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Integrating intensive livestock and cropping systems: Sustainable design and location

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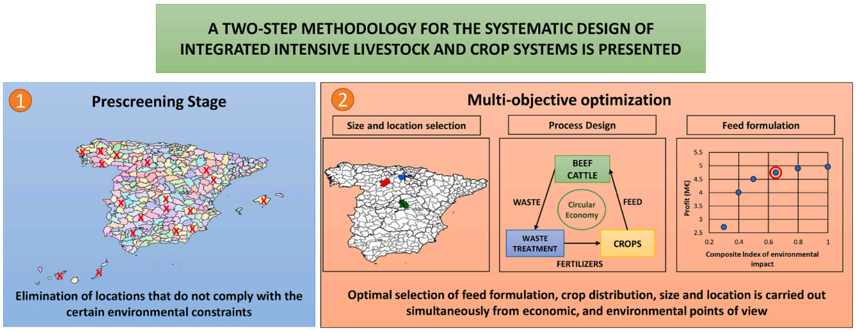
HIGHLIGHTS

- Location is a key factor for the sustainable design of integrated intensive livestock and crop management systems.
- A two-step multi-objective (environmental and economic) and multi-period methodology integrates the location dimension.
- Feed formulation, crop distribution, nutrient recovery, size and the selection of location are simultaneously optimized.
- A farm of 1000 animals, initially, in "Bureba-Ebro" is suggested. Almost half of the locations considered are discarded.
- 35% reduction in environmental impact is achieved through crop distribution that consumes 12% less fertilizer.

GRAPHICAL ABSTRACT



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ABSTRACT

CONTEXT: A mismatch between nutrient demand and consumption in livestock and cropping systems makes these sectors responsible for 24.5% of greenhouse gas emissions. In order to reduce the gap between the two industries, approaches focused on integrating livestock and crop management have been presented. Location is a key factor in the sustainable operation of these integrated systems since this variable affects both the economic and environmental dimensions of the design of the farm.
OBJECTIVE: In this work, a two-step methodology is proposed to address simultaneously the formulation of the feed, the design of the nutrient recovery process, the location of the facilities, and its size, from economic and environmental points of view.
METHODS: First, prescreening is used to discard locations that do not meet a series of environmental constraints. Next, an optimization framework is developed by integrating empirical models that estimate the nutritional needs of the animals, fertilizer consumption, waste production, as well as the effect of selection of locations and the size of the farm on the objective function. The farm is designed to produce the feed on the premises and animal wastes are used to produce fertilizers and biogas, implementing the circular economy. The optimization framework is used to estimate the optimal feed formulation, crop selection, size and location, following a multi-objective approach.

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RESULTS AND CONCLUSIONS: The methodology is applied to a case study in Spain. Of the 345 agricultural districts considered, 145 are discarded in the prescreening. The optimal number of initial animals is 1000. The results show that the selection of 'Bureba-Ebro' and a crop distribution that consumes 12% less nutrients than the economic scenario, results in the reduction of 35% in the environmental impact. In addition, meat production cost is 8.87€/kg (1.6€/kg corresponds to the waste treatment). Nevertheless, it can be reduced down to 1.51€/kg by considering the income from crop sales.

SIGNIFICANCE: Only through this integrated framework it is possible to determine the feed formulation and facility location that best balance the economic and environmental objective, and determines the percentage of nutrients that can be recovered. The methodology is generic enough to be applied to other locations, crops, and animals.

1. Introduction

Livestock and cropping systems represent two of the largest sources of greenhouse gas emissions, accounting for 24.5% of total global emissions (U.S. Environmental Protection Agency, 2021). The decoupling of both sectors has led to a mismatch between sources of nutrients through livestock waste and areas with high requirements of these. This results in nutrient pollution, leading to eutrophication and soil deterioration (Peyraud et al., 2014), as well as a significant carbon footprint due to the extraction, treatment, and transport of mineral fertilizer. Regarding livestock waste, several treatment processes have been proposed, including composting, anaerobic digestion (Loyon, 2017), and nutrient recovery (Martín-Hernández et al., 2021). Nevertheless, the cost associated with these processes, as well as the transportation of the products from livestock areas to crop areas, can be economic and environmental bottlenecks for the sustainable use of these wastes. (Makara and Kowalski, 2018; Case et al., 2017).

With the aim of bridging the gap between the two industries, approaches focusing on the integration of livestock and crop management have been presented. These integrated systems have several advantages beyond reducing transportation costs, such as increasing crop yields and nutrient use efficiency, as well as decreasing total greenhouse gas emissions, and maintaining soil quality (Moraes et al., 2014). All these advantages are aimed at promoting the circular economy of waste and achieving zero waste emission. However, most of these studies have focused on extensive livestock farming (Sulc and Franzluebbers, 2014; Bell et al., 2014) when the real problem lies in intensive livestock farming (Tullo et al., 2019). While extensive farming has several advantages over intensive farming (preservation of the natural environment, ecosystem, government support, less environmental impact, and resource consumption), it has an important disadvantage, its productivity. As a result, the food generated by this type of farming is more expensive than intensive farming, requires a higher land use and more labor (Novikova and Startiene, 2018). Therefore, intensive farming is necessary to supply food in an economically sustainable way to a growing population. Authors, such as Taifouris and Martin (2021) have addressed this type of integration for intensive livestock farming. Through models for estimating energy and nutritional requirements, waste treatment, nutrient recovery, and crop management, it is possible to determine the optimal feed formulation for the animals, the required crops, as well as the operating conditions of the waste treatment process, and the optimal formulation of fertilizers. By establishing a multi-objective approach, these models suggest an optimal solution that is a trade-off between the economic and environmental optimums. However, the proposed design misses the effect of localization of the facility.

