fields (i.e. 88K tons of nitrogen) were lower than the availability of nitrogen from animal manure (i.e. 116K tons of nitrogen). This means that the produced amount of manure/nitrogen from livestock agriculture can completely satisfy the total needs of crop farms and it would be particularly important in areas corresponding to the vulnerable zones defined by the nitrogen EU directive[3]. As some crop

Table 1
The actual number of farms and animals, manure produced and nitrogen produced for different animal types as of 2016 in Catalonia, Spain.

Animal type	No. of farms	No. of animals	Yearly manure produced	Yearly nitrogen produced
Pigs	6.115	7,2 M	1,4 M tons	53 K tons
Cattle and dairy cows	6.599	701 K	874 K tons	30 K tons
Chicken	8.207	75,35 M	265 K tons	18 K tons
Sheep	3.755	101 K	166 K tons	14 K tons
Turkey	617	3,66 K	7,7 K tons	1 K ton
Totals	**25.293**	**83,38 M**	**2,71 M tons**	**116 K tons**

---

[1] According to the agricultural statistics for 2016, provided by the Ministry of Agriculture, Government of Catalonia.

[2] Department of Agriculture, Government of Catalonia. http://agricultura.gencat.cat/ca/serveis/cartografia-sig/aplicatius-tematics-geoinformacio/sigpac/

[3] The Nitrates Directive of European Commission. http://ec.europa.eu/environment/water/water-nitrates/index_en.html

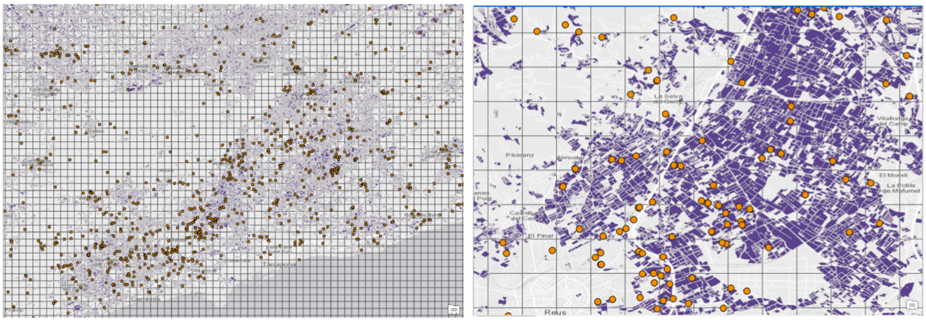


Fig. 2. Division of the territory of Catalonia in cells of 1 square kilometre each (left). Demonstration of livestock farms and crop fields at grid cells in a dense agricultural area of the region (right). This is a zoom of the map shown on the left. Livestock farms are shown as brown circles, and crop fields as blue polygons.

farms in Catalonia fall within *nitrate vulnerable zones*, only a maximum of 170 kg/ha (i.e. kilogram/hectare) of nitrogen from organic origin can be applied inside these zones. Thus, the area of each crop field (located inside nitrogen vulnerable zones) in hectares was multiplied by the constraint of 170 kg/ha, setting a maximum (possible) yearly application of manure/nitrogen at each crop field. The vulnerable areas are depicted with yellow color in Fig. 3.

Furthermore, each transport vehicle (i.e. truck, trailer) used to transfer manure has a limited capacity to transfer manure/nitrogen. This capacity was specified as shown in Table 2, based on the existing capacity of standard slurry tanks and manure trailers found in the area of Catalonia (i.e. 20 cubic meters, Tractor 175 CV - Tanker 20 m^3) Ministerio de Agricultura (2015). It was assumed that each vehicle could carry the maximum possible manure at each transfer, but manure types cannot be combined (i.e. pig slurry/liquid cannot be transferred together with pig solids), nor can the same manure type from different unrelated farms. Furthermore, the technical equipment for spreading liquid slurries and solid manure are incompatible at the moment, thus cannot be combined. Another common constraint respected by our simulator is that manure from different farms cannot be loaded to the same truck to be applied to some crop fields. These are existing policies around Catalonia and standard policies worldwide to prevent zoonotic diseases.

In contrast to our previous publications Kamilaris et al. (2020,), the transportation cost required for the vehicle to return to its basis after each transfer has now been considered.

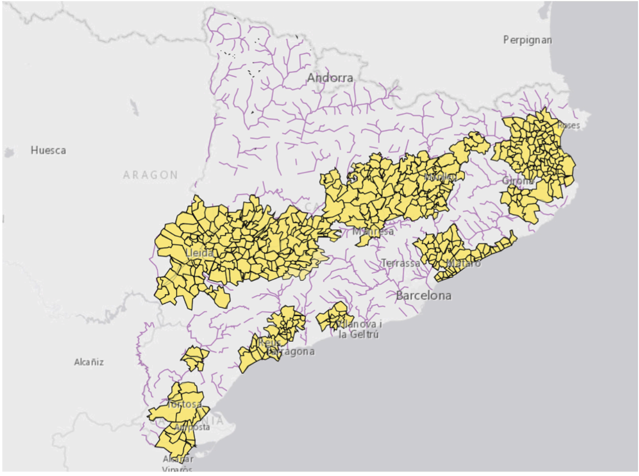


Fig. 3. Areas vulnerable to nitrate pollution in Catalonia, Spain.

Another critical consideration refers to which periods of the year fertilizer can be applied on the land, depending on the crop (Jones et al., 2011). We recorded the allowed periods (depending on whether the crop falls within a vulnerable area or not) based on the Directive 153/2019 of the Government of Catalonia Ministerio de Agricultura (2019). Allowed periods are summarized in Fig. 4.

Table 2
The capacity of vehicles (Tractor 175 CV - Tanker 20 m^3) in transporting nitrogen (kg). Source: Ministerio de Agricultura (2015) (see table of page 15). It has been assumed that pig slurries have an average density of 0.8 kg/L while the liquid fraction is close to 1.0 kg/L. For other solid fractions of animal manure, a density of 0.8 kg/L has been considered.

Type of manure	Vehicle capacity in transporting nitrogen
Solid pig manure	128 kg
Liquid pig manure	93 kg
Cow manure compost	163 kg
Cow manure liquid	93 kg
Other types of manure	93 kg

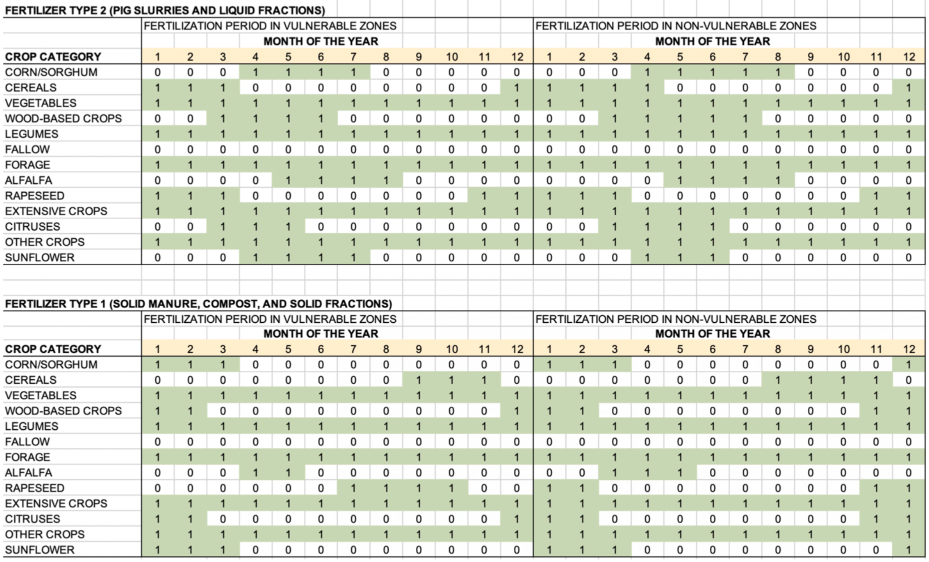
There are two different main types of fertilizers coming from manure, a) pig slurries and liquid fractions[4] and b) solid manure or other solid fractions and compost. Depending on the crop, these types of manure have different seasons of the year (i.e. months) when they are allowed to be applied on soils (marked as ”1”, highlighted with green color if allowed, otherwise ”0” in Fig. 4). The fertilization period is also affected by the area being in a vulnerable zone or not. If inside a vulnerable zone, the fertilization period becomes shorter through the year.

In most cases, pig slurries are preferred to be applied during spring or summertime, while solid manure and compost during late autumn and winter. This is because pig slurries (or their liquid fraction) are rich in ammonia, which is a nitrogen form readily available to the plant when it is mainly needed (*top dressing*). Compost (or the solid fraction) is rich in organic nitrogen, which is slowly released to the soil (*base dressing*).

Since the modelling of the problem considers monthly applications of manure to crops, it was fair to divide the yearly production of manure by the livestock farms for each month separately (i.e. divide by 12). We assumed that there is uniform production of manure through the year, not affected by the season. Assuming this, it was also relevant to consider the potential volatilization of nitrogen from the manure through time, during storage before application to the crop field soils. This monthly reduction of nitrogen was considered to be 5%, based on the recommendations by Rotz Rotz (2004). This means that if some livestock farm fails to transfer manure at some month x, then the produced manure is assumed to be stored locally. Thus, the percentage in nitrogen becomes 95% than its initial value, which is then added to the quantity of manure of the coming month $x+1$ (i.e. during the run of the

---

[4] The solid–liquid separation technology is the most commonly used method for processing pig slurries and is considered a significant one globally (Ministerio de Agricultura, 2015), for reducing pig manure environmental pollution effects.



