Non-cooperative game theory to ensure the marketability of organic fertilizers within a sustainable circular economy

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ABSTRACT

To optimize the environmental performance and the conflicting economic interests of the stakeholders that interact within circular integrated waste management systems (CIWMSs), life cycle analysis and game theoretical models – based on the Stackelberg equilibrium – were integrated into a multi-objective optimization framework. The framework was used to determine the operational decisions and the configuration of a CIWMS that simultaneously minimize the total global warming impacts (GWI) and maximize the profits of i) the waste managers that valorize the municipal organic waste generated in the Spanish region of Cantabria, and ii) the regional farmers that purchase the organic fertilizers derived from this waste. The resulting bilevel problem was solved applying the Karush-Kuhn-Tucker conditions. The balance between the stakeholders' objectives is reflected in the low prices set for the organic fertilizers (0-2 €·metric ton^{-1} of compost, and 0-1 €·metric ton^{-1} of digestate). Although the minimal GWI are constrained by the waste managers' profits, it is possible to push the Pareto frontier toward better outcomes increasing the waste management taxes. The proposed framework proved to be a useful instrument to plan for a sustainable circular economy, warranting that the production and purchase of organic fertilizers is profitable for both ends of the supply chain.

KEYWORDS

Circular integrated waste management systems
Organic waste
Nutrient recovery
Stackelberg game
Multi-objective optimization
Life cycle assessment
Global warming impacts
Life Cycle Costing

INTRODUCTION

The economic sector that encompasses agriculture, forestry and other land uses emits almost a quarter of the anthropogenic greenhouse gases.[1] The nitrogen use efficiency of the most cultivated crops is typically below 40%; the remaining nitrogen is released to the atmosphere as N_2O – a powerful greenhouse gas – or leaches into the water bodies causing eutrophication.[2] Moreover, around 45% of the phosphorus mined worldwide for agricultural purposes ends in the ocean, contributing to eutrophication and the depletion of this non-renewable nutrient.[3]

On the other hand, solid waste management accounts for about 5% of global warming impacts (GWI).[4] The diversion of organic waste from landfills prevents the degradation of carbon into CH_4 – a significant contributor to global warming – that occurs under the anaerobic conditions of landfills, and represents an opportunity for nutrient recovery; it has been estimated that the total nitrogen, phosphorus and potassium contained in food, animal and human waste amount to 2.7 times the nutrients processed by the fertilizer industry.[5]

Finding a common strategy to meet the ever-increasing demand for nutrients and manage organic waste while minimizing the associated environmental impacts and the removal of resources from the environment falls within the scope of a circular economic system. However, a standardized systematic approach to quantify, assess and optimize the performance of a circular economy is still lacking.

Cobo et al.[6,7] illustrated how process systems engineering can effectively assist decision-makers in this respect by developing a life cycle optimization framework for the sustainable design of Circular Integrated Waste Management Systems (CIWMSs) targeting nutrient circularity. Nonetheless, their study did not consider that an increase in the market share of the fertilizing products recovered from organic waste (hereafter referred to as organic fertilizers) can only be achieved if farmers are willing to purchase these products.

Indeed, the worse performance of organic fertilizers compared with industrial fertilizers – more product is required to fertilize the same area –[8,9] renders them uncompetitive in the absence of subsidies. To avert a scenario where waste managers do not get back a return on the investment made in sustainable technologies and accumulate a stock of organic fertilizers that cannot be sold, trade-offs between their economic interests and those of the farmers must be made. Therefore, modeling the farmers' response to the prices set for the organic fertilizers is critical to accurately foresee the behavior of CIWMSs.

Game theory can be applied to optimize the decisions and actions of all the parties involved in a circular supply chain in accordance with their individual – and conflicting – objectives. Nevertheless, few studies have reportedly approached the design of circular systems from a game theoretical perspective. Some authors have analyzed the payoff matrices derived from the alternative decisions that the relevant actors within circular systems can make,[10-13] whereas others have developed more complex optimization frameworks.[14-16] To the best of the authors' knowledge, the optimization of the interactions between the waste managers that valorize municipal organic waste and the farmers that purchase the resulting fertilizing products has not been described in the literature.

Thus, the goal of this paper is to explore how game theory optimization can be used to plan for the implementation of a sustainable circular economy of nutrients by guaranteeing that the production and agricultural application of organic fertilizers is profitable for both ends of the supply chain. This research builds on previous studies that focus on a CIWMS aimed at the valorization of the municipal organic waste generated in the Spanish region of Cantabria.[7-9] The results of the study will determine the operational decisions and the configuration of the Cantabrian CIWMS that minimize its GWI and optimize the economic performance of the involved stakeholders. Specifically, the research will reveal the types of organic fertilizers that must be produced and the range of prices that should be assigned to them to ensure their acceptance in the market under the restrictions of the case study.

METHODOLOGY

The integration of life cycle and game theoretical models underpinned the holistic and decentralized optimization of the system. The assumptions made and the methodological procedure followed are described below.

System model

Figure 1 depicts the superstructure containing all the alternative unit processes that could be integrated into the optimal system design. Once the unit processes were separately characterized, the system model was constructed in the GAMS (General Algebraic Modeling System) 28.2.0 optimization platform.[17]

To align this modular modeling approach with the game theoretical model that describes the stakeholders' behavior, the unit processes were split into two subsystems comprising the activities of different groups of agents: the waste management and the agricultural subsystems. The boundaries that delimit the studied CIWMS and the two subsystems are identified in Figure 1.

Regarding the spatiotemporal boundaries of the study, the CIWMS processes the municipal organic waste collected from all the Cantabrian municipalities in one year (83,544 metric ton).[18] The farmers, who purchase the amount of fertilizing products required to grow their crops during that year, are located across the region.

- *Life cycle model*

An attributional Life Cycle Assessment (LCA) model (based on average data and focusing on the environmentally relevant flows that enter and exit the system)[19] was developed. The functional unit was defined as the area that must be annually fertilized to meet the nutrient requirements of the two most cultivated crops in Cantabria – corn and wheat –, which in 2018 occupied 4,118 and 674 ha, respectively.[20] The analyzed CIWMS also supplies the electricity generated at the incineration, landfill and anaerobic digestion unit processes. To address the system multi-functionality, the direct substitution method was applied, presuming that the electricity generated by the CIWMS replaces the same amount of electricity produced with the average Spanish technology mix.

The GWI were modeled with the ReCiPe 1.11 method,[21] considering a 100-year time horizon. The biogenic carbon derived from food waste was quantified as neutral; i.e., it was assumed to have been removed from the atmosphere in the crop production stage.