Location is a key factor since it determines the growing yield of the crops, through climate and soil characteristics (Liliane and Charles, 2020; Mechiche-Alami and Abdi, 2020). In addition, the location selected also determines the availability and cost of the land and water. These parameters affect both the economic performance and the environmental impact of the farm. The design of the product (feed), the process (waste treatment and nutrient recovery) and the selection of the location are closely related and synergistic. Depending on the location, the crops with the highest production yields in that agricultural district are selected, favoring some feed formulas over others. In the same way, the process design depends on the composition of the residues (Weinrich and Nelles, 2015) and that is a function of the feeding of the animals (Council, 2000). In addition to the parameters related to the economic aspects of the farm, there are environmental constraints (nitrate vulnerable zone, natural parks, and water scarcity) that limit the location of this type of facility. Integrated product and process design and, ultimately, three-dimensional concurrent engineering (3DCE) have proven to be the most efficient way to design production systems (Ellram et al., 2007). However, its application has been rather limited and focused on the chemical industry, (Gani, 2004; Martin and Martinez, 2013; Bernardo and Saraiva, 2005), leaving the food industry with a limited number of studies, (Almeida-Rivera et al., 2007), and even less in the case of animal feed (Csikai, 2011). Therefore, the development of a methodology to systematically select the best feed formulation, crops, process conditions, size, and locations is paramount to globally address the design of livestock-cropping systems. To the best of the knowledge of the authors, the integrated design of the animal feed, and waste treatment process together with the selection of optimal size and location for this type of facility has not been addressed in the literature.

Therefore, this work presents a methodology that aims to simultaneously select the optimal number of animals, the annual crop distribution, the properties of the nutrient recovery process, as well as the location of the facilities. This methodology is implemented through a multi-objective (economic and environmental) and multi-period mathematical optimization model. This model determines the operating costs, income, amount of each crop, and environmental indexes, as well as other data of interest, such as the cost of waste treatment with respect to the cost of meat. Besides, it is generic enough to be easily applied to any set of locations, crops, and animal types. The rest of the paper is organized as follows. In Section 2, the methodology is developed including a description of the problem, the reference framework used as starting point, and the main modifications introduced in this work. The solution procedure is also included in this section. In Section 3, the model is applied to a case study in Spain and the results are shown. Finally, in Section 4, the conclusions are presented.

2. Framework development

2.1. Description of the problem

This work addresses the integrated design of an intensive beef cattle farm and the cropping system, as well as its location and size, analyzing a set of variables that influence both the environmental impact and economic performance of the farm. The conceptual idea of the integrated system is shown in Fig. 1.

The farm is designed to produce the feed necessary for the animals on the premises. Therefore, the design of the cropping system is performed by estimating the area needed, for the amount of crop required, using experimental yields. These yields are estimated from technical reports published by governments every year collecting agricultural results and are based on average values ((Ministerio de Agricultura, 2019)). The amount and type of crop are set by the nutritional and energy requirements of the animals. Several studies have been used to establish experimental relationships between these requirements and the age, weight, sex, and life stage of the animals. This allows estimating the variation in feed composition, as well as crop distribution, throughout the animal's life cycle. These correlations are widely known and can be consulted in the supplementary material. In addition, there are also empirical models that determine the degradation of feed in the digestive process of ruminants (Council, 2000), allowing to estimate the composition of residues as a function of feeding. These correlations, yields, and mass balances have also been included in the supplementary material. The food that is not used as animal feed is sold as a by-product (only barley and wheat since the rest of the crops are either fully fed or have no market value (Taifouris and Martin, 2021)). In addition, the manure is treated to produce biogas and digestate through an anaerobic digestion system. This process is modeled using stoichiometric relationships from the protein, carbohydrate, and lipid composition of the manure, experimental kinetics, and biodegradability yields, following the work of Taifouris and Martín (2018). Nitrogen, potassium, and phosphorous are recovered using a combined mechanical and membrane separation system. The nutrients recovered are estimated with empirical yields obtained from the literature (Martín-Hernández, 2022). Location is integrated through a series of parameters related to environmental and economic aspects. Some of these are used directly to discard locations (protected areas, nitrate vulnerable zone, natural parks, etc.) while others (crop yields, soil and water availability, land rental prices, etc.) affect the objective function of the optimization model. It is worth highlighting, that the model is multi-objective account for trade-off between the economic and environmental performances. Rather, the model is also multi-period, because the optimization variables are evaluated over 240-time units (20 years).

The solution of this model allows for the simultaneous design of the feed formulation, the waste treatment process, the nutrient recovery system, and the crop distribution, as well as, the location and the size of the facilities.

2.2. Optimization framework

For the development of the optimization framework, previous work (Taifouris and Martin, 2021), that integrates most of the models described in Section 2.1, such as models for estimation of nutritional and energy requirement, crops yield, nutrient recovery and fertilizer consumption, is taken as a starting point. These models are detailed in the supplementary material. Nevertheless, several important modifications are required to account for the selection of the location and to increase the realism of the work of Taifouris and Martin (2021). These modifications are the introduction of population groups that grow simultaneously over time, a longer time horizon, a new technology for nutrient recovery, and the integration of the location as a new dimension of the model. The integration of the different locations is expected to increase the size and complexity of the reference model. Therefore, a profound reformulation of the previous models must be performed to solve it.