FERTILIZER TYPE 2 (PIG SLURRIES AND LIQUID FRACTIONS)

	FERTILIZATION PERIOD IN VULNERABLE ZONES												FERTILIZATION PERIOD IN NON-VULNERABLE ZONES											
	MONTH OF THE YEAR												MONTH OF THE YEAR											
CROP CATEGORY	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12
CORN/SORGHUM	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	1	1	1	1	1	0	0	0	0
CEREALS	1	1	1	0	0	0	0	0	0	0	0	1	1	1	1	1	0	0	0	0	0	0	0	1
VEGETABLES	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
WOOD-BASED CROPS	0	0	1	1	1	1	0	0	0	0	0	0	0	0	1	1	1	1	1	0	0	0	0	0
LEGUMES	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
FALLOW	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FORAGE	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
ALFALFA	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	1	1	1	1	0	0	0	0
RAPESEED	1	1	1	0	0	0	0	0	0	0	1	1	1	1	1	0	0	0	0	0	0	0	1	1
EXTENSIVE CROPS	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
CITRUSES	0	0	1	1	1	0	0	0	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0
OTHER CROPS	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
SUNFLOWER	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0

FERTILIZER TYPE 1 (SOLID MANURE, COMPOST, AND SOLID FRACTIONS)

	FERTILIZATION PERIOD IN VULNERABLE ZONES												FERTILIZATION PERIOD IN NON-VULNERABLE ZONES											
	MONTH OF THE YEAR												MONTH OF THE YEAR											
CROP CATEGORY	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12
CORN/SORGHUM	1	1	1	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	1
CEREALS	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	1	1	1	1	0
VEGETABLES	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
WOOD-BASED CROPS	1	1	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	1	1
LEGUMES	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
FALLOW	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FORAGE	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
ALFALFA	0	0	0	1	1	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0
RAPESEED	0	0	0	0	0	0	1	1	1	1	0	0	1	1	0	0	0	0	0	0	0	0	1	1
EXTENSIVE CROPS	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
CITRUSES	1	1	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	1	1
OTHER CROPS	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
SUNFLOWER	1	1	1	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	1

Fig. 4. Periods of the year when animal manure is allowed to be used as fertilizer on different crops.

simulator).

3.2. *Objective Function*

The problem under study is a single-objective problem, with the overall goal of optimizing the logistics process of satisfying nutrient crops needs utilizing livestock waste. This goal has the following (conflicting) sub-objectives:

1. The total nutrient needs at the crop fields have to be satisfied as much as possible.
2. The total aggregated travel distance covered from the livestock farms to the crop fields to deposit the manure/organic fertilizer needs to be as short as possible.

These two sub-objectives can be reformulated as a single one by combining them linearly, assuming the following:

- The price of agricultural petrol fuel in Catalonia, Spain is about 0.90 Euro per liter[5].
- The fuel consumption of tanks is 20.3 liters per 100 kilometres[6]. This is equivalent to 0.203 liters per kilometre.
- Based on the price of fuel in Spain, as given above, the transportation cost per kilometre is 0.1827 Euro.
- Based on the local monthly average prices for fertilizers in Catalonia[7], the price of pure ammonia (NH3) is 307 Euro per ton. The nitrogen content in NH3 can be calculated by the factor of 17/14. Transforming tons to kilograms, the market price of pure nitrogen becomes 0.41 Euro per kilogram of nitrogen.Based on the aforementioned assumptions, the general objective is defined as:

$$GO = \max\{(NT \times 0.41 \times l) - (TD \times 0.1827 \times g) - CV - CTP\} \tag{1}$$

where *NT* is the total nitrogen transferred in kilograms, and *TD* is the total distance in kilometres covered to transport manure from the livestock to the crop farms. The parameter *l* captures the nutrient losses of manure during its storage time, i.e. the time when the manure is stored at the livestock farm until it is transferred to the crop field, while the parameter *g* is an approximation of real-world distance, based on the Manhattan distance used in the calculations of travel distance from the livestock to crop farms. Depending on animal type and storage method, nutrient losses vary. Further, the parameter *CV* represents the costs of the truck involved in the transfer: truck amortization, maintenance and labour. Finally, the parameter *CTP* represents the costs of the manure treatment plants in the scenarios where treatment plans are being employed (see Section 4.1, Scenarios 2–7).

We selected a value of the parameter $l = 1.0$, because we captured the nutrient losses monthly during the simulator's operation (see Section 3.1, considered a 5% monthly reduction of nitrogen, based on the recommendations by Rotz Rotz (2004)). In related work, Porter and James (Porter and James, 2020) ignored the time dimension considering a fixed value of 15–35% reduction, depending on animal type, while Leytem et al. (Leytem et al., 2021) considered mineralization rates 15–30%. The parameter *g* weights the calculated Manhattan distance by a factor of $g = 1.30$, a value appropriate for semi-rural landscapes (Wenzel and Peter, 2017). The parameter *CTP* takes values according to Table 3, based on (Ministerio de Agricultura, 2015). We note that there is a trade-off here between the cost of manure treatment *CTP* and the total nitrogen transferred *NT*, because treatment allows more manure to be transferred at each vehicle's trip (see Table 2). The parameter *CV* takes values depending on the number of kilometres travelled (*TD*), according to (Ministerio de Agricultura, 2015) (see page 15, values for Tractor 175 CV - Tanker 20 m^3).

The objective *GO* is assumed to be in Euro, as it represents a simplified cost/benefit relationship of the manure transfer problem, i.e. benefit of selling nitrogen to the crop fields and transport cost needed to transfer the nitrogen. The overall goal is to maximize *GO*, whose value

Table 3
Cost of treatment units considered for separation/composting of slurry/manure.

Type of manure	Method	Cost per ton of manure
Pig slurry	Separation to 15% solid and 85% liquid	5 Euro
Cow manure	Composting	14 Euro

---

[5] GlobalPetrolPrices. http://es.globalpetrolprices.com/Spain/gasoline_prices/ (for December 2019, category B diesel)

[6] Natural Resources Canada. http://www.nrcan.gc.ca/energy/efficiency/transportation/cars-light-trucks/buying/16745

[7] Ministry of Agriculture of Catalonia. http://agricultura.gencat.cat/ca/departament/dar_estadistiques_observatoris (ammonium sulphate in September 2019)

can be translated to gains or losses of each solution of the problem. *GO* can also take negative values, which means that some solution had produced a cost.

Finally, the Department of Agriculture requested to maintain the average travel distance (and standard deviation) from every livestock farm to the crop fields as small as possible, i.e. to keep the proposed solution *well-balanced and fair* for all livestock farms.

3.3. Centralized Optimal Algorithm

A centralized optimal approach has been developed based on the following algorithm, which generalized and adapted the well-known Dijkstra's algorithm for finding shortest paths (Cherkassky et al., 1996), together with the use of origin–destination cost matrices as used in the travelling salesman problem for choosing the best routes (Lin and Kernighan, 1973).

Each livestock farm aims to maximize a *local GO*, which is the objective function applied only to this farm. In case of conflicts with other livestock farms for the common use of resources, the solution that maximizes the *global GO*, as defined in Section 3.2, wins.

The concept of the algorithm in the context of the problem under study is illustrated in Fig. 5. Let us assume that the "travelling salesman" is the livestock farm at the red circle. This farm builds its own OD cost matrix, based on the possible values of the local objective function *GO*, applied at each nearby grid cell, up to a Manhattan distance of 100. For reasons of simplicity, Fig. 5 shows the matrix up to a Manhattan distance of 4. We may observe that, generally, grid cells in larger distances have smaller rewards. However, some crop fields located far away might have greater demands in nitrogen, which gives larger values to the local *GO*. It is also possible that crop fields near competing livestock farms might have reduced demands in nitrogen, as they might have already received nitrogen/fertilizer from these competing farms. After the livestock farm at the red circle builds its OD matrix, it uses Dijkstra's algorithm to find the path that maximizes the local *GO*. In the example of Fig. 5, this is the path shown by the yellow circles and arrows, which gives a value of $GO = 33$. If a conflict with another livestock farm (i.e. the two farms share the same grid cell in their paths), the solution maximizing the global objective *GO* would be considered.

In detail, the algorithm works as follows:

1. Every livestock farm makes a complete plan, having visibility of the whole grid regarding where to transfer manure/nitrogen. The most rewarding paths from the source (i.e. initial position) to all other cells in the grid where crop farms are located are calculated, producing an origin–destination cost matrix (ODCM). To make calculations easier, only crop farms up to a maximum distance of 100 kilometres have been considered. The cost (or better, reward) of every path is calculated based on the objective function *GO*, considering both the actual transportation distances and the possible transfer on nitrogen.
2. Like a travelling salesman problem, the possible routes passing from more than one candidate crop farm (i.e. till the availability of manure gets satisfied or the hard constraint of 100 kilometres is reached) are added to the ODCM. The goal is to maximize local *GO*, as it applies to the current livestock farm. The selected travel plan involves all the cells that must be visited, starting from the nearest one, which has the highest local *GO*.
3. If a conflict appears between the selected travel plans of two livestock farms (i.e. at cell (x, y), where some crop farm is located), the livestock farm involved at the solution that maximizes the global *GO* wins the conflict. If the need for manure/nitrogen at this cell (x, y) is higher than the combined availability of nitrogen by the two livestock farms, then no conflict occurs.
4. If the conflict still exists, the livestock farm which has failed in the conflict needs to recalculate a plan that maximizes its local *GO*, this time without considering the cell (x, y) or considering only the remaining need of manure/nitrogen at the crop farm(s) at this cell (i.e. assuming that the livestock farm winning the conflict will deposit its nitrogen there).
5. Steps 1–4 continue iteratively till there is a global consensus, i.e. no livestock farm can find a better plan to transfer its manure. At the time of a consensus, both the global *GO* and the individual objective functions for each livestock farm (local *GO*s) have been maximized and cannot be further improved. Any more efforts for conflict resolution do not yield a higher global *GO*.