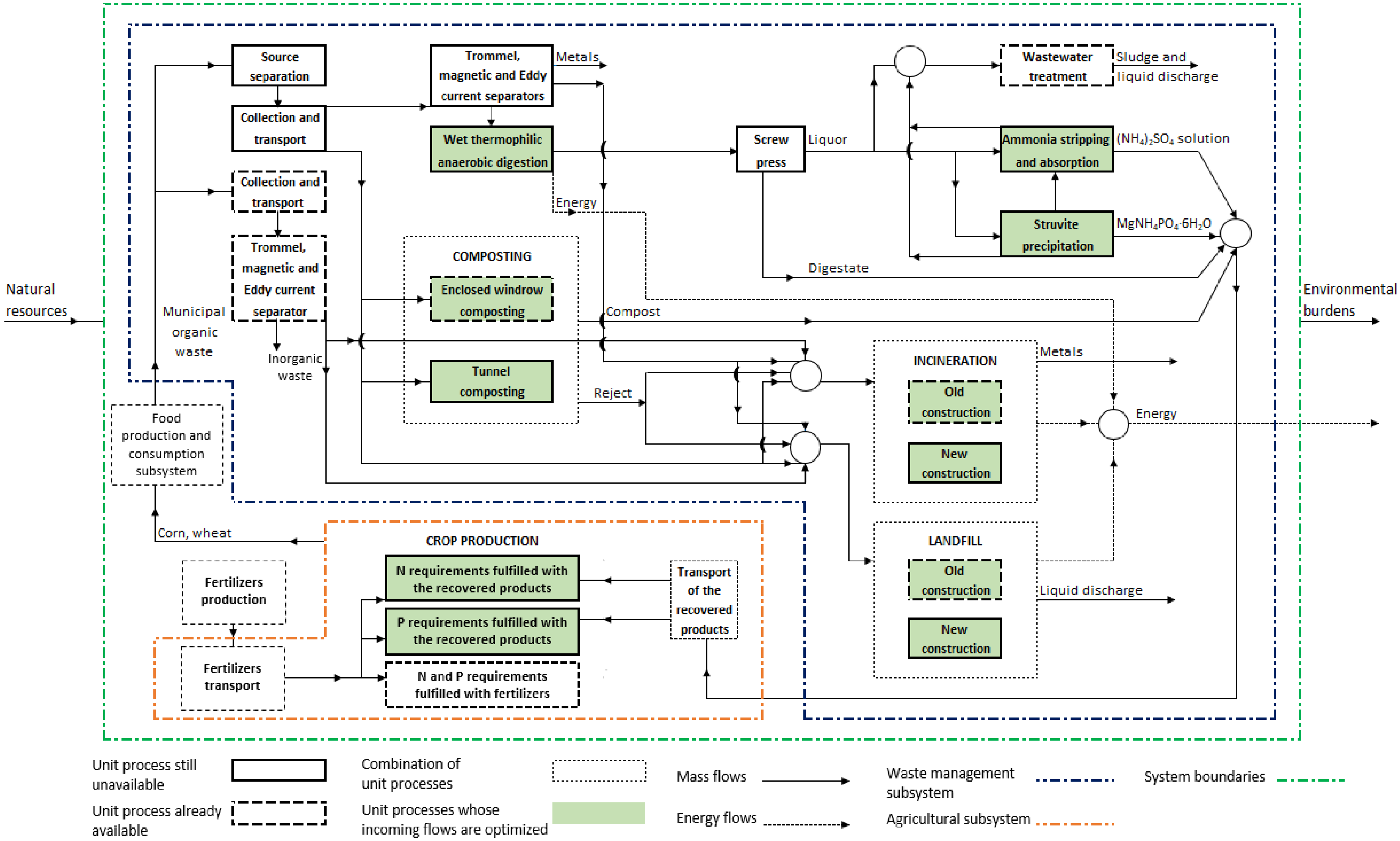

Figure 1. System boundaries and superstructure

The LCA of the individual unit processes that compose the system was carried out with the EASETECH (Environmental Assessment System for Environmental Technologies) 2.3.6 software.[22] EASETECH also calculated the composition and flows of the streams exiting each unit process, which served as the input data to the models of the units that further process those streams. The DNDC (Denitrification-Decomposition) 9.5 simulation model[23] was used to predict the mean annual fertilization requirements, crop yields, and carbon and nitrogen emissions due to the application of the different fertilizers to the soil in the 100-year timeframe. The DNDC results were transferred to EASETECH to determine the associated GWI. The data required to conduct the LCA, namely the waste composition (Appendix A), the life cycle inventories of the waste management unit processes (Appendix B), and the DNDC input data and results (Appendix C) are in the Supporting Information.

Life Cycle Costing was used to determine the stakeholders' profits. The economic models of the waste management unit processes were mainly derived from SWOLF (Solid Waste Optimization Lifecycle Framework),[24] whereas various sources provided the data to estimate the farmers' profits.[25-31] The selected reference year for the economic data related to the waste management and the agricultural subsystems (Appendix D) is 2015.

It was assumed that the waste managers are free to fix a gate price for the compost and digestate between -10 and 10 €·metric ton^{-1}. It is not unusual for European waste managers to pay for the transportation and spreading costs of the organic fertilizers;[32,33] even negative prices have been reported as a measure to incentivize farmers to purchase organic fertilizers.[34] The same minimum gate prices were considered for the struvite and $(NH_4)_2SO_4$ produced by subjecting the liquid digestate to struvite precipitation and ammonia stripping and absorption processes, but their maximum gate prices were calculated as the product of their nitrogen and phosphorus content and the market values of the industrially synthesized $(NH_4)_2SO_4$[35] and $(NH_4)_2HPO_4$,[36] expressed per kg of nitrogen and phosphorus, respectively.

The capital costs of the unit processes available in the current Cantabrian waste management plant (differentiated in Figure 1 with a discontinuous line) and the costs associated with the farmers' equipment and land were assumed to be already amortized. The capital costs of the other unit processes were annualized considering an amortization period of 15 years and a 7% interest rate, consistently with the Spanish banks' lending rates.[37]

A previous study suggested that the GWI related to infrastructure do not constitute a significant fraction of the total GWI of waste management systems,[38] and therefore the GWI of the capital goods were excluded from the analysis.