2.2.1. Integration of the location

The location is integrated by analyzing the parameters that can affect the operation from economic and environmental points of view. The integration is performed at two levels. On the one hand, a set of environmental constraints (i.e. protected natural areas, nitrate vulnerable zones, and water scarcity) are used to discard locations previously to solve the optimization model. On the other hand, another set of parameters (price, yield, and availability of land and water) is added to the model affecting both environmental and economic objectives. Besides, binary variables are defined to select the location and the type of crops (rainfed or irrigated). In each agricultural district, up to 10 crops (wheat, barley, barley forage, corn, corn forage, oat, rye, sorghum, alfalfa, and vetch) can be selected. Nevertheless, only one of the possible locations is selected.

Thus, the reference framework is converted from nonlinear programming (NLP) problem to a mixed-integer nonlinear programming (MINLP) problem. A large number of locations are expected to be considered, making the model too complex to be addressed directly. Therefore, reformulation is necessary to transform it into a mixed-integer linear programming (MILP) problem. This reformulation is explained in Section 2.2.3.

2.2.2. Time horizon and animal population groups

In the reference work (Taifouris and Martin, 2021), not only the time horizon is limited to 5 years, but also all the animals grew at the same time. In this work, the time horizon is extended up to 20 years, and there are animal population groups, of different ages, growing simultaneously, increasing the realism of the farm model. Each group is formed by those calves that have the same date of birth, constituting a group in which all animals have the same age. It is possible to estimate the age and the number of the animals in each group, as well as the total number of groups as a function of the life cycle of the farm, before solving the optimization model. For this purpose, it is necessary to consider that each cow can have 3 calves and whose births occur in the time unit (TU) 36, 54, 72 of the animal life cycle (Taifouris and Martin, 2021). Females have a life cycle of 72 TU (each TU is equivalent to 24 days to match digester operating time), in contrast to males which are slaughtered in

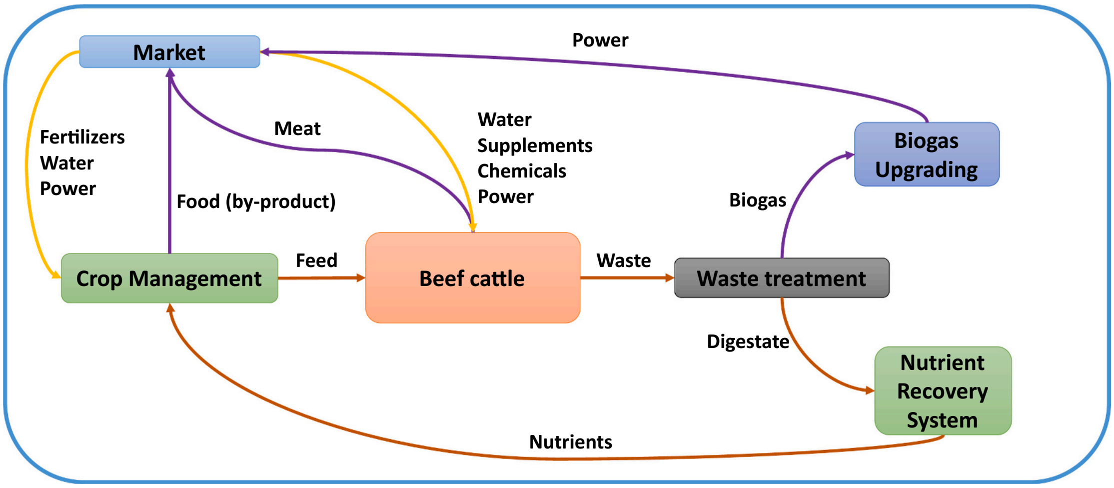


Fig. 1. Diagram of an integrated system of intensive livestock and cropping system.

the 22 TU. In the last year of the farm operation, all animals are slaughtered. In addition, it is important to consider that the farm starts with yearlings of 12 TU of age. There are 26 population groups in total along the 20 years. With this information, the groups can be modeled outside of the optimization framework and added as parameters. Therefore, the interval, the number of animals in each group, and the age are known before solving the optimization model. The Gantt chart of different groups can be seen in Fig. S.1 in the supplementary material.

The analysis of the animal population groups is important to estimate the animal's requirements and the production of waste per TU. It is necessary to completely reformulate the model to integrate these distributions and to apply all calculations to each population group, considering the time gap between them. To do this, the variables related to nutritional and energy needs, as well as waste production have a new dimension called 'group' (see Sections 1 and 2 of the supplementary material). For each group, these variables have a value other than 0 when the time unit of the farm is within the life cycle of that group and 0 otherwise.