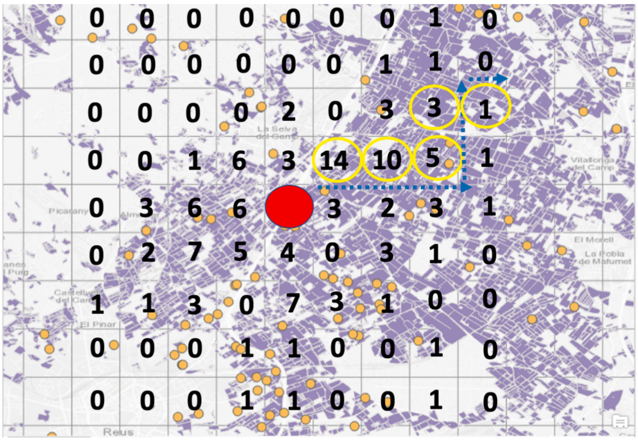


Fig. 5. Concept of the COA algorithm illustrated (Source: (Kamilaris et al., 2020)).

Summing up, the COA solves the problem by the classic Dijkstra's algorithm, considering a shortest-path problem on an undirected, non-negative, weighted graph. To use the algorithm within the context of the problem under study, the algorithm has been modified to respect the necessary configurations and constraints, i.e. by modelling the weights of the graph to represent both transport distances and crop farms' nitrogen needs, combined using the linear function *GO*. All combinations of visits to nearby farms (within 100 kilometres) are added to an ODCM, where the most profitable route for maximizing *GO* is selected. Contrary to the typical travelling salesman problem, here, the possible stop locations vary depending on which combinations of candidate crop farms maximize *GO*. The flow of the COA algorithm is also illustrated in the flowchart of Fig. 6.

4. Results

This section presents the findings obtained by solving the problem of manure transport optimization, examining different possible scenarios/policies. First, Section 4.1 describes the scenarios under study, and then Section 4.2 presents the findings after running the simulator based on the different policies.

4.1. Scenarios Considered

Seven scenarios/policies have been considered, briefly described below:

1. No treatment applied. Nutrient transfer through organic fertilizers is carried out exclusively with untreated animal dejections (i.e. pig slurries and cow manure). The crop constraints in terms of fertilization periods are applied only for liquid manure (see Fig. 4). This scenario is named *no_policy* for reasons of convenience from now on.
2. Treatment units applied to all pig farms (i.e. 6.115 farms). It is assumed that each pig farm has a small solid/liquid separation unit, with an average nitrogen separation efficiency of 15% solid and 85% liquid fractions (Ministerio de Agricultura, 2015). This scenario is

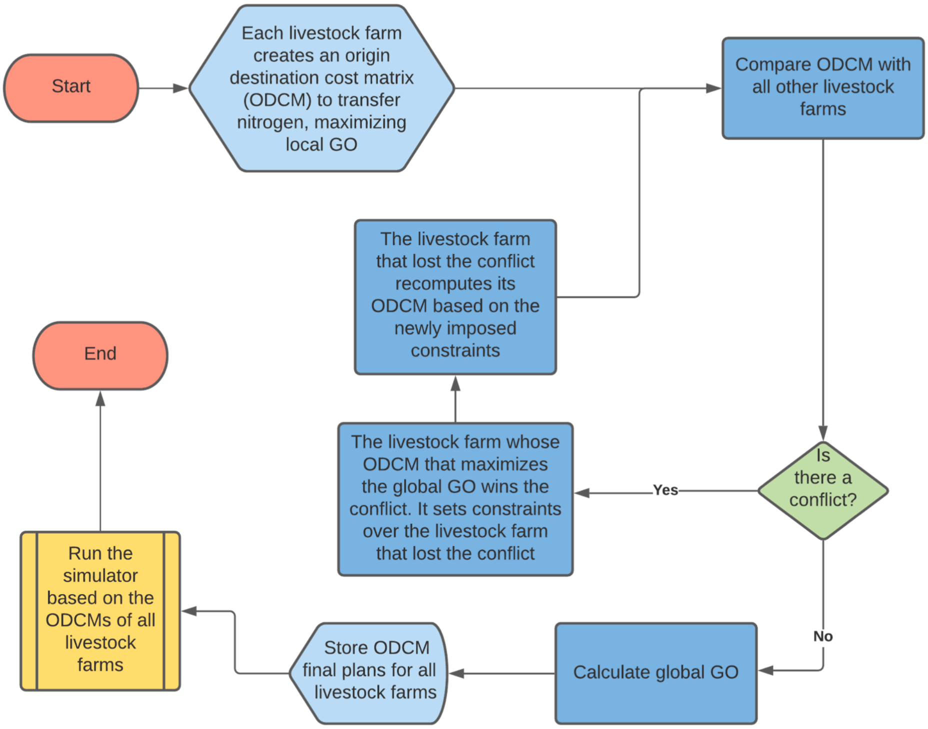


Fig. 6. Flowchart of the COA algorithm.

named *treatment_pigs_all*. No treatment is considered for cow farms in this scenario.

3. Treatment units applied only to big pig farms. Criteria here are fixed, and they are a) a threshold based on nitrogen produced yearly (above 35.000 kg, 659 farms in total) and/or b) whether the pig farm is located inside a vulnerability zone (5.612 farms). In total, 5.969 farms were selected for installing treatment units, based on this scenario (i.e. there was some overlap between big pig farms located inside vulnerable zones). This scenario is named *treatment_pigs_big*. No treatment is considered for cow farms in this scenario.
4. Treatment units applied to selected pig farms based on their location. The simulator decides whether the location of the pig farm, considering nearby crop farms and their needs in fertilizer, justifies the installation of a treatment unit. These farms were chosen based on the remaining nitrogen available (i.e. more than 5.000 kg remaining) after running the *no_policy* scenario of the simulator. A total of 1.108 farms have been selected. This scenario is named *treatment_pigs_smart*. No treatment is considered for cow farms in this scenario.
5. Composting treatment for all cow farms (i.e. 6.599 farms). The manure produced in cow farms is treated as compost. We considered 3–4 months for the duration of the composting process before compost was ready to be applied to the field, based on the guidelines in (Ministerio de Agricultura, 2015). This scenario is named *treatment_cows_all*. No treatment is considered for pig farms in this scenario.
6. Composting treatment for selected cow farms based on their location. Choosing a fixed radius of kilometres (i.e. 20 km), the simulator decides a priori whether the location of the cow farm, considering nearby crop farms and their needs in fertilizer, justifies the installation of a treatment unit. These farms were selected (i.e. 1.156 farms) based on the remaining nitrogen available (i.e. more than 10.000 kg remaining) after running the *no_policy* scenario of the simulator. This scenario is named *treatment_cows_smart*. No treatment is considered for pig farms in this scenario.
7. Treatment units applied to selected pig and cow farms based on their location. A combination of the *treatment_pigs_smart* and *treatment_cows_smart* scenarios. This scenario is named *treatment_pigs_cows_smart*.

We note that in all scenarios as mentioned earlier, treatment of manure takes place before the distribution of nutrients to nearby crop farms. It also noted that all scenarios consider small treatment units per farm instead of centralized treatment approaches. The reason is that the centralized approaches have some important drawbacks:

1. They have relatively high investment and running costs and, often, complex processes that require specialized personnel. It is not easy to find an operational scheme for management and financing that works for them.
2. Centralized treatment tends to be more expensive in terms of transport and, therefore, it requires an integrated fertilization plan at a regional level, which is often not feasible on such a dispersed sector as farming.
3. Additional measures are needed to prevent the spread of diseases linked to manure processing.

4.2. Overall Findings

Table 4 summarizes the results of the simulator, based on the different scenarios considered and described above. The fourth row indicates the score of each scenario about the objective *GO*. Rows 5–6 of the table show the average transportation distance of each livestock farm, as well as standard deviation. Although these aspects were not included to the objective *GO*, they are considered necessary by the Department of Agriculture of Catalonia. The last two rows of Table 4 summarize the exploitation/reuse of nitrogen, based on the different scenarios explored in this paper, considering a yearly nitrogen production of 116K tons in 25.293 livestock farms around Catalonia, as well as the yearly needs of 88K tons of fertilizer in 20.526 crop fields.

Fig. 7 illustrates the total nitrogen transported from livestock farms to crop fields, for different grid cell Manhattan distances between them. Most of the nitrogen transfer happens for all the scenarios up to a Manhattan distance of 5 grid cells, after which nitrogen transfer

Table 4
Summarized values of the experiments performed, based on the different scenarios considered.