Another weakness of the model is that DNDC considers that all the phosphorus contained in the organic fertilizers is in a mineral form that the crops can easily take up. Although this is a common supposition,[39] certain studies pinpoint that the products recovered from municipal organic waste contain small amounts of organic phosphorus.[40-42]

- *Game theoretical model*

The Stackelberg game is a sequential game model that makes a distinction between two types of non-cooperative players – the leader and the followers – who do not coordinate their strategies and only seek to optimize their own performance. The leader has the strategic advantage of making the initial decisions knowing how the followers will respond.[43] The Stackelberg game reflects the hierarchical relationships between leaders and followers, and thus it was applied to model the case study; the waste managers were identified as the leaders, who determine the quantities and prices of the produced organic fertilizers, and the farmers, as the followers who decide which product to purchase among the fertilizers available in the market. The waste managers must anticipate that, given the choice between alternative fertilizing products that provide the same function, the farmers will acquire the ones with the lowest associated costs.

Optimization method

The Stackelberg game was formulated as a bilevel optimization problem, in which the upper level problem corresponds to the leader's problem, and the nested lower level problem, to the followers' problem.[44] To solve the bilevel problem, it was reformulated into a single-level problem by means of the Karush-Kuhn-Tucker conditions, which – provided that the lower level problem is convex – transform the lower level problem into a set of constraints appended to the upper level problem.[45]

If the problem included discrete lower level variables, a more complex reformulation algorithm would be required.[46,47] Reformulating the bilevel problem allows the upper and lower level problems to be solved concurrently to attain a Nash equilibrium where none of the players can improve their performance by unilaterally changing their actions; i.e., each player adopts the strategies that optimize their objectives given the actions taken by the other players.[43]

Although the minimization of the GWI of the entire system entails decisions in the upper and lower level problems, given the limited information that the followers have access to, and their more restricted decision-making power, the environmental objective function was considered as one of the leader's goals.[48] To simultaneously optimize the leader's environmental and economic objectives, a multi-objective optimization approach was adopted. Following the ε-constraint method,[49] a set of Pareto-efficient solutions – all of which are better than the others in at least one criterion – was obtained.

PROBLEM STATEMENT

The reformulated single level problem – a single period mixed integer linear program composed of 345,234 constraints, 148,470 continuous variables and 1,597 binary variables – was solved with the CPLEX algorithm[50] in an Intel(R) Core(TM) i7 CPU-4500U of 1.8 GHz and 8 GB of RAM. Setting the absolute optimality tolerance to 0, the computational time varied between 40 minutes and 27 hours, depending on the selected scenario and the defined constraints.

Upper level problem

The leader's profits were calculated as the sum of the annual revenues from the sale of organic fertilizers and the waste management tax paid by the municipalities minus the Total Annual Costs (TAC) of the waste management subsystem. To maximize the waste managers' profits and minimize the total GWI of the CIWMS, the leaders must make decisions on the configuration of the waste management subsystem and the price of the organic fertilizers.

The optimal design of the waste management subsystem is determined by the binary variables that indicate which unit processes integrate this subsystem and the continuous variables that reflect the amount of waste that each unit process handles. As Figure 1 illustrates, only the municipal organic waste that has been source separated is allowed into the solid waste recycling processes (wet thermophilic anaerobic digestion and tunnel or windrow composting); the organic waste that has been mixed with inorganic materials must be sent to the landfill or the grate incinerator, along with the solid rejects of the other unit processes. Hence, the Source Separation Rate (SSR) – the fraction of municipal organic waste that is source separated – was identified as one of the leader's decision variables.

The price of the organic fertilizers was defined as an upper level decision variable that equates the sum of the product of a matrix of binary variables ($y_{p,r}$) and a matrix of parameters within the predefined range of gate prices ($FP_{p,r}$). This formulation allowed us to apply Glover's method[51] to linearize the product of a continuous and a binary variable, ensuring that that the solutions to the optimization problem are global optimums.

The system model relies on the assumption that all the produced organic fertilizers are sold to the regional farmers. This equation limits the amount of produced organic fertilizers (upper level variable) to the total amount of organic fertilizers purchased by the farmers (lower level variable), which is in turn restricted by the fertilization requirements of the regionally grown corn and wheat, quantified in the lower level problem. Nevertheless, the mass balance that connects the waste management and agricultural subsystems constitutes an upper level constraint because the waste managers are the stakeholders in control of the production and sale operations. In addition to the mass and energy balances that describe the waste management subsystem, the upper level problem must satisfy these constraints:

- The waste managers' profits must be positive.
- Different types of composting processes cannot be concurrently integrated into the system.
- Capacity restrictions. The minimal and maximal capacity restrictions of the waste management unit processes are shown in Table S47 of the Supporting Information. The minimal capacity restrictions were set as a requisite for the construction of new infrastructure to avoid the nonlinearities derived from the exponential equations that quantify how the TAC of the waste management unit processes decrease as the annual waste flows that they handle increase.[52-57]

These restrictions enabled us to assume that the incremental changes in the TAC with the incoming waste flows are constant. The validity of this assumption was investigated in Figures S10-S19, which compare the TAC considered in this study with the TAC exponential curves provided in the literature.[55,57]

- New waste management unit processes with the same function as those already present in the Cantabrian waste management plant can only be implemented if the capacities of the previous ones are exceeded.
- In accordance with Directive 1999/31/EC,[58] the amount of landfilled biodegradable waste is limited to 35% of the total biodegradable municipal solid waste produced in 1995.

Lower level problem

The followers, who aim at maximizing their annual profits by reacting rationally to the leader's decisions, are the regional farmers that cultivate corn and wheat. Each farmer is characterized by their geographic location, the type of cereal they grow and the area they have available for crop production. A total of 63 followers were identified, only three of whom harvest wheat. Appendix E compiles the data that describe the farmers' activities, including the road distances from the agricultural sites to the waste management plant and to the two closest fertilizer plants, which are assumed to supply all the industrial fertilizers.

The amount and type of fertilizers purchased by each farmer depend on the chosen fertilization strategy. To account for the fact that the nitrogen/phosphorus ratio in the organic fertilizers (excluding $(NH_4)_2SO_4$) is lower than the proportion of these nutrients required by corn and wheat, three fertilization strategies were defined:

1. Application of industrial fertilizers (NH_4NO_3 and $(NH_4)_2HPO_4$) to satisfy the crop demand for nitrogen and phosphorus. Farmers acquire these products from the nearest fertilizer plant to their fields.
2. Application of organic fertilizers to cover the crop nitrogen requirements. This strategy leads to excess phosphorus in the soil, unless $(NH_4)_2SO_4$ is applied, in which case $(NH_4)_2HPO_4$ must be added.