2.2.3. *Updated estimation of dry matter intake and offline calculation*

The integration of locations, especially in cases where the number of these is high, together with the increase of the time horizon and the integration of population groups, make the model larger and more complex. Thus, it is necessary to reformulate the original model to transform it into a mixed-integer linear programing (MILP) problem. In the reference model, there are several non-linear correlations that complicate the problem. The most important non-linear correlation is used to estimate the dry matter intake per day (DMI). It depends on the weight of the animal and the net energy for maintenance (NEMA) content of the feed (Council, 2000). Since the weight of the animal at the beginning of each of the gestation and calving is fixed through experimental data (Council, 2000), the daily weight gain of the animal is known (see Eq.(*S*.2)-(S.4) in the supplementary material). Therefore, the weight of the animals in each TU and in each population group can be introduced into the model as a parameter. In the same way, the NEMA of each ingredient is also known (see Table S.6 of the supplementary material). Using this information, it is possible to calculate the DMI per type of ingredient 'j' ($\text{DMIf}_{j,t}$) and per TU 't'. Next, the dry matter intake using the feed ($\text{DMI}_{t,group}$) can be calculated using Eq.1, where $x_{t,j,group}$ represents the formulation of the feed. This equation is linear.

$$\text{DMI}_{t,group} = \sum_{j} x_{t,j,group} \cdot DMIf_{j,t} \quad \forall \text{t, group} \tag{1}$$

In addition, there is a set of variables formed by the total weight and daily weight gain, energy required, the protein required, milk produced (if lactating), and energy consumed in pregnancy (if pregnant) that can be estimated separately from the main model. This is because these variables depend only on the weight of the animal and, therefore, they can be included as parameters. Following these changes, the model is completely linear.

2.3. *Solution procedure*

The solution procedure is performed in two stages. A prescreening and a multi-objective approach to select the feed formulation, crop distribution, size of the farm, and its location.

The prescreening is used to discard those locations that do not meet the following set of environmental restrictions:

- Protected natural areas: The agricultural districts where the national park (Ministerio de transición ecológica y de reto demográfico, 2021c), Red Natura 2000 (Ministerio de transición ecológica y de reto demográfico, 2021a), or protected landscape (Ministerio de transición ecológica y de reto demográfico, 2021b) cover an extension of the territory greater than or equal to 50%, are discarded. This percentage was selected because it is assumed that the rest of the area is large enough to locate the farm without affecting the protected area. However, the framework is flexible so that this value can be easily modified without significantly affecting the methodology presented in this work.
- Nitrate vulnerable zones: All water bodies that exceed a nitrate concentration of 50 mg/l are considered to be 'Nitrate vulnerable zones' (Ministerio de la presidencia, relaciones con las cortes y memoria democrática, 1996). It is not possible to locate the farm in those agricultural districts where these zones (Ministrerio de transición ecológica y el reto demográfico, 2021) coincide with irrigating crops or where these exceed 50% of districts with rainfed crops.
- Water scarcity: The amount of water used for irrigation is limited in each place according to the hydrological plan. By consulting these documents (Ministerio para la transición ecológica y reto demográfico, 2021), it is possible to establish a maximum limit on water consumption. It is assumed that only 1% of the resources currently dedicated to cropping and livestock systems can be used. These limits are established by provinces.

The software 'Arcmap' (Esri, 2015) together with data from the literature presented above are used to represent and estimate the area occupied by the protected and vulnerable zones in each agricultural district. Thus, it is possible to verify whether the agricultural districts meet the constraints.

Once the districts where farms cannot be installed have been filtered out, the next stage which consists of applying the optimization framework over the rest is performed. The solution determines the size of the farm, the best composition of feed, and the location as well as the requirements of cultivation area, the waste treatment, and the nutrient recovery processes. The models that are included in the optimization framework are shown in Fig. 2. The equations that constitute each of the models can be found in the supplementary material. All these equations are introduced into the optimization model as constraints. Most of them correspond to mass and energy balances, as well as empirical correlations and yields. These models are used to simulate each of the processes described in Section 2.1. In addition to the equations, the optimization model requires information on the fertilizer requirement of the crops (Table S.5), nutritional and energy properties of the crops (Table S.6), water availability and price (Table S.8), land rental price (Table S.9), the available rainfed (Table S.10) and irrigated (Table S.11) area. The production yields in both types of land are given in Tables S.12 and S.13. All this information can be found in the supplementary material.

As the optimization framework is multi-objective, the ϵ-constraint method (Mavrotas, 2009) is used to account for both the economic and environmental dimensions of the problem. The objective function used profit (Pro) as an economic indicator (Eq.2), while the environmental impact is introduced in the model as an additional constraint, limiting its value. This is quantified by simultaneously considering the effect of the farm on the atmosphere, soil, and water consumption, through a composite index that is explained at the end of this section. All prices used in the economic evaluation correspond to the latest annual average prices published in the literature.

$$\begin{aligned}\text{Pro} = \quad & In_{Mt} + In_{Crp} + In_{Bio} - Cst_{Crop} - Cst_{Field} - \\ & Cst_{Fertilizer} - Cst_{Storage} - Cst_{Labor} - Cst_{Aux} - Cst_{WasteT}\end{aligned} \tag{2}$$

The income from the sale of meat (In_{Mt}) is calculated by analyzing the price of the animal (which depends on sex, age, and weight of animals), the meat yield per animal (Huerta-Leidenz et al., 2013), and the number of animals produced in 20 years (which can be estimated from the procedure shown in Section 2.2.2).