Objective	no policy	treatm. pigs all	treatm. pigs big	treatm. pigs smart	treatm. cows all	treatm. cows smart	treatm. pigs/ cows smart
Nitrogen transferred (Thousand tons)	22.394	22.315	22.324	22.316	22.489	22.411	22.346
Transportation (Manhattan distance in km)	108.221	107.410	107.231	107.624	114.751	109.206	108.893
Objective *GO* (Thousands Euro)	9.289	8.974	9.088	9.174	9.039	9.198	9.158
Average transportation distance of each livestock farm (Manhattan distance)	10,98	11,29	11,15	11,30	11,40	11,06	11,38
Standard deviation of the average transportation distance of each livestock farm (Manhattan distance)	8,74	9,60	9,34	9,61	9,14	8,80	9,65
Exploitation of nitrogen based on the yearly production of livestock farms	19.3%	19.2%	19.2%	19.2%	19.4%	19.3%	19.2%
Exploitation of nitrogen based on the yearly needs of crop fields	25.4%	25.3%	25.3%	25.3%	25.5%	25.4%	25.4%

becomes relatively low.

Fig. 8 presents the transportation distance covered between livestock and crop farms for every successful transfer of nitrogen (i.e. at each different Manhattan distance recorded for each transfer that took place). For example, if some livestock farm was located in grid cell $(5,2)$ and performed a transaction at the crop farm located in grid cell $(7,3)$, this transaction would be recorded at a Manhattan distance of 3.

The total transactions of animal manure/nitrogen performed at different Manhattan distances are presented in Fig. 9. Similar to Fig. 8, a transaction at some distance x implies that the Manhattan distance between the initial position of the livestock farm and the position of the crop farm is x. The reader can understand the graph in the following way: when there are y transactions for some Manhattan distance x, this means that the total transactions that occurred during the simulation, in which the livestock farm involved was located at a Manhattan distance x from the crop field involved, were y.

Fig. 10 shows the transfer of manure to different crop types, in different periods of the year (i.e. monthly), based on the *no_policy* scenario. Green color denotes transfers of manure/nitrogen. The darker the color, the more nitrogen transferred at some particular month for some specific crop. Comparing the results of Fig. 10 with the constraints set in Fig. 4, it can be observed that the simulator respects the constraints and restrictions of the crop fields in regards to needs in fertilizer. Most transfers occur between December-July for crops of legumes, sunflower, soya, dry fruits, crops of protein, vegetables and cereals.

5. Discussion

This section discusses the overall findings and possible implications of this research. Section 5.1 analyzes the findings presented in Section 4.2, while Section 5.3 touches upon the impact of the proposed research on local and global policies. Then, Section 5.4 comments on some design decisions for implementing this study, as well as some limitations involved. Finally, Section 5.5 proposes future work on this topic.

5.1. Discussion on Findings

The findings after running the simulator on the different scenarios described in Section 4.1 show that there are only small differences between the scenarios about the objective *GO* (0,3% up to 3,4%). The reason is that the availability of manure is higher than the needs in fertilizer; thus, the production of manure through the year is easily matched with the needs of nearby crop fields in organic nutrients. As Figs. 7–9 indicate, most of the transfers occur in Manhattan distances less than 6. Most of the nitrogen transfer occurs at the *treatment_cows_all* scenario, a fact that shows the effectiveness of composting in transporting manure. The least aggregated transportation distance occurs at the *treatment_pigs_big* scenario, indicating that the installation of treatment units in big pig farms allows to reduce the total distances when transferring manure. Interestingly, this has almost the same effect as if treatment units were installed in all pig farms (i.e. *treatment_pigs_all* scenario). This observation implies that treatment units should be installed only in big farms or -even better in terms of using manure as fertilizer- via a smart approach considering the needs in nitrogen of nearby crop fields (i.e. *treatment_pigs_smart* scenario).

The changes are minimal in all scenarios in terms of average transportation distances and standard deviation of each livestock farmer. Each livestock farmer would need to cover around 11 kilometres on average each year (i.e. approximation from Manhattan distance) for transporting manure to nearby crop farms, with a deviation of around 9 kilometres (i.e. each livestock farmer covers $[2,20]$ kilometres yearly under the proposed schemes.

Another important finding is that liquid slurries are needed for covering periods when solid manure is not allowed to be placed on land (see Fig. 4). As there is already much availability for manure coming from cows (i.e. 30K tons of nitrogen yearly, see Table 1), it seems that the manure coming from pigs is more valuable as a liquid than as a solid fraction. The scenarios *treatment_pigs_all/big/smart* score less than the *no_policy* scenario. This implies that the use of treatment units in pig farms is not effective, *considering this particular use of manure*. It could still be useful for other environmental reasons, though. This result means that the saved travel costs in the pig slurry treatment scenario do not compensate for the manure processing expenses. This happens with all scenarios, but, interestingly, the smart approaches yielded more profitable results than the more indiscriminate alternatives.

In contrast to the inefficiency of treatment units applied in pig farms, manure treatment is more important for cow farms when used for composting. The *treatment_cows_all* scenario is the most profitable (see Table 4) in terms of total nitrogen transferred, indicating the importance of composting manure. The reason for this is that trucks can carry more nitrogen in every transfer (see Table 2) by composting manure. This fact makes some transfers profitable (according to *GO*) in larger distances. This can be observed in Fig. 7 (yellow line). However, this has a higher cost on the transportation costs.

Surprisingly, the *no_policy* scenario gives the highest value of the *GO* objective, in comparable performance to the *treatment_cows_smart* scenario (1% higher). However, the *no_policy* scenario transfers 1% less nitrogen between farms than the *treatment_cows_smart* scenario. We argue that the scenario *treatment_cows_smart* is suitable for a real-world policy because it reduces the cost of installation of treatment units in cow farms dramatically, while it maintains a very high score of the *GO*, maximizing the utilization of animal manure as nitrogen. In this intelligent scheme, instead of 6.599 cow farms installing treatment units as in the *treatment_cows_all* scenario, only 1.156 farms are selected in a more intelligent way ($17,5\%$ of all cow farms), with 1,7% higher *GO* score. This possibility reduces the installation and yearly maintenance costs of composting treatment units, as well as possible depreciation costs not included in this analysis.

Fig. 11 illustrates how the application of COA in the area of Catalonia affects availability (i.e. blue color) and needs (i.e. orange color) of manure/nitrogen, based on the *treatment_cows_smart* scenario. We can observe that the algorithm creates separate blue- and orange-colored

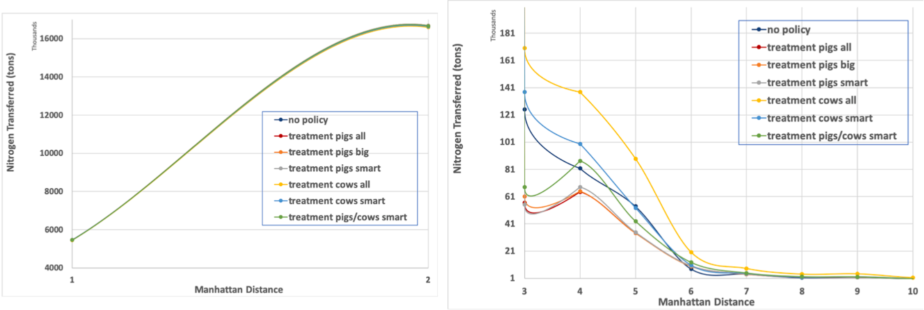


Fig. 7. A comparison between the scenarios for the total nitrogen transferred from livestock farms to crop fields at different Manhattan distances, [1–2] (left) and [3–10] (right).

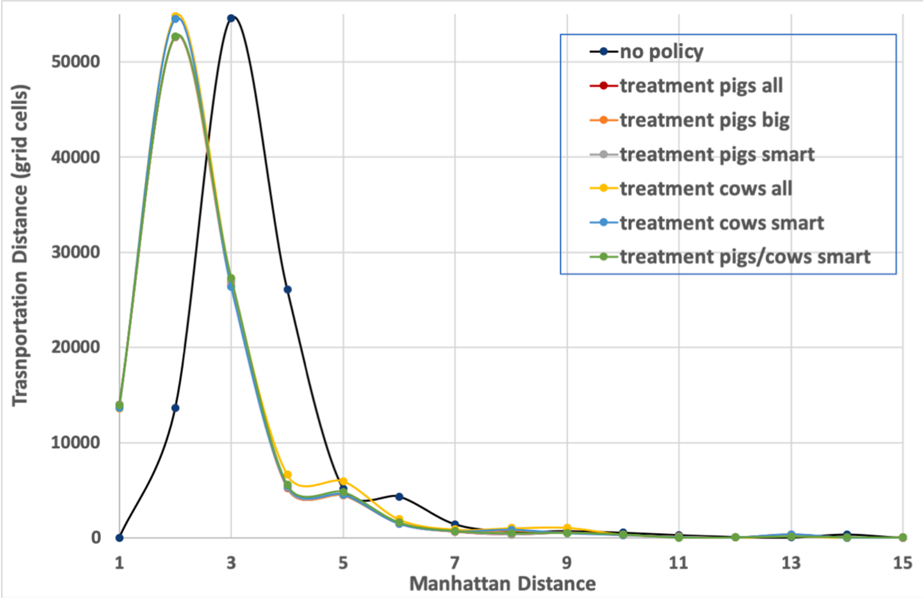


Fig. 8. Total transportation distance covered between livestock farms and crop fields, based on the different scenarios at different Manhattan distances.