3. Application of organic fertilizers to supply the phosphorus needed by the crop. To correct the nitrogen deficiency, NH_4NO_3 is provided.

The followers' decisions are reflected by variable $xf_{c,m,p,s}$, which was defined as the amount of each type of fertilizer purchased by each farmer and applied to the soil in accordance with each fertilization strategy. The other variables and parameters involved in the lower level problem are described in the nomenclature section.

The lower level problem was formulated as follows:

$$\max z\left(xf_{c,m,p,s}, y_{p,r}\right) \equiv \sum_{c\epsilon C}\sum_{m\epsilon M}\sum_{p\epsilon P}\sum_{s\epsilon S}\frac{CP_c \cdot Yield_{c,p,s}}{P_{c,p,s}} \cdot xf_{c,m,p,s} \\ -(\sum_{r\epsilon R} FP_{p,r} \cdot y_{p,r} + IFP_{c,p} + sc + tc \cdot Dp_m) \cdot O_{c,m,p,s} \cdot xf_{c,mp,s} \\ -\left(\frac{\sum_{f\epsilon F} CF_{c,f,p,s} \cdot \left(CFP_f + sc + tc \cdot Df_m\right) \cdot O_{c,m,p,s}}{P_{c,p,s}}\right) \cdot xf_{c,m,p,s} - (wc \cdot w_c + lc) \cdot At_{c,m} \tag{1}$$

$$s.t.\ \ h_1(xf_{c,m,p,s}, Aorg_{c,m}) \equiv Aorg_{c,m} - \sum_{p\epsilon P}\sum_{s\epsilon S}\frac{xf_{c,m,p,s}}{P_{c,p,s}} \cdot Vorg_p = 0 \tag{2}$$

$$h_2\left(xf_{c,m,p,s}, Aorg_{c,m}\right) \equiv \\ \sum_{p\epsilon P}\sum_{s\epsilon S} xf_{c,m,p,s} \cdot Vfert_{s,p} - \left(\sum_{p\epsilon P}\sum_{s\epsilon S} P_{c,p,s} \cdot Vfert_{s,p}\right) \cdot (At_{c,m} - Aorg_{c,m}) = 0 \tag{3}$$

$$g_1\left(xf_{c,m,p,s,}, y_{p,r}, Aorg_{c,m}\right) \equiv \\ \sum_{p\epsilon P}\sum_{s\epsilon S} Vorg_p \cdot \left(\sum_{r\epsilon R} FP_{p,r} \cdot G_{r,c,m,p,s} + sc \cdot xf_{c,m,p,s} + tc \cdot Dp_m \cdot xf_{c,m,p,s}\right) \\ +Vorg_p \cdot \frac{\sum_{f\epsilon F} CF_{c,f,p,s} \cdot \left(CFP_f + sc + tc \cdot Df_m\right) \cdot O_{c,m,p,s}}{P_{c,p,s}} \cdot xf_{c,m,p,s} \\ -Aorg_{c,m} \cdot (\sum_{p\epsilon P}\sum_{s\epsilon S} P_{c,p,s} \cdot Vind_p \cdot O_{c,m,p,s} \cdot \left(IFP_{c,p} + sc + tc \cdot Df_m\right)) \leq 0 \quad \forall\, c, m \tag{4}$$

$$g_2\left(Aorg_{c,m}\right) \equiv Aorg_{c,m} - At_{c,m} \leq 0\ \ \forall\, c, m \tag{5}$$

$$g_3\left(xf_{c,m,p,s}\right) \equiv xf_{c,m,p,s} - At_{c,m} \cdot P_{c,p,s} \leq 0 \quad \forall\, c, m, p, s \tag{6}$$

$$g_4\left(xf_{c,m,p,s}\right) \equiv -xf_{c,m,p,s} \leq 0\ \ \forall\, c, m, p, s \tag{7}$$

The objective function was calculated as the annual revenues from the sale of grain minus the annual costs associated with fertilization (including the transportation and spreading of fertilizers), irrigation and labor.

Constraints h_1 and h_2 express that the total surface fertilized by the farmers must equal the area of their respective fields. Constraint g_1 captures the behavior of the followers in the Stackelberg game: if the cost of purchasing, transporting and spreading a given amount of organic fertilizers exceeds the cost of fertilizing the equivalent area with industrial fertilizers, the farmers will fertilize their fields solely with industrial fertilizers. Finally, constraints g_2 to g_4 indicate the upper and lower bounds of the lower level variables.

- *Reformulation of the lower level problem*

The leaders make their decisions prior to the followers, which allows the binary upper level variables that appear in the lower level problem ($y_{p,r}$) to be treated as parameters.[43,45] In the absence of discrete variables, the lower level problem can be replaced by its Karush-Kuhn-Tucker conditions, which are composed of:

- Primal feasibility constraints. These are the lower level constraints: h_1, h_2, g_1, g_2, g_3 and g_4.
- Dual feasibility constraints. They are based on the derivatives of the lower level functions with respect to the lower level variables:

$$\frac{(CP_c \cdot Yield_{c,p,s} - \sum_{f\epsilon F} CF_{c,f,p,s} \cdot \left(CFP_f + sc + tc \cdot Df_m\right) + vorg_p \cdot \mu 1_{c,m}) \cdot O_{c,m,p,s}}{P_{c,p,s}}$$
$$-\left(\sum_{r\epsilon R} FP_{p,r} \cdot y_{p,r} + IFP_{c,p} + sc + tc \cdot Dp_m - vfert_{s,p} \cdot \mu 2_{c,m}\right) \cdot O_{c,m,p,s}$$
$$-\left(\left(\sum_{r\epsilon R} FP_{p,r} \cdot y_{p,r} + sc + tc \cdot Dp_m\right) + \frac{\sum_{f\epsilon F} CF_{c,f,p,s} \cdot \left(CFP_f + sc + tc \cdot Df_m\right)}{P_{c,p,s}}\right) \cdot O_{c,m,p,s} \cdot Vorg_p \cdot \lambda 1_{c,m}$$
$$-\lambda 3_{c,m,p,s} \leq 0 \tag{8}$$

$$\mu 1_{c,m} + \sum_{p\epsilon P} \sum_{s\epsilon S} P_{c,p,s} \cdot Vfert_{s,p} \cdot \mu 2_{c,m}$$
$$-\sum_{p\epsilon P} \sum_{s\epsilon S} P_{c,p,s} \cdot Vind_p \cdot O_{c,m,p,s} \cdot \left(IFP_{c,p} + sc + tc \cdot Df_m\right) \cdot \lambda 1_{c,m} + \lambda 2_{c,m} = 0 \tag{9}$$