Nutritional models (see Section 2.1 and supplementary material) adjust the amount of crop needed for the animals. Nevertheless, it is necessary to generate the entire crop to produce certain ingredients. This is the case for barley or wheat straw, which require producing both straw and grain. If the model does not select both for animal feed, one of them (grain or straw) can be sold. Therefore, 4 types of ingredients

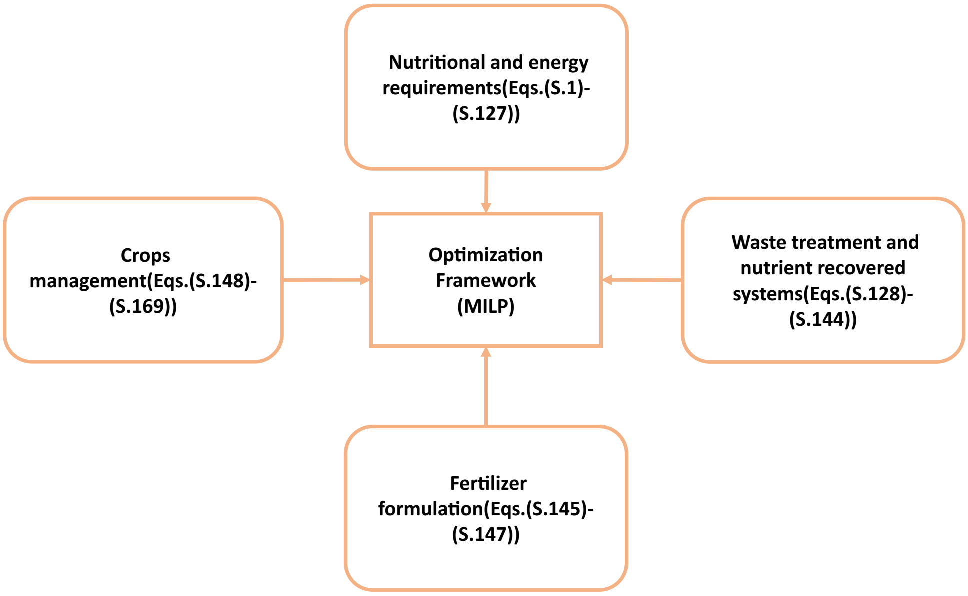


Fig. 2. Optimization framework.

(barley straw, barley grain, wheat straw, and wheat grain) are considered for sale, and the model selects the destination of the crop. Income from crop sales (In_{Crp}) depends on the amount of barley and wheat destined to be sold. The rest of the crops are either fed entirely to the animal, or their straw has no market value. As biogas is used to produce power, its heat of combustion (HC), the yield of biogas to produce power (yd), and the price of power (Pr_{power}) are used to estimate its income (In_{Bio}), following Eq.3. The amount of biogas produced can be estimated (Amt_{biogas}) from the waste treatment (see Section 2.1 and supplementary material) by using mass balances.

$$\mathrm{In_{bio}} = \mathrm{Amt}_{biogas} \cdot \mathrm{yd} \cdot \mathrm{Pri_{power}} \cdot HC \tag{3}$$

Regarding costs, they are either estimated using amounts or areas. The cost of land (Cst_{Field}) and labor (Cst_{Labor}) depend on the area cultivated. This is shown in Eq.4–5.

$$\mathrm{Cst_{Field}} = \sum_{l}\sum_{j}\sum_{year} \mathrm{PriS}_{\mathrm{Rent}_l} \cdot \mathrm{AreaS}_{j,l,year} + \mathrm{PriR}_{\mathrm{Rent}_l} \cdot \mathrm{AreaR}_{j,l,year} \tag{4}$$

$$\mathrm{Cst_{Labor}} = \sum_{j,l,year} \mathrm{Pri_{MP}} \cdot \left(\mathrm{AreaS_{j,l,year}} + \mathrm{AreaR_{j,l,year}}\right) \tag{5}$$

Where $AreaS_{j,l,year}$ and $AreaR_{j,l,year}$ are the area occupied by crop 'j' (rainfed or irrigated crops) at location 'l' in year 'year'. $PriS_{Rentl}$ and $PriR_{Rentl}$ are the rental prices of rainfed and irrigated crop fields, respectively, at location 'l'. Pri_{MP} is the price of labor. These areas are determined according to the amount of crop selected as well as its production yield (kilogram per hectare). The cost of fertilizer ($Cst_{Fertilizer}$), storage ($Cst_{Storage}$), auxiliary costs (Cst_{Aux}), and waste treatment costs (Cst_{WasteT}) depend on the amount of fertilizer needed, crop stored, chemicals used (including water and supplements), and residues treated, respectively. These costs are calculated by Eq.6–9.

$$\mathrm{Cst_{Fertilizer}} = \mathrm{Amt_N} \cdot \mathrm{Pri_N} + \mathrm{Amt_P} \cdot \mathrm{Pri_P} + \mathrm{Amt_K} \cdot \mathrm{Pri_K} \tag{6}$$

$$\mathrm{Cst_{Storage}} = \mathrm{Pri_{storage}} \cdot \left(\sum_{\mathrm{t}}\sum_{group} \mathrm{DMI_{t,group}}\right) \cdot \frac{\mathrm{LC_{farm}}}{\mathrm{LC_{silo}}} \tag{7}$$

$$Cst_{Wtre} = \sum_{group}\sum_{t} \mathrm{WAS}_{\mathrm{t},group} \cdot CstUw \tag{8}$$

$$\begin{aligned} \mathrm{Cst_{aux}} = {} & \mathrm{Amt_{supP}} \cdot \mathrm{Price_{supP}} + \mathrm{Amt_{supCa}} \cdot \mathrm{Price_{supCa}} \\ & + Cst_{waterAgry} + Cst_{waterLiv} \end{aligned} \tag{9}$$