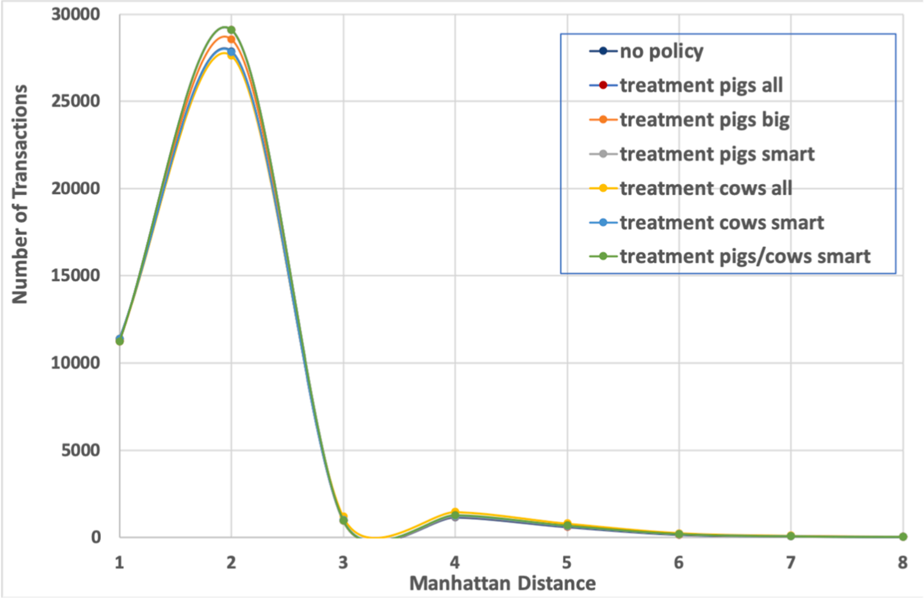


Fig. 9. Total transactions of animal manure between livestock farms and crop fields, based on the different scenarios at different Manhattan distances.

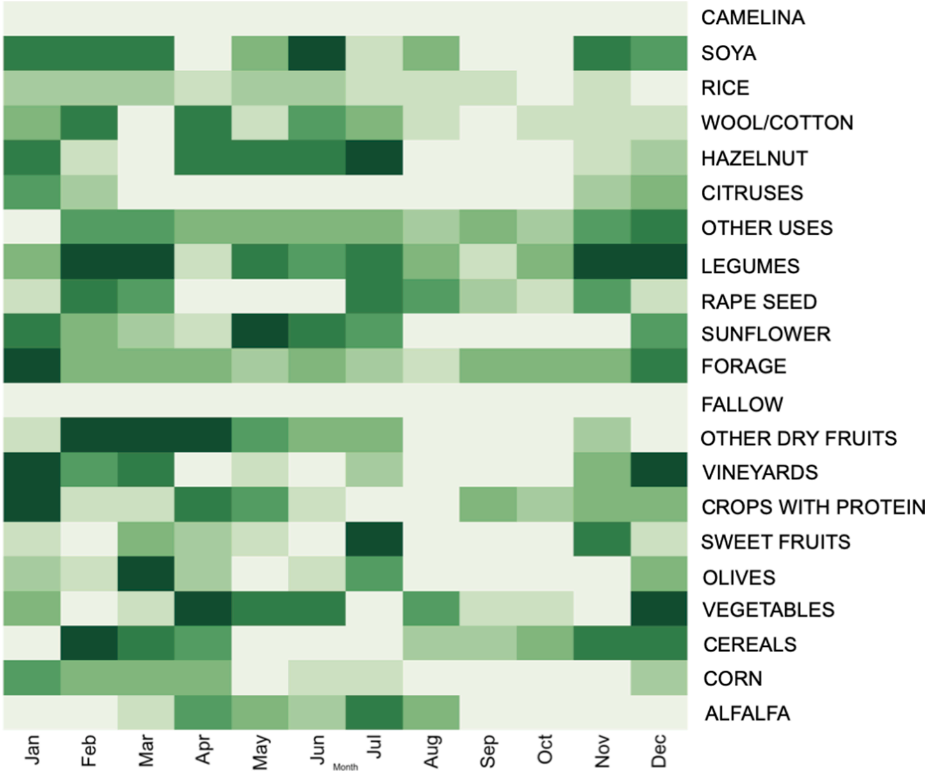


Fig. 10. A heatmap showing the exchange of nitrogen between livestock farms and crop fields, comparing various crop types in different months of the year.

spots (i.e. livestock farms and crop fields, respectively). The map (Fig. 11a) indicates that the largest production of nitrogen occurs in the regions of Girona (north-east), Lleida (west) and Tortosa (south-west). The largest needs in nitrogen happen in Lleida and Girona (Fig. 11c). After the use of COA for one year, the need for nitrogen is drastically decreased all around Catalonia, with remaining needs near Lleida (Fig. 11d). Nitrogen availability is also drastically decreased, although the "hotspot" of Lleida remains active. This indicates that policy-making should focus on this region, which could include a locally centralized, selective installation of treatment and composting units.

Fig. 11f shows the production and needs of nitrogen together after COA has been applied for a year. The distance between different color spots is more significant than a profitable transfer, i.e. there is not enough manure available for the transaction to give positive values to the *GO* function. Note that darker colors of blue and orange correspond to larger availability/needs of manure at some farm respectively. Fig. 11 is another indication that COA, via the use of our realistic simulator, solves the problem effectively. We have produced similar figures for the other scenarios, but the differences are minor and hard to observe.

5.2. Comparison with related work

As mentioned in Section 2, it was difficult to compare this project with related work due to the limited number of similar studies as well as the wide difference in requirements, assumptions and constraints, design decisions and policies in different regions and pilots around the world.

A similar work that could enable some comparisons is the work of Akdeniz et al. Li et al. (2021), Li et al. (2021), using the region of Hangzhou, China as a case study, as well as the work of Porter and James (Porter and James, 2020), using the state of Minnesota, USA, as a study. Table 5 compares this paper and the works mentioned above in aspects where this is possible and meaningful.

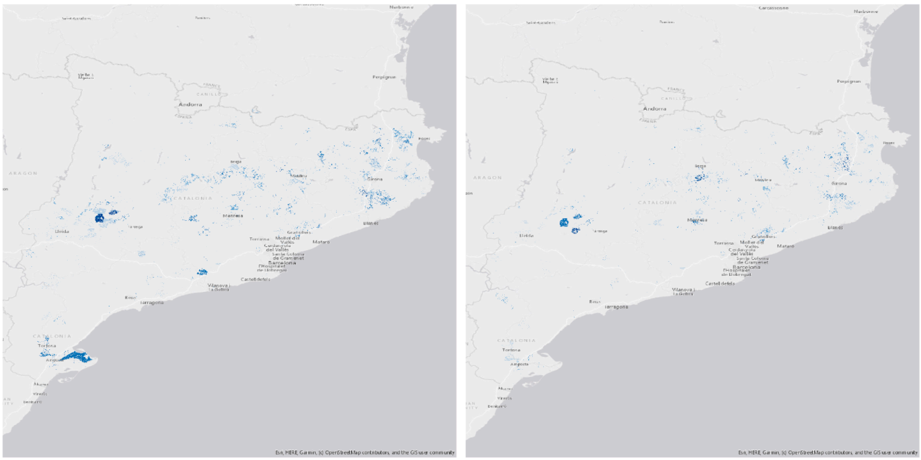
It is difficult to compare our work with Akdeniz et al., due to the very different landscape (Hangzhou is also a mountainous area) and the extensive use of centralized manure processing facilities (CPF). Akdeniz et al. considered both nitrogen and phosphorous constraints when planning nutrient utilization. The extensive watershed system in Hangzhou leads to stringent regulation to manure nutrient surplus. Thus, most nutrients were extracted as a solid portion and shipped out of Hangzhou for other applications (not in the study's scope). In contrast to our work using Manhattan distances, distances in Li et al. (2021), Li et al. (2021) were calculated based on the existing road network.

Comparing with the study of Porter and James Porter and James (2020) makes more sense since Minnesota, USA, has a similar landscape to Catalonia, Spain. While we achieved 19% nitrogen distributed as organic fertilizer, Porter and James managed to achieve 28–39%. However, we need to take into account that some manure over-application was observed in the Minnesota study (up to 4.6% of crop fields), while at the most intensive *Yield Goal* rate, combined state-wide nitrogen totals exceeded crop requirements by 10%. Further, in the Minnesota study, nitrogen availability was much less than the needs of crops in fertilizer (i.e. 28–40% of the total needs, while in our study, nitrogen was 75% of the needs). On the other hand, the Minnesota study did not include manure treatment operations while real-world distances have been used for transportation costs.

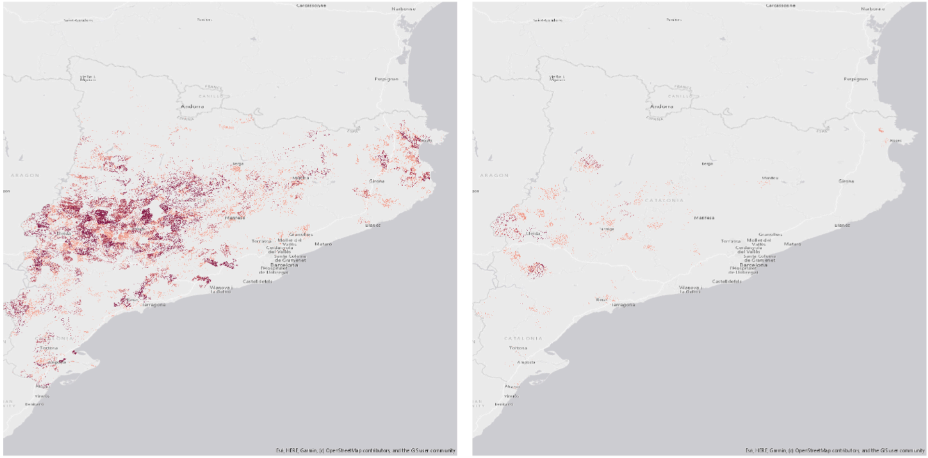
Finally, comparing cost savings and monetary benefits is difficult due to the differences mentioned above. It is worth mentioning that the Minnesota study refers to potential cost savings of over 180 M Euro annually from a state-wide perspective. These savings are 20 times bigger than the 9 M Euro savings through our work, but we are not sure whether the Minnesota study also included the costs of the trucks involved for the transport of nutrients plus the fact that Minnesota has an area 7 times larger than Catalonia, with much higher production of animal manure and nitrogen.