The domains of the auxiliary variables used to formulate the dual feasibility constraints are defined below:

$\mu 1_{c,m} \epsilon \mathbb{R}$

$\mu 2_{c,m} \in \mathbb{R}$

$$\lambda 1_{c,m} \geq 0 \;\; \forall\, c, m \tag{10}$$

$$\lambda 2_{c,m} \geq 0 \;\; \forall\, c, m \tag{11}$$

$$\lambda 3_{c,m,p,s} \geq 0 \;\; \forall\, c, m, p, s \tag{12}$$

- Complementary slackness constraints. They indicate that the product of the left-hand side of the inequalities that compose the lower level problem and their associated dual variables must equal 0:

$$\lambda 1_{c,m} \cdot lhsg1_{c,m} = 0 \tag{13}$$

$$\lambda 2_{c,m} \cdot lhsg2_{c,m} = 0 \tag{14}$$

$$\lambda 3_{c,m,p,s} \cdot lhsg3_{c,m,p,s} = 0 \tag{15}$$

$$lhsdfcx_{c,m,p,s} \cdot xf_{c,m,p,s} = 0 \tag{16}$$

Each complementary nonlinear slackness constraint was replaced by two equivalent linear constraints using binary variables and a sufficiently large (or big-M) parameter:

$$\lambda 1_{c,m} \leq y1_{c,m} \cdot M_{c,m} \;\;\; \forall\, c, m \tag{17}$$

$$-lhsg1_{c,m} \leq \left(1 - y1_{c,m}\right) \cdot M_{c,m} \;\;\; \forall\, c, m \tag{18}$$

$$\lambda 2_{c,m} \leq y2_{c,m} \cdot M_{c,m} \;\;\; \forall\, c, m \tag{19}$$

$$-lhsg2_{c,m} \leq \left(1 - y2_{c,m}\right) \cdot M_{c,m} \;\;\; \forall\, c, m \tag{20}$$

$$\lambda 3_{c,m,p,s} \leq y3_{c,m,p,s} \cdot M_{c,m,p,s} \;\;\; \forall\, c, m, p, s \tag{21}$$

$$-lhsg3_{c,m,p,s} \leq \left(1 - y3_{c,m,p,s}\right) \cdot M_{c,m,p,s} \;\;\; \forall\, c, m, p, s \tag{22}$$

$$xf_{c,m,p,s} \leq y4_{c,m,p,s} \cdot M_{c,m,p,s} \;\;\; \forall\, c, m, p, s \tag{23}$$

$$-lhsdfcx_{c,m,p,s} \leq \left(1 - y4_{c,m,p,s}\right) \cdot M_{c,m,p,s} \;\;\; \forall\, c, m, p, s \tag{24}$$

RESULTS AND DISCUSSION

Before proceeding with the multi-objective optimization, the objective functions of the reformulated single-level problem were separately optimized. The maximal profits that the waste managers can earn, and the resulting GWI are represented in Figures 2A and 2C, whereas the profits they would make if their only objective was to attain the minimal GWI (shown in Figure 2D) are displayed in Figure 2B. In order to ascertain the influence of the uncertainty associated with the behavior of the citizens responsible for waste generation and separation on the results, the single objective optimization problems were solved for five SSR intervals (0≤SSR≤0.1, 0.1≤SSR≤0.2, 0.2≤SSR≤0.3, 0.3≤SSR≤0.4, 0.4≤SSR≤0.5); i.e., an optimal SSR was obtained for each interval.

Figures 2A and 2B prove that, regardless of the SSR, the revenues derived from the sale of organic fertilizers are negligible with respect to the waste management tax. Moreover, the costs related to the collection and recycling of the source separated waste increase with the SSR, but the incineration and landfilling costs are reduced.

The trade-off between the GWI of the waste management and agricultural subsystems is evidenced in Figures 2C and 2D. In general, as the SSR increases, the agricultural subsystem is responsible for more GWI because of the greater emissions associated with the transportation, spreading and soil application of the larger mass of organic fertilizers required to fulfill the fertilization needs compared with industrial fertilizers. Nonetheless, the GWI of the waste management subsystem decrease with the SSR because more waste can be processed by the anaerobic digestion and composting technologies instead of incinerated or landfilled

Thus, as Figures 2A and 2D illustrate, the relationship between the SSRs and the optimal economic and environmental objectives could be described with a curve; the optimal profits and GWI are attained with the median SSR (0.25). However, that does not imply that the economic and environmental objectives follow the same trend. Figure 2B shows that the waste managers' profits would drop to nearly 0 if they only pursued a reduction in the GWI. These results provide grounds for the multi-objective optimization.