Where Amt_N, Amt_P, and Amt_K are the amount of fertilizer used to provide the nitrogen, phosphorus, and potassium required by the crops selected to produce the feed, and PriN, PriP, and PriK represent their respective prices. $DMI_{t,group}$ is the daily dry matter intake of the animals, LC is the life cycle of the farm and storage facilities, and $Pri_{storage}$ is the storage price. $WAS_{t,group}$ represents the daily amount of waste generated, while CstUw is the unit cost of manure treatment. Amt_{supP} and Amt_{supCa} are the amount of phosphorus and calcium supplements needed to meet the nutritional requirements of the animals. $Price_{supP}$ and $Price_{supCa}$ are the prices of these supplements. $Cst_{waterAgry}$ and $Cst_{waterLiv}$ are the cost of irrigation water and the cost of feed water, respectively. These costs are estimated by Eq.(10)–(11).

$$\mathrm{Cst_{waterAgri}} = \mathrm{CstU}_{\mathrm{waterAgri}_l} \cdot \mathrm{CAA}_j \cdot AreaR_{l,j,year} \tag{10}$$

$$\mathrm{Cst_{waterLiv}} = \mathrm{Wa_{Animal}} \cdot \mathrm{NA}_{\mathrm{Animals}_{\mathrm{group}}} \cdot \mathrm{lt_{Animal}} \tag{11}$$

Where $CstU_{waterAgri}$ is the unit price (€/m^3) of irrigation water, CAA_j is the annual water consumption of the crop 'j' and $AreaR_{l,year}$ is the cultivation area of the irrigated crop 'j' in the region 'l' en the year 'year'. Wa_{Animal} is the water consumption of the animals (calves, yearlings, or cows), $\mathrm{NA}_{\mathrm{Animal}_{group}}$ is the number of each type of animal in each group, and lt is the lifetime of each animal. Cst_{Crop} is the cost associated with feeding the animals (only tillage, sowing, and harvesting of the used crops) to grow the animals from birth to slaughter. This cost is estimated by Eq.12

$$\mathrm{Cst_{Crop}} = \sum_{group}\sum_{\mathrm{t=1}}^{\mathrm{t=240}} \mathrm{DMI_{t,group}} \cdot \mathrm{Cs}t_j \cdot x_{t,j,group} \cdot \mathrm{NA}_{\mathrm{animal}_{group}} \tag{12}$$

Where Cst_j is the cost of production of each crop and $\mathrm{NA}_{\mathrm{animal}_{group}}$ is the number of animals (calves, yearlings, or cows, depending on the life cycle of the animal) in each group, that can be estimated following the procedure shown in Section 2.2.2. $x_{t,j,group}$ is the fraction of the crop 'j' in the DMI for each TU 't' and for each group.

These costs as well as the previous ones are fixed by the size of the farm, its location, and crop selection. To meet specific nutritional requirements, which are set by the model explained in Section 2.1 and shown in the supplementary material, different crops (type and amount) can be used. They consume different amounts of fertilizer (see Table S5 of the supplementary material) and have different production yields (see Table S12 and S13 of the supplementary material) determining the area occupied. The composition of the selected crops does not only affect the amount and composition of the residues, but also the amount of supplement to be added. Therefore, the determination of both costs and income is carried out in conjunction with the rest of the models explained in Section 2.1 (see Fig. 2). The procedure for the calculation of each of these terms is explained in detail in the supplementary material (Eqs. (S170)–(S189)).

Regarding the environmental impact, a composite index (CI) is presented to estimate the impact of the facility on the atmosphere (global warming potential (GWP)), soils and water bodies (eutrophic potential (EUi)), as well as the water footprint (WF) of both animals and crops. This is introduced into the model through Eq. (13).

$$\mathrm{CI} = \sum_{x} \omega_x \cdot In_x \quad \forall \mathrm{x} \ \ \mathrm{x} \in \{\mathrm{GWP}, \mathrm{EUp}, \mathrm{WF}\} \tag{13}$$

Where ω_x is the weight of each contribution and In_x are the normalized indexes. These weights are estimated based on the literature (Sala and Cerutti, 2018) and the indexes are standardized, with the min-max method (OECD & European Commission, 2008) using Eq. 14. The unit value ($\mathrm{Iu}_{x,f}$) of the indexes 'x' for each type of fertilizer 'f' can be found in Table S.2 of the supplementary material. The indexes corresponding to the GWP and EUi are calculated by Eq. 15, while the index corresponding to WF is calculated by Eq. 16.

$$In_x = \frac{I_x - min(I_x)}{max(I_x) - min(I_x)} \quad \forall \mathrm{x} \ \ \mathrm{x} \in \{\mathrm{GWP}, \mathrm{EUp}, \mathrm{WF}\} \tag{14}$$

$$I_x = \sum_{f} \left(Iu_{x,f} \cdot AmtF_f \right) \quad \forall \mathrm{x} \in \{\mathrm{GWP}, \mathrm{EUp}\}, \forall \mathrm{f} \in \left\{ \mathrm{NH_4NO_3}, \mathrm{Ca(H_2PO_4)_2}, \mathrm{K_2SO_4} \right\} \tag{15}$$

$$I_x = \sum_{j} \left(A_j \cdot AmtUW_j \quad + AmtC_j \cdot WFC_j \right) \quad \forall \mathrm{j}, \mathrm{x} \in \{\mathrm{WF}\}, \tag{16}$$

Where AmtF_f and AmtC_j are the amount of each type of fertilizers 'f' and crops 'j', respectively. AmtUW_j is the amount of water per unit of area of each irrigated crop 'j' and WFC_j is the water footprint of each rainfed crop 'j' (see Table S.5 and S.3, respectively, in the supplementary material). For more details on the evaluation of the indexes and their integration into the model, see the supplementary material.