5.3. Policies

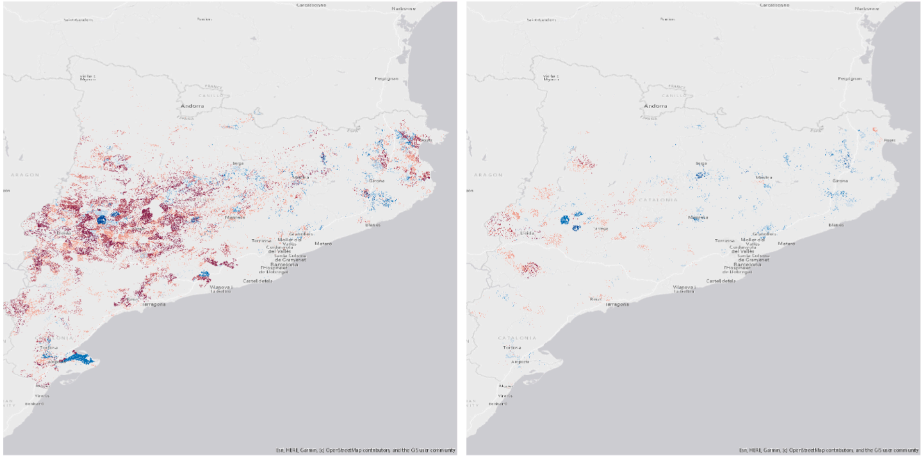
The aforementioned potential scenarios, problem modelling and overall findings have been prepared, studied, and analyzed in



(a) Production of N before COA. (b) Production of N after COA.



(c) Needs of N before COA. (d) Needs of N after COA.



(e) Production/needs of N before COA. (f) Production/needs of N after COA.

Fig. 11. The map of Catalonia before (Figures a, c, e) and after applying COA (Figures b, d, f), based on the *treatment_cows_smart* scenario. The maps show yearly needs in manure (orange color) and availability of manure (blue color), before (left column) and after (right column) COA. Color intensity indicates different needs or availability of manure. For example, darker colors of blue and orange correspond to larger availability and needs of manure at some farms, respectively. Livestock farms whose manure availability is zero and/or crop farms whose needs in fertilizer are zero do not appear on the map.

collaboration with the Ministry of Agriculture of Catalonia. Hopefully, these findings will help design the future policies and regulations to be applied to the agricultural territory of Catalonia.

We argue that specific incentives might need to be provided to the farmers for the *treatment_cows_smart* or the *treatment_pigs/cows_smart* scenario to work in real life, especially to the livestock farmers, with a view on a globally organized and more sustainable nutrient redistribution. Such policies could compensate for the farmers' efforts to collect and transport the manure to crop fields, including transportation costs. The incentives could be partially derived from the potential profits of the COA implementation (i.e. around 9 million Euro yearly according to our rough calculations based on the objective *GO* and the *treatment_cows_smart* scenario), while governmental funds could also be used. We note that these estimations include the costs of buying/maintaining trucks and treatment units for cow farms, but they should still be considered with much caution due to the simplistic nature of the estimations. After all, the possible environmental damage and cost caused by animal manure would be much higher long-term; hence this problem must be

Table 5
Comparison of this paper with related work Li et al. (2021), Li et al. (2021), Porter and James (2020).

Aspect	This paper	**Akdeniz et al.** Li et al. (2021), Li et al. (2021)	**Porter and James** Porter and James (2020)
Region	Catalonia, Spain (32,108 km^2)	Hangzhou, China (16,596 km^2)	Minnesota, USA (225,181 km^2)
Landscape	Mostly plain, except from north	Mostly mountainous	Mostly plain, hilly in north-east
Major livestock farm types	Swine, cattle and dairy cows, poultry, sheep, turkey	Swine, cattle, poultry and sheep	Poultry, swine, beef cattle and dairy cattle.
Major crop field types	Olive trees, barley, wheat, corn, alfalfa, legumes, soya, grape trees, rapeseed, sunflower and rice	Rice, corn, wheat, tubers and soya	Corn, soybean, sugar beet, legumes, wheat, barley, sorghum
Manure treatment operations	Pig solid/liquid separation units, cow manure composting	Converting solid manure into organic fertilizer, processing slurry manure	Not considered/included
Use of centralized manure processing facilities (CPF)	No	Yes (30 certified CPF and 2 waste treatment facilities)	No
Algorithm/method used to solve the manure distribution problem	COA	RMUC model with an optimization objective	Code implemented in ArcGIS based on a series of manure application loops, prioritizing nearest fields first.
Availability of nitrogen	116 K tons	6.4 K tons (slurry and liquid manure). Solid manure is not used in local cycle.	244 K tons
Needs in fertilizer	88 K tons (nitrogen)	232 K tons (nitrogen and phosphorous)	615–862 K tons (nitrogen, depending on use of commercial fertilizer)
Percentage of nitrogen distributed as organic fertilizer	19% (including areas vulnerable in nitrates)	36% (reduced to 14% in areas vulnerable in nitrates), becomes 16% under the Illinois land application policy Illinois Environmental Protection Agency (2003)	28.4–39.7%
Transportation distance per farmer	11 km (average, for all animal and manure types, considering Manhattan distances)	40 km (average, solid manure), 15.7 km (average, slurry manure)	12–21 km (maximum to reach yield goals, depends on animal type)

tackled effectively even if funding from stakeholders is additionally required.

Incentives can also be targeted, based on our observation that large farms produce considerably more manure and potential contamination than medium-sized or small ones. This observation was also evident in the Hangzhou study Li et al. (2021): *the worst 10% of broiler farms generate 7.8 times more manure than the median level farms, and the worst 10% of sheep farms produce 6.8 times more manure than the median level farms*.

A key element in this approach is the behavior of the livestock and crop farmers, in respect to whether they would embrace such a scheme (Battel and Krueger, 2004; Pampuro et al., 2018; Leytem et al., 2021). Understanding this behavior is essential in order to design the policies and regulations involved carefully. In this aspect, the work in (Williams, 1999) has identified and discussed various factors that influence farmers' manuring decisions, either positively (i.e. herd size, contractual arrangements, seasonal migration and its effect on livestock investment) or negatively (i.e. farm size, the distance of fields, the proportion of cultivated land). Economic returns, yield goals and cost of implementation were the three most important factors that influence decision making related to nutrient management in (Leytem et al., 2021). These factors must be considered before any policy scheme becomes realized. Properly communicating potential benefits to farmers is crucial to get their acceptance (Pampuro et al., 2018), while education is crucial (Leytem et al., 2021). Another dimension worth investigating is the combination of manure and commercial fertilizer. A recent study in Minnesota, USA, revealed that by combining the two, nitrogen exceeded state-wide crop requirements (110%155%), suggesting that significant application of nitrogen above recommended rates was likely occurring (Porter and James, 2020).

Moreover, it is important to note that most countries around the world have national policies related to manure management (Teenstra et al., 2014). However, these policies have inconsistencies, are not well regulated or are not followed, especially in developing countries (Vu et al., 2007; Ndambi et al., 2019). Achieving reductions of methane emissions and meeting renewable energy targets or lowering the energy costs at the farm level are critical drivers of manure-related policies, which differ in each country between storage, treatment, digestion, discharge and application (Oenema et al., 2007). A general observation is that manure is not optimally used by farmers around the world, especially in developing countries (Teenstra et al., 2014; Vu et al., 2007; Oenema et al., 2007; Ndambi et al., 2019). Our work aims to contribute to the efforts towards an effective solution to the problem via a geo-informatic simulation and optimization tool that assist in policy development and implementation.

5.3.1. *Policies for Vulnerable Zones*

Policies are generally stricter inside zones vulnerable in nitrates (see Fig. 3 for the vulnerable areas in Catalonia, Spain). As mentioned before, only a limited amount of nitrogen from organic origin can be applied inside these zones. Aiming to find effective solutions to the animal manure problem occurring inside these zones by livestock farms located there, two scenarios were additionally considered:

1. Prioritize transfers of manure from livestock farms located inside vulnerable zones (VZ). Transfer can occur anywhere, either to crop fields inside or outside these zones. This scenario is named as *VZ1*.
2. Prioritize manure transfers from livestock farms located inside VZ to crop fields inside these zones. This scenario is named as *VZ2* and is more constrained than *VZ1* because now livestock farms inside VZ need to visit crop fields inside VZ first before searching for crop fields outside VZ.

Table 6 shows the results of these additional scenarios, based on the *treatment_cows_smart* scenario used as basis for implementing the extra constraints of the scenarios *VZ1* and *VZ2*. Very similar results have been recorded for the other scenarios as well. A total of 5.612 livestock farms and 12.820 crop fields have been recorded inside VZ in Catalonia.