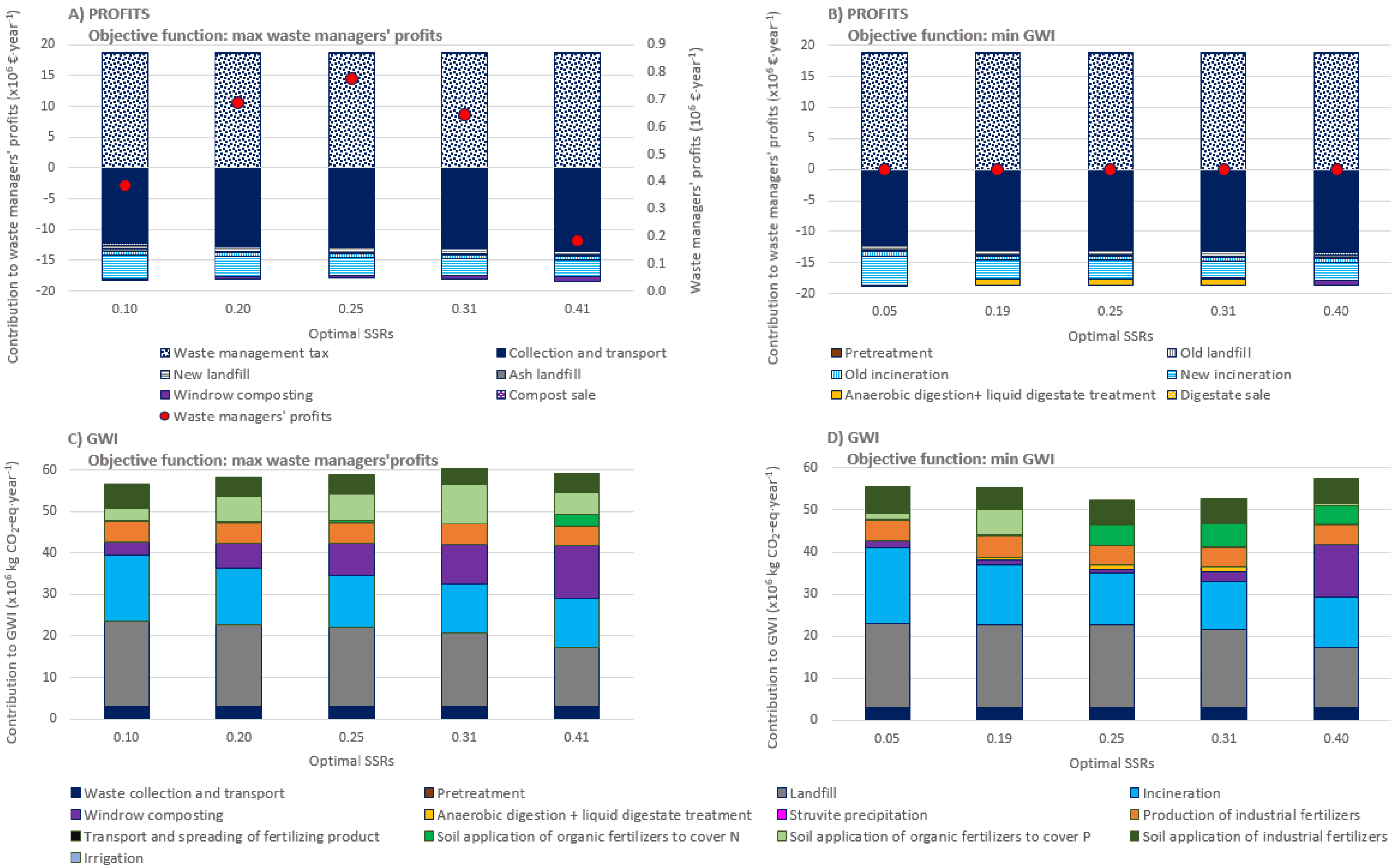

Figure 2. Results of the single-objective optimizations of the leader's objective functions in the reformulated single-level problem for the defined SSR intervals

Figure 3A depicts the Pareto fronts and the prices of the organic fertilizers obtained for two scenarios: i) the decentralized scenario described by the bilevel problem, and ii) a centralized scenario wherein the farmers' economic interests are disregarded. The latter was optimized solving the upper level problem subject to the restrictions of the lower level problem. Both Pareto fronts confirm that the optimal SSR range is 0.2-0.3, and that the improvement in the GWI is accomplished at the expense of the waste managers' profits. The amount of digestate produced is progressively reduced as the restriction on the GWI is relaxed, allowing the waste managers to increase their profits.

The balance between the farmers' and waste managers' economic interests in the decentralized scenario is reflected in the lower prices set for the organic fertilizers (0-2 €·metric ton^{-1} of compost, and 0-1 €·metric ton^{-1} of digestate), whereas in the centralized scenario the waste managers set the maximum prices allowed by the restrictions of the lower level problem. The results of the decentralized scenario are more consistent with the symbolic prices that European farmers usually pay for organic fertilizers.[32-34] The digestate is assigned lower prices than compost to compensate for the larger mass of digestate required to achieve the same fertilizing function, and therefore the digestate transportation and spreading costs are higher than those of compost.

The farmers' better economic performance in the decentralized scenario is accompanied by a reduction in the waste managers' profits and increased GWI with respect to the centralized scenario. This happens because the solutions to the bilevel problem rely to a greater extent on the use of the organic fertilizers to cover the crops' phosphorus requirements, which reduces the amount of $(NH_4)_2HPO_4$ needed. This fertilization strategy is based on the application of NH_4NO_3, a fertilizer that is less expensive than $(NH_4)_2HPO_4$, but also has a higher carbon footprint. Nevertheless, as Figure 3A shows, the relative differences between the leader's economic and environmental objectives in both scenarios are not remarkable. This can be attributed to the small fraction of the revenues due to the sale of organic fertilizers, and to the low contribution of the agricultural subsystem to the overall GWI.