3. Results

The methodology described in Section 2 is applied to a case study formed by 345 locations, corresponding to the agricultural districts in Spain. They can be seen in Fig. 3.

First, the prescreening discards the agricultural districts following the constraints described in Section 2.3. A total of 145 districts are discarded. Subsequently, the multi-objective approach determines the size of the facility, its location, and the crop distribution by looking for a trade-off between economic profit and environmental impact. At this point, the distributions of crops and animals are also analyzed to establish relations between them. The model is an MILP with 6 million equations and 5.3 million variables (36 thousand binary variables). It is solved using CPLEX (GAMS) in an Intel Core i7–7700 computer at 3.6 GHz.

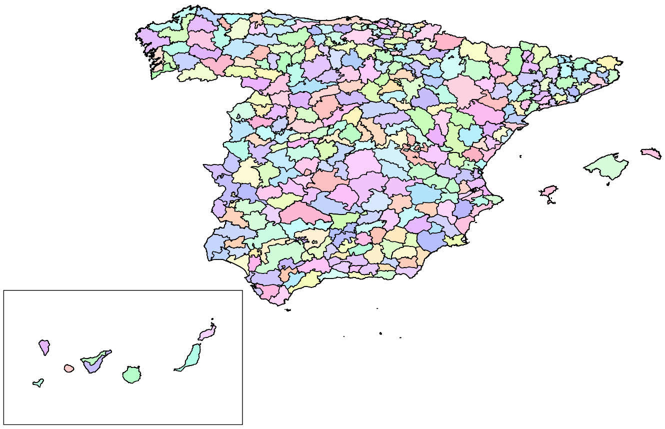


Fig. 3. .-Agricultural districts in Spain.

3.1. Selection of the size and location of the farm

A sensitivity multi-objective analysis is performed to determine the optimal initial number of animals and the farm location. Profit is used as an economic indicator and the composite index as an environmental impact indicator. Therefore, the variation of profit for different values of CI, farm size, and locations are analyzed and shown in Fig. 4. It is assumed that up to 10% of the total available area in each agricultural district can be used. This value was set so there is sufficient area for an intensive livestock facility (more than 1000 animals living in the facility) and at the same time be a conservative and realistic value. However, this value can be easily changed depending on the specific characteristics of each case study. The composite index is calculated by using of minimum value of GWP, EUi, and WF of the smallest facility of each location and the maximum values of these indexes of the largest possible facility in each agricultural district. After applying the optimization, there are 3 locations suitable for the installation of the farm, 'Campiña','Bureba-Ebro', and 'Campos'.

In addition, the crop production is also evaluated against the initial number of animals (Fig. 5) to determine the reason for the difference in profit and composite index between the locations considered.

Fig. 4 shows that 'Campiña' is the best option with respect to profit when the number of initial animal units is small (less than 450), while the district 'Campos' is the only option when the number of animals is larger than 1400. 'Bureba-Ebro' is the district with the highest profit from 500 animals, but it has a size limit of 1400 animals. From this point, the area of cultivation to produce feed is insufficient and this district cannot be chosen.

'Bureba-Ebro has the point of highest possible profit considering all the agricultural districts (i.e 1200 initial animals). However, analyzing profit together with the composite index of environmental impact, it can be observed that there are points with similar profit but with a larger difference in the value of CI. For instance, the point corresponding to 1200 animals, with a composite index of 0.307, has a benefit of 4.95 M€, while in the case of 1000 animals, there is a scenario with a similar profit (only 1.6% lower) but with an environmental impact 18.56% lower. The same occurs with other points corresponding to the cases of 1000 and 1200 animals. Nevertheless, in the rest of the scenarios, the points are farther away from each other. For this reason, it is considered that the size that best balances both objectives (economic and environmental) is the initial 1000 animals.

By analyzing Fig. 5, it shows that the main crop is barley for the three agricultural districts. In addition, this crop is also the most produced for any size of farm. Therefore, those districts that have a higher yield to produce this crop have lower operating costs and lower environmental impact to produce the same amount of barley. Of the three districts considered, 'Campiña' and 'Bureba-Ebro' have a similar yield to produce barley straw (see Table S.13 of the supplementary material). However, this yield in 'Campos' is 1.52 times lower than in 'Bureba-Ebro' and 'Campiña' (1.8 t/ha vs 2.8 t/ha). This means that an increase in the cultivation area is required to produce the same amount of barley, which in turn results in an increase in the costs related to the area and fertilizer consumption. This explains the large difference in profits between this location and the others. The difference between 'Campiña' and 'Bureba-Ebro' lies in the cost of the land, being 2.63 times cheaper in 'Campiña' (see Table S.10). In addition, since barley straw is a key ingredient for animal feed, its availability limits the selection of districts. 'Campiña' can only handle up to an initial number of animals of 470 since its available area is 1.41 times lower than 'Bureba-Ebro' for barley