The key goal here is to reduce the nitrogen that remains inside VZ, as this could potentially pollute nearby soils and waters. There is a 4% reduction at the remaining nitrogen inside VZ at the livestock farms via the *VZ1* scenario, in comparison to the *treatment_cows_smart* basic scenario. This reduction is reduced to 3% via the *VZ2* scenario due to the additional constraints. However, these reductions occur with a penalty

Table 6
Results of the additional scenarios prioritizing transfers inside vulnerable zones.

Scenario	Remaining nitrogen inside VZ at livestock farms (Thousand tons)	Remaining needs in nitrogen inside VZ for crop fields (Thousand tons)	Objective GO
treatment_cows_smart	34.864	52.260	9.198
VZ1	33.563	52.360	9.102
VZ2	33.856	52.219	9.042

of 1.1% (*VZ1*) and 1.7% (*VZ2*) in overall performance, in terms of the objective *GO*. The remaining needs in nitrogen inside vulnerable zones have minimal changes among the scenarios. Penalty in performance vs gains in reduction of remaining nitrogen might make the additional scenarios attractive for policy-makers.

5.4. Design Decisions and Limitations

COA belongs to the class of network flow problems approximated by linear integer programming (ILP). COA runs on a simulator developed by the authors, choosing an adapted generalization of Dijkstra's algorithm for shortest paths, plus the use of origin–destination cost matrices for choosing optimal paths, as used in the travelling salesman problem. The development of a simulator from scratch was decided because of the scale, conditions, objectives and constraints of the problem under study, which made the use of popular ILP solvers (e.g. CPLEX, GLPK, Gurobi) difficult. The many constraints of the problem (see Section 3.1) influenced the decision to develop a new simulator for reasons of flexibility and more freedom during the implementation of the simulator.

Although this work has addressed numerous existing limitations of related as well as of our previous work (see Section 2), it still has some limitations:

- Phosphorous, another fundamental crop nutrient present in manure, has not been considered. Phosphorous has been considered in the related work of Akdeniz et al. Li et al. (2021), Li et al. (2021).
- Used a simplified objective function to optimize, based on general estimations of nitrogen value, transport cost (i.e. cost of fuel), cost of vehicles used and treatment units. This objective does not encode the requirement of a balanced, fair solution that minimizes the average distance that needs to be covered by the livestock farmers.
- Not considered actual, real-world transportation distances between livestock and crop farms. It has been considered in some important related work Li et al. (2021), Li et al. (2021), Porter and James (2020).

The consideration of phosphorous and the use of a more elaborate objective function are aspects of future work (see Section 5.5). Although the objective *GO* did not consider balance and fairness among livestock farmers, all scenarios implied transportation distances of $[2, 20]$ kilometres to be covered per livestock farmer, which is highly acceptable. Finally, the use of Manhattan distances was necessary due to the problem's complexity. It was very computationally expensive to compute real-world distances for every possible transfer of manure, plus the popular online mapping services set limitations on the use of their geospatial APIs. An approximation of Manhattan distances to real-world distances was attempted in Section 3.2, when defining the objective *GO*.

5.5. Future work

The relevance of the problem under study (i.e. management of livestock manure) makes the investigation of possible solutions equally important. This paper proposes a solution based on the optimized transfer of manure as organic fertilizer to nearby crop fields. The findings are promising, and it is highly desirable to see this approach applied to some European country or region, considering all variables and parameters involved, such as actual costs of the equipment and infrastructure needed to support this initiative. For example, the profits gained by COA under the different scenarios would need to be reconsidered, taking into account additional costs such as the extra time wasted by the livestock farmers or the personnel in charge of realizing the transfers of animal manure, plus the costs of depreciation of vehicles and treatment units in selected farms.

It must be acknowledged that transportation is a source of environmental pollution, and minimizing the environmental effects through distance minimization does not mean that this solution is necessarily eco-friendly. Further, the risk of disseminating antibiotic resistance genes to the farm environment via fertilizing with animal manure needs to be assessed (Ruuskanen et al., 2016). Thus, a complete Life-Cycle Analysis (LCA) (Curran, 2008), together with Life-Cycle Costing (LCC) (Swarr et al., 2011), would consider a more comprehensive coverage of the problem. LCA/LCC should embrace environmental parameters, incorporating environmental damage and comparisons with alternatives. This is an interesting topic of future work and it would allow policy-makers to understand the overall implications better and consider the real-world application of this solution to their regions. For example, replacing diesel trucks with electric cars may reduce the total transportation costs and GHG emissions by 28% and 14%, respectively, as related work suggests Li et al. (2021), Li et al. (2021).

As mentioned in Section 5.4, future work will also consider phosphorous as another fundamental crop nutrient and a more detailed/complete optimization function. The possibility to consider larger manure transport vehicles will also be examined, taking into account their cost of operation. Currently, the case of trucks with a capacity of 20 cubic meters have been considered (see Section 3.1).

Moreover, the evaluation of carbon footprint, which is a complex balance between energy consumption during transport, emissions during manure storage, treatment, and application; as well as the substitution of the effect of reducing the needs for mineral fertilization[8] will be taken into account.

Finally, the region of Catalonia, Spain was selected by the authors for their experiments, as it constitutes one of the densest farming regions around Europe, with considerable challenges related to environmental pollution from livestock manure. The majority of EU livestock are reared in just a few EU member states (Eurostat, 2020): Spain accounts for 22% of the EU's pigs, 9% of the EU's bovines and 25% of the EU's sheep. Germany accounts for 18% of the EU's pigs and 15% of the EU's bovines. France accounts for 9% of the EU's pigs, 24% of the EU's bovines and 12% of the EU's sheep. Some other EU states use a relatively large percentage of land for agriculture being specialized to some particular animal types: Denmark accounts for 9% of the EU's pig population and the Netherlands a further 8%, although their land area is only 1% and 0.8% of the whole EU land area respectively (The World Bank, 2020). Those key regions mentioned above should be explored in the future via similar studies and results should be compared with the outcomes of this study.

6. Conclusion

This paper addressed the problem of the environmental impact of animal manure from livestock agriculture, considering a more sustainable approach based on nutrient redistribution, where manure was transported as fertilizer from livestock farms to crop fields. A centralized approach (COA) was adapted and used to solve the problem, based on an adapted version of Dijkstra's algorithm for finding shortest paths and origin–destination cost matrices for finding optimal routes. Different possible scenarios have been considered based on a realistic simulator

---

[8] The production of synthetic ammonia through the Haber–Bosch process is very energy-intensive.

that addresses many limitations and constraints of related work. The findings indicate that the most efficient scenarios are either not to apply any policy or to apply treatment units on selected cow farms for composting manure (i.e. 17% of the total cow farms), for which there are no nearby crop fields to deposit manure as fertilizer. Regarding pig farms, the use of treatment units is not profitable due to the predefined periods of the year when only liquid manure is allowed to be placed on soils. The paper also discusses implications on future policies and proposes future work on this proposed solution. Finally, a comparison of our findings with those of two similar studies in Hangzhou, China and Minnesota, USA, have been performed.

CRediT authorship contribution statement

Andreas Kamilaris: Conceptualization, Methodology, Validation, Investigation, Visualization, Software, Writing – original draft, Supervision, Writing – review & editing. **Francesc X. Prenafeta-Boldú:** Supervision, Writing – review & editing.

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.

Acknowledgements

Special thanks to Mr. Jaume Boixadera Llobet and Mr. Mario Carrillo Salagre from the Ministry of Agriculture, Government of Catalonia. Their feedback, help and advice had been very important in understanding the problem of livestock agriculture in Catalonia and seeking ways to reduce it. This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 739578 and the Government of the Republic of Cyprus through the Deputy Ministry of Research, Innovation and Digital Policy.

References

Acutis, M., Alfieri, L., Giussani, A., Provolo, G., Di Guardo, A., Colombini, S., Bertoncini, G., Castelnuovo, M., Sali, G., Moschini, M., et al., 2014. Valore: An integrated and gis-based decision support system for livestock manure management in the lombardy region (northern italy). Land use policy 41, 149–162.

Almeida, R., Queiroz, I., Mikhael, J., Oliveira, R., Borges, E., 2019. Enriched animal manure as a source of phosphorus in sustainable agriculture. International Journal of Recycling of Organic Waste in Agriculture 8, 203–210.

Basnet, B.B., Apan, A.A., Raine, S.R., 2001. Selecting suitable sites for animal waste application using a raster GIS. Environ. Manage. 28, 519–531.

Battel, R.D., Krueger, D.E., 2004. Barriers to change: farmers' willingness to adopt sustainable manure management practices. Ph.D. thesis. Michigan State University. Department of Community, Agriculture, Recreation.

Bayu, W., Rethman, N., Hammes, P., 2005. The role of animal manure in sustainable soil fertility management in sub-saharan africa: a review. Journal of Sustainable Agriculture 25, 113–136.

Borhan, S., Mukhtar, S., Capareda, S., Rahman, S., 2012. Greenhouse gas emissions from housing and manure management systems at confined livestock operations, in: Waste Management - An Integrated Vision. InTech, pp. 259–296.

Bruinsma, J., 2003. World agriculture: towards 2015/2030: an FAO perspective. Earthscan.

Cheng, H., Ouyang, W., Hao, F., Ren, X., Yang, S., 2007. The non-point source pollution in livestock-breeding areas of the heihe river basin in yellow river. Stoch. Env. Res. Risk Assess. 21, 213–221.

Cherkassky, B.V., Goldberg, A.V., Radzik, T., 1996. Shortest paths algorithms: Theory and experimental evaluation. Mathematical programming 73, 129–174.

Curran, M.A., 2008. Life cycle assessment. Wiley Online Library.