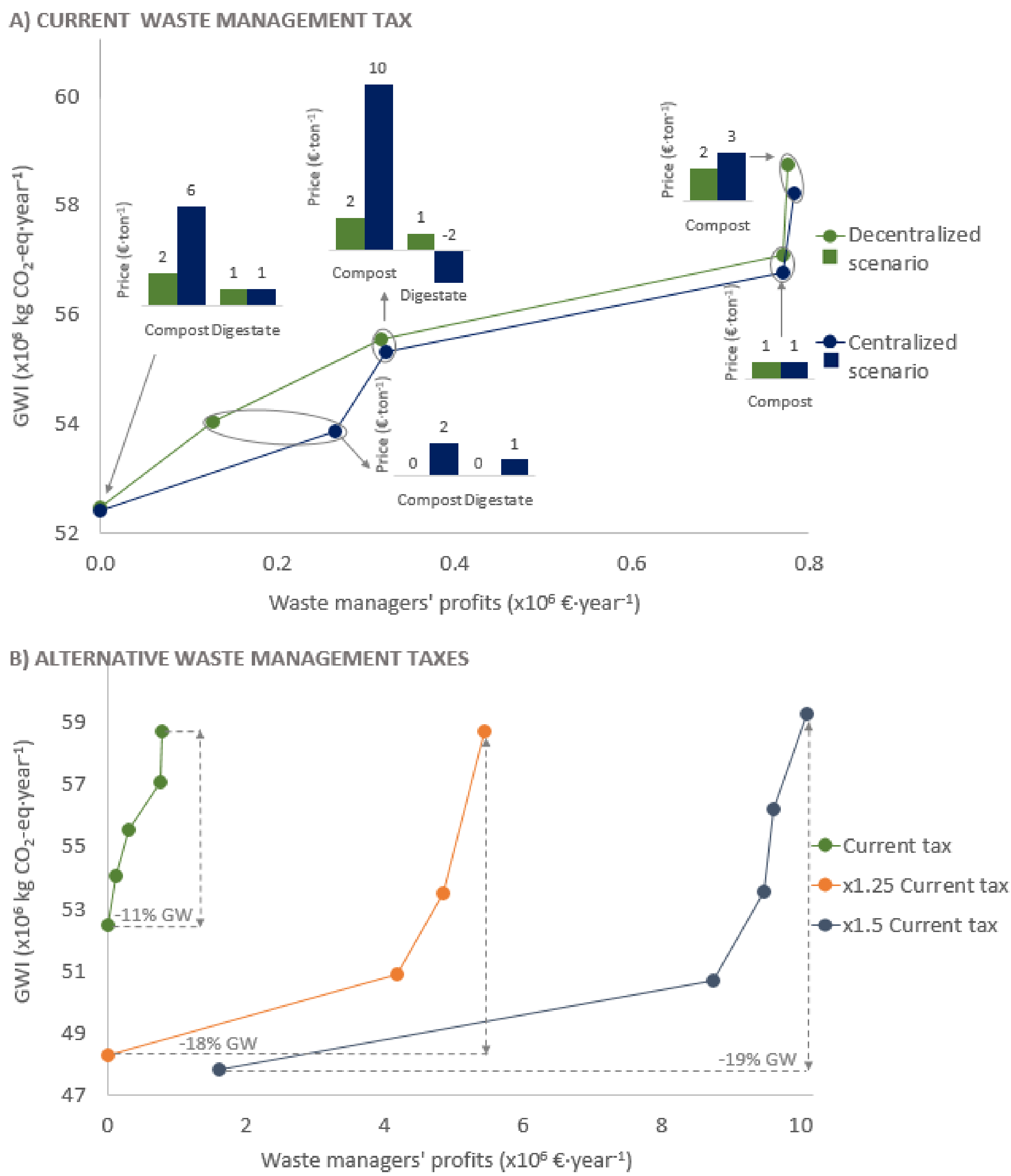

Figure 3. Pareto fronts and prices of the organic fertilizers for the analyzed scenarios

Figures 2 and 3A show that the waste managers' margin for profits and environmental improvement are quite slight. However, the decision-makers can push the Pareto frontier changing some of the fixed operating decisions that act as model parameters. Since the waste management tax is the main source of income to the waste managers and hence it will determine the feasibility of the CIWMS, a sensitivity analysis considering increases of 25% and 50% in the current waste management tax was carried out for the decentralized scenario. The resulting Pareto fronts are presented in Figure 3B.

Raising the waste management tax could bring about reductions of up to 19% in the GWI, which are significant compared with the maximal 11% reduction that can be achieved with the current tax. The reason is that the minimal GWI are no longer limited by the restriction on the minimal profits that the waste managers must make. The rise in the revenues allows the waste managers to implement larger SSRs; the scenarios with the increased waste management taxes attain the minimal GWI based on a 49% SSR, the valorization of all the source separated organic waste in the anaerobic digester, and the ammonia stripping and absorption of the liquid digestate, which enables the sale of $(NH_4)_2SO_4$ for prices between 29 and 43 €·metric ton^{-1}. However, the optimal SSR the waste managers should implement to maximize their profits irrespective of the tax is 25%.

The results of Figure 4 – which indicates the geographic location of the regional farmers and the type of organic fertilizers they purchase –correspond to the Pareto optimal solutions that generate 54x10^{6} kg CO_2-eq·year^{-1} in the decentralized scenario. For all the analyzed waste management taxes, the farmers that purchase the organic fertilizers are located within a 32 km radius around the waste management plant; the farmers located further away opt to purchase industrial fertilizers to reduce the transportation costs. In the scenario with the highest waste management tax, struvite is produced at a price of 58.49 €·metric ton^{-1}. Struvite is the fertilizer sent to the farthest agricultural site because of the lower amount of product required to fertilize the same area relative to the other organic fertilizers.

The individualized recommendations that can be made to the farmers and the waste managers based on these results prove that the integration of life cycle and game theoretical models constitutes an improvement with respect to the existing centralized life cycle optimization frameworks.

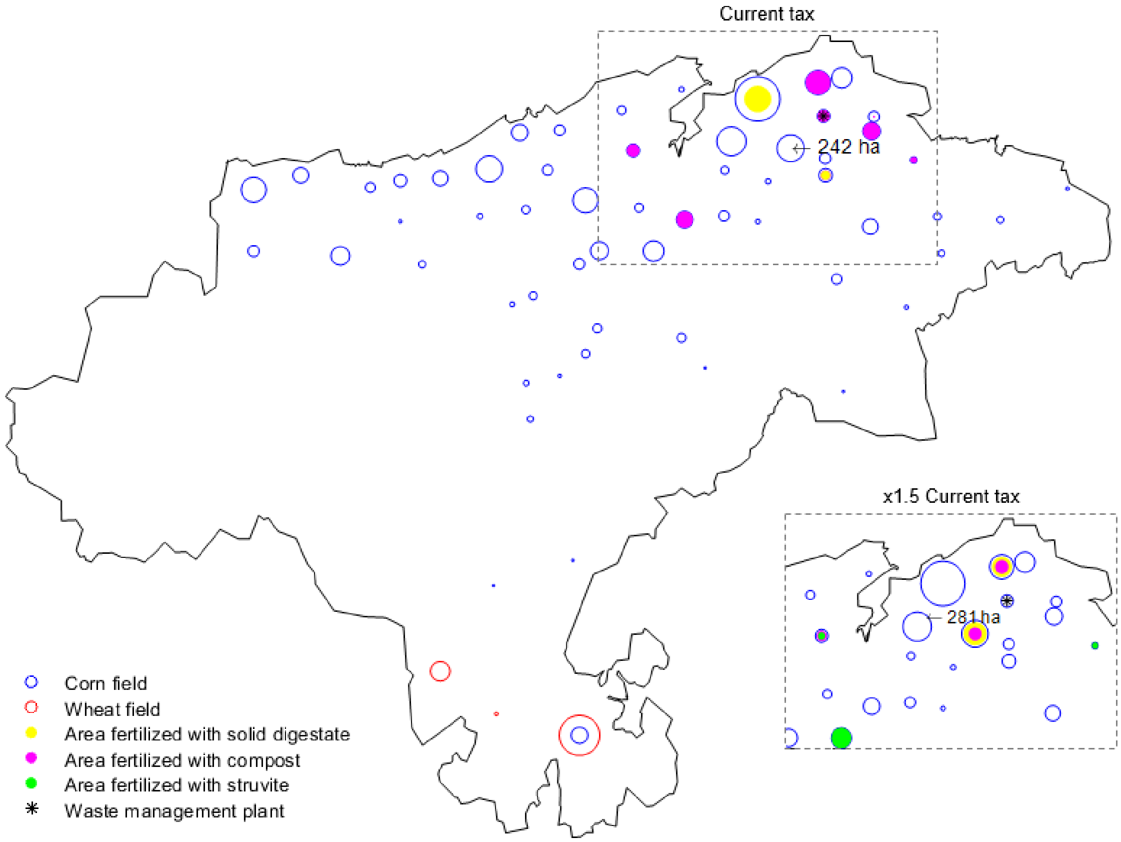

Figure 4. Distribution of organic fertilizers between the Cantabrian farmers for the Pareto solutions that generate 54x10^6 kg CO_2-eq·year^{-1} in the decentralized scenarios with increased taxes. The size of the blank circles is proportional to the area of the field, and the size of the colored circles is proportional to the area fertilized with the organic fertilizers

CONCLUSIONS

The proposed optimization framework allows the analysis of the environmental and economic consequences of the adoption of a circular economy through the lens of all the stakeholders, and the simultaneous optimization of their decisions in accordance with their conflicting objectives.

The results demonstrate that a deviation from the objective of economic growth – understood as an increase in profits – is needed to achieve a reduction in the GWI. To improve the competitiveness of the organic fertilizers in the market, their prices must be set quite low with respect to the industrially produced fertilizers. Therefore, the sale of organic fertilizers constitutes an insignificant source of revenues for the waste managers; without economic incentives that spur the investment in novel technologies, it is unlikely that waste managers will change their mindset and start viewing organic wastes as valuable products.

Moreover, an 11% reduction in the GWI of the system can be achieved at most with the current waste management tax, which suggests that the implementation of a circular economy is not the most effective strategy to combat climate change.

Although these results cannot be extrapolated to other case studies, the developed framework can be adapted to different systems. Future studies should model the behavior of the agents that generate waste, who determine the amount of waste that is source separated and will be affected by the changes in the waste management tax and the cost of staples.

The further improvements and deployment of this framework could bridge the gap between the theoretical concept of a circular economy and its industrial applications, helping policy-makers devise a roadmap to attain a sustainable circular economy.

ABBREVIATIONS

CIWMS	Circular Integrated Waste Management System
GWI	Global Warming Impacts
LCA	Life Cycle Assessment
SSR	Source Separation Rate
TAC	Total Annual Costs

NOMENCLATURE

Sets

C crops

F Industrial fertilizers

M Municipalities

P Fertilizers

R Prices of the organic fertilizers

S Fertilization strategies

Upper level variable

$y_{p,r}$ Binary decision on the price of the organic fertilizers

Lower level variables

$Aorg_{c,m,p,s}$ Area fertilized with the organic fertilizers (ha)

$TFC_{c,m,p,s}$ Total costs related to the purchase, transportation and spreading of the fertilizers (€·ha^{-1})

$xf_{c,m,p,s}$ Amount of each fertilizing product purchased by each follower and applied to the soil in accordance with each fertilization strategy (kg)

Reformulation variables

$\mu1_{c,m}$, $\mu2_{c,m}$, $\lambda1_{c,m}$, $\lambda2_{c,m}$, $\lambda3_{c,m,p,s}$ Continuous variable used to define the dual feasibility constraints

$G_{r,c,m,p,s}$ Auxiliary variable used to apply Glover's linearization method and equal to the product of $xf_{c,m,p,s}$ and $y_{p,r}$

$lhsdfcx_{c,m,p,s}$ Left-hand side of the dual feasibility constraint based on the derivatives with respect to $xf_{c,m,p,s}$

$lhsg1_{c,m}$, $lhsg2_{c,m}$, $lhsg3_{c,m,p,s}$ Left-hand side of constraints g1-g3

$Y1_{c,m}$, $Y2_{c,m}$, $Y3_{c,m,p,s}$, $Y4_{c,m,p,s}$ Binary variables used for the linearization of the complementary slackness constraints

Parameters

$At_{c,m}$ Total fertilized area (ha)

$CF_{c,f,p,s}$ Amount of industrial fertilizers required to complement the fertilization of 1 ha with organic fertilizers ($kg\cdot ha^{-1}$)

CFP_f Gate price of industrial fertilizers ($€\cdot kg^{-1}$)

CP_c Crop price (€·metric ton^{-1})

Df_m Distance from the industrial fertilizer plant to the fields (km)

$Dp_{m,p}$ Distance from the fertilizer production sites to the fields (km)

$FP_{p,r}$ Gate price of fertilizers ($€\cdot kg^{-1}$)

$IFP_{c,p}$ Average gate price of the industrial fertilizers required to fertilize each crop ($€\cdot kg^{-1}$)

lc Labor costs ($€\cdot ha^{-1}$)

$M_{c,m}$ Matrix of large parameters

$M_{c,m,p}$, $M_{c,m,p,s}$ Tensors of large parameters

$O_{c,m,p,s}$ Tensor of zeros and ones indicating the possible combinations of c, m, p and s

$P_{c,p,s}$ Amount of fertilizers required to fertilize 1 ha ($kg\cdot ha^{-1}$)

sc Spreading costs ($€\cdot kg^{-1}$)

tc Transportation costs ($€\cdot kg^{-1}\cdot km^{-1}$)

$TCFC_{c,m,p,s}$ Total costs related to the purchase, transportation and spreading of the industrial fertilizers required to complement the fertilization of 1 ha with organic fertilizers ($€\cdot ha^{-1}$)

$Vfert_{p,s}$ Matrix of ones and zeros indicating the selection of industrial fertilizers

$Vind_p$ Vector of ones and zeros indicating the selection of the industrial fertilizers

$Vorg_p$ Vector of ones and zeros indicating the selection of the organic fertilizers

w_c Water requirements ($m^3 \cdot ha^{-1}$)

wc Water costs (€$\cdot m^{-3}$)

$Yield_{c,p,s}$ Crop yield (metric ton$\cdot ha^{-1}$)

SUPPORTING INFORMATION

Model parameters, DNDC, LCA and Life Cycle Costing results.

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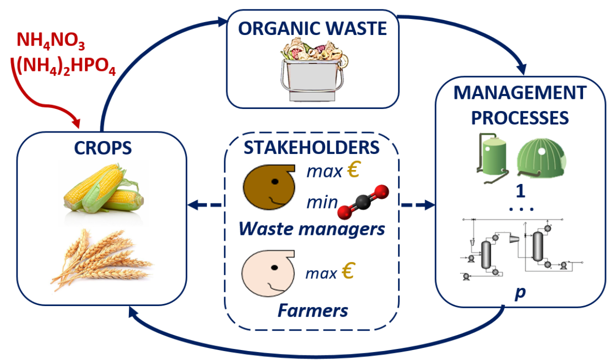

SYNOPSIS

A multi-objective optimization framework integrating life cycle and Stackelberg models was developed to design sustainable circular waste management systems