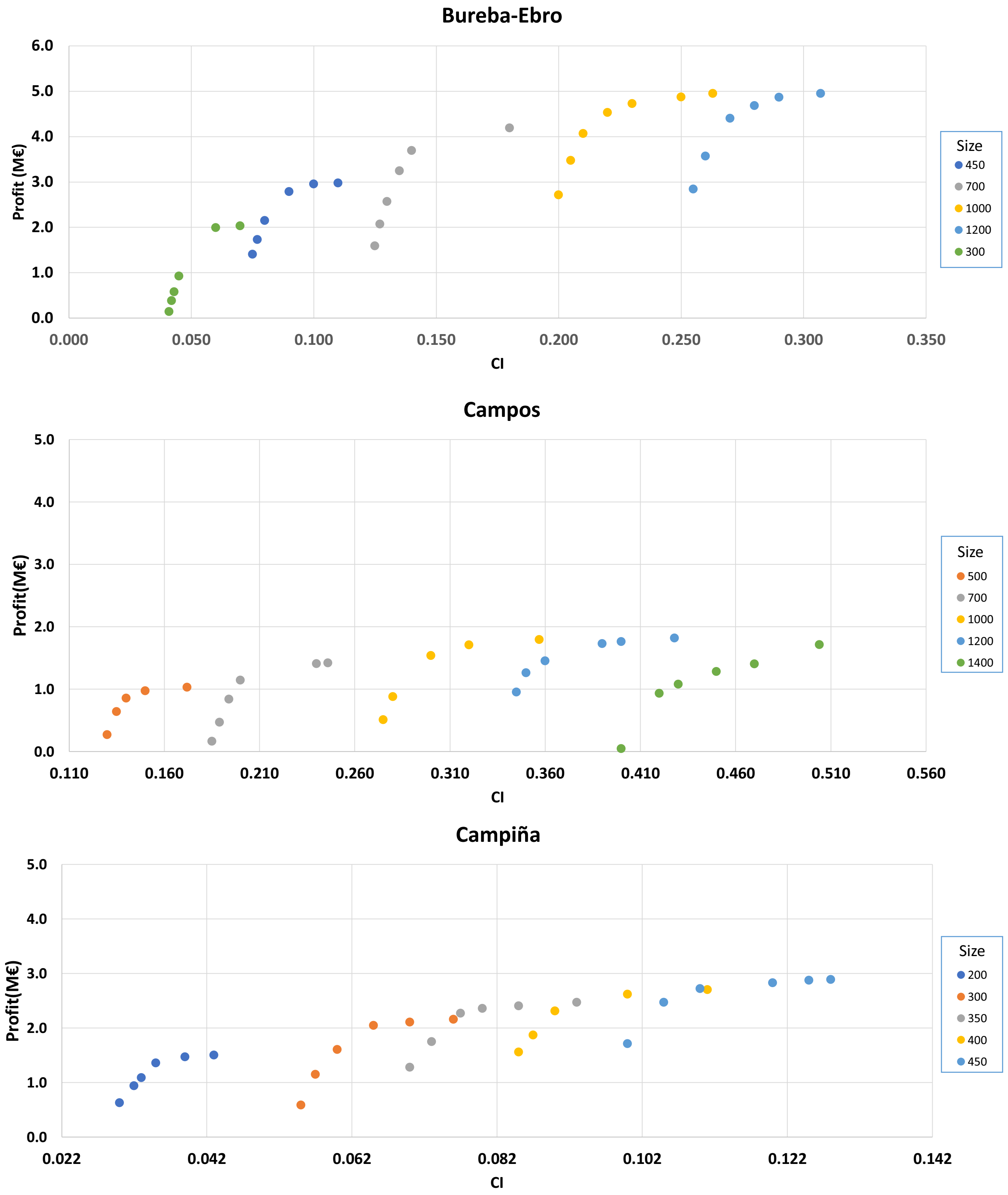


Fig. 4. Multi-objective analysis of locations and sizes of the facility.

($1.8{\cdot}10^4 ha/year$ vs $2.6{\cdot}10^4 ha/year$), 1.7 times for rye ($5.7{\cdot}10^2 ha/year$ vs $9.7{\cdot}10^2 ha/year$), and 6.92 times for wheat ($5.2{\cdot}10^3 ha/year$ vs $3.6{\cdot}10^4 ha/year$), which are the three main crops following the Fig. 5. However, 'Campos' can be selected for an animal's number of 1400 since it is the district with the highest availability of barley crops, 3.4 times higher than Bureba-Ebro ($6.1{\cdot}10^4 ha/year$ vs $1.8{\cdot}10^4 ha/year$).

Currently in Spain, one of the most important intensive livestock farms is in 'Caporroso' (Muñoz, 2021)(a municipality in the agricultural district of 'Ribera Alta Aragón'). If the methodology described in this work is applied, this location would have been discarded beforehand in the prescreening because it is a nitrate vulnerable zone. In addition to this installation, two more are in the planning stage, one for the municipality 'Torralba de Aragon' (Villanueva, 2021) (in the agricultural district of 'Monegros') and another for the municipality of 'Noviercas' (Villanueva, 2020) (in the agricultural district of 'Campos de Gomara'). 'Noviercas' does not exactly coincide with a nitrate vulnerable zone but it is very close (less than 10 km) so the procedure would also discard it. The only location that would pass the prescreening would be 'Torralba