Davidson, E.A., 2009. The contribution of manure and fertilizer nitrogen to atmospheric nitrous oxide since 1860. Nat. Geosci. 2, 659–662.

Eurostat, 2020. Livestock population in numbers. https://ec.europa.eu/eurostat/web/products-eurostat-news/-/ddn-20200923-1.

Food and Agriculture Organization of the United Nations, 2009. How to Feed the World in 2050.

Garnier, M., Lo Porto, A., Marini, R., Leone, A., 1998. Integrated use of gleams and gis to prevent groundwater pollution caused by agricultural disposal of animal waste. Environmental management 22, 747–756.

Ghimire, S., Wang, J., Fleck, J.R., 2021. Integrated crop-livestock systems for nitrogen management: A multi-scale spatial analysis. Animals 11, 100.

Gracia, C., Velázquez-Martí, B., Estornell, J., 2014. An application of the vehicle routing problem to biomass transportation. Biosystems engineering 124, 40–52.

He, C., Shi, C., 1998. A preliminary analysis of animal manure distribution in michigan for nutrient utilization. JAWRA Journal of the American Water Resources Association 34, 1341–1354.

Heinrich-Böll-Stiftung, Chemnitz C., Becheva, S., 2014. Meat atlas: Facts and figures about the animals we eat. Heinrich Böll Foundation.

Illinois Environmental Protection Agency, 2003. Illinois Livestock Management Facilities Act, Section 900.803.

Infascelli, R., Faugno, S., Pindozzi, S., Pelorosso, R., Boccia, L., 2010. The environmental impact of buffalo manure in areas specialized in mozzarella production, southern italy. Geospatial health 5, 131–137.

Intergovernmental Panel on Climate Change (IPCC), 2006. Chapter 10: Emissions from livestock and manure management. IPCC Guidelines for National Greenhouse Gas Inventories, Agriculture, Forestry and Other Land Use, p. 4.

Jianya, Y.Y.G., 1999. An efficient implementation of shortest path algorithm based on dijkstra algorithm [j]. Journal of Wuhan Technical University of Surveying and Mapping (WTUSM) 3.

Jones, C., Olson-Rutz, K., Dinkins, C., 2011. Nutrient uptake timing by crops. Technical Report. Montana State University, Montana, USA.

Kamilaris, A., Assumpcio, A., Blasi, A.B., Torrellas, M., Prenafeta-Boldu, F.X., 2017. Estimating the Environmental Impact of Agriculture by means of Geospatial and Big Data Analysis: The Case of Catalonia, in: Proc. of EnviroInfo, Luxembourg.

Kamilaris, A., Engelbrecht, A., Pitsillides, A., Prenafeta-Boldu, F.X., 2020. Transfer of Manure as Fertilizer from Livestock Farms to Crop Fields: The Case of Catalonia. Computers and Electronics in Agriculture 175, 1–11.

Kamilaris, A., Engelbrecht, A., Pitsillides, A., Prenafeta-Boldu, F.X., 2020b. Transfer of Manure from Livestock Farms to Crop Fields as Fertilizer using an Ant Inspired Approach, in: XXIVth International Society for Photogrammetry and Remote Sensing (ISPRS) Congress, Nice, France.

Kamilaris, A., Ostermann, F.O., 2018. Geospatial Analysis and the Internet of Things. In: ISPRS International Journal of Geo-Information, Special Issue on Geospatial Applications of the Internet of Things (IoT), p. 7.

Kandiller, L., Eliiyi, D.T., Taşar, B., 2017. A multi-compartment vehicle routing problem for livestock feed distribution. In: Operations Research Proceedings. Springer, pp. 149–155.

Keplinger, K.O., Hauck, L.M., 2006. The economics of manure utilization: model and application. Journal of Agricultural and Resource Economics 31, 414–440.

Leytem, A.B., Williams, P., Zuidema, S., Martinez, A., Chong, Y.L., Vincent, A., Vincent, A., Cronan, D., Kliskey, A., Wulfhorst, J., et al., 2021. Cycling phosphorus and nitrogen through cropping systems in an intensive dairy production region. Agronomy 11, 1005.

Li, J., Akdeniz, N., Kim, H.H.M., Gates, R.S., Wang, X., Wang, K., 2021. Optimal manure utilization chain for distributed animal farms: Model development and a case study from hangzhou, china. Agric. Syst. 187, 102996.

Li, J., Akdeniz, N., Kim, H.H.M., Gates, R.S., Wang, X., Wang, K., 2021. Quantification of sustainable animal manure utilization strategies in hangzhou, china. Agric. Syst. 191, 103150.

Lin, S., Kernighan, B.W., 1973. An effective heuristic algorithm for the traveling-salesman problem. Operations research 21, 498–516.

Ministerio de Agricultura, Alimentación y Medio Ambiente, Gobierno de Espania, 2015. Evaluacion de tecnicas de gestion de deyecciones en ganaderia. https://www.mapa.gob.es/es/ganaderia/temas/ganaderia-y-medio-ambiente/evaluaciondetecnicasdegestiondedeyeccionesganaderas_tcm30-108245.pdf.

Ministerio de Agricultura, Alimentación y Medio Ambiente, Gobierno de Espania, 2019. DECRETO 153/2019, de 3 de julio, de gestión de la fertilización del suelo y de las deyecciones ganaderas y de aprobación del programa de actuación en las zonas vulnerables en relación con la contaminación por nitratos procedentes de fuentes agrarias. https://dogc.gencat.cat/es/pdogc_canals_interns/pdogc_resultats_fitxa/index.html?action=fitxa&documentId=853461&language=ca_ES&newLang=es_ES.

Ndambi, O.A., Pelster, D.E., Owino, J.O., De Buisonje, F., Vellinga, T., 2019. Manure management practices and policies in sub-saharan africa: implications on manure quality as a fertilizer. Frontiers in Sustainable Food Systems 3, 29.

Nitrate Directive, 1991. Council directive 91/676/eec of 12 december 1991 concerning the protection of waters against pollution caused by nitrates from agricultural sources. Official Journal EUR-Lex 375, 12.

Oenema, O., Oudendag, D., Velthof, G.L., 2007. Nutrient losses from manure management in the european union. Livestock science 112, 261–272.

Oppen, J., Løkketangen, A., 2008. A tabu search approach for the livestock collection problem. Computers & Operations Research 35, 3213–3229.

Pampuro, N., Caffaro, F., Cavallo, E., 2018. Reuse of animal manure: A case study on stakeholders' perceptions about pelletized compost in northwestern italy. Sustainability 10, 2028.

Paudel, K.P., Bhattarai, K., Gauthier, W.M., Hall, L.M., 2009. Geographic information systems (GIS) based model of dairy manure transportation and application with environmental quality consideration. Waste Manage. 29, 1634–1643.

Porter, S.A., James, D.E., 2020. Using a spatially explicit approach to assess the contribution of livestock manure to minnesota's agricultural nitrogen budget. Agronomy 10, 480.

Rotz, C., 2004. Management to reduce nitrogen losses in animal production. Journal of animal science 82, E119–E137.

RuralCat, 2015. Departament d'Agricultura, Ramaderia, Pesca i Alimentació, Ruralcat dossier tecnic No. 79.

Ruuskanen, M., Muurinen, J., Meierjohan, A., Pärnänen, K., Tamminen, M., Lyra, C., Kronberg, L., Virta, M., 2016. Fertilizing with animal manure disseminates antibiotic resistance genes to the farm environment. Journal of environmental quality 45, 488–493.

Sanford, G.R., Cook, A.R., Posner, J.L., Hedtcke, J.L., Hall, J.A., Baldock, J.O., 2009. Linking wisconsin dairy and grain farms via manure transfer for corn production. Agronomy journal 101, 167–174.

Stoate, et al., 2009. Ecological impacts of early 21st century agricultural change in europe - a review. Journal of environmental management 91, 22–46.

Swarr, T.E., Hunkeler, D., Klöpffer, W., Pesonen, H.L., Ciroth, A., Brent, A.C., Pagan, R., 2011. Environmental life-cycle costing: a code of practice 16, 389–391.

Teenstra, E., Vellinga, T.V., Aktasaeng, N., Amatayaku, W., Ndambi, A., Pelster, D., Germer, L., Jenet, A., Opio, C., Andeweg, K., 2014. Global asessment of manure management policies and practices. Technical Report. Wageningen UR Livestock Research.

Teira-Esmatges, M.R., Flotats, X., 2003. A method for livestock waste management planning in NE Spain. Waste management 23, 917–932.

The World Bank, 2020. Land area (sq. km) - European Union. https://data.worldbank.org/indicator/AG.LND.TOTL.K2?locations=EU.

Van Lanen, H., Wopereis, F., 1992. Computer-captured expert knowledge to evaluate possibilities for injection of slurry from animal manure in the netherlands. Geoderma 54, 107–124.

Vu, T., Tran, M., Dang, T., 2007. A survey of manure management on pig farms in northern vietnam. Livestock Science 112, 288–297.

Wenzel, S., Peter, T., 2017. Comparing Different Distance Metrics for Calculating Distances in Urban Areas with a Supply Chain Simulation Tool. Simulation in Produktion und Logistik, p. 119.

Whalen, J.K., Chang, C., Clayton, G.W., Carefoot, J.P., 2000. Cattle manure amendments can increase the ph of acid soils. Soil Sci. Soc. Am. J. 64, 962–966.

Williams, T.O., 1999. Factors influencing manure application by farmers in semi-arid west africa. Nutr. Cycl. Agroecosyst. 55, 15–22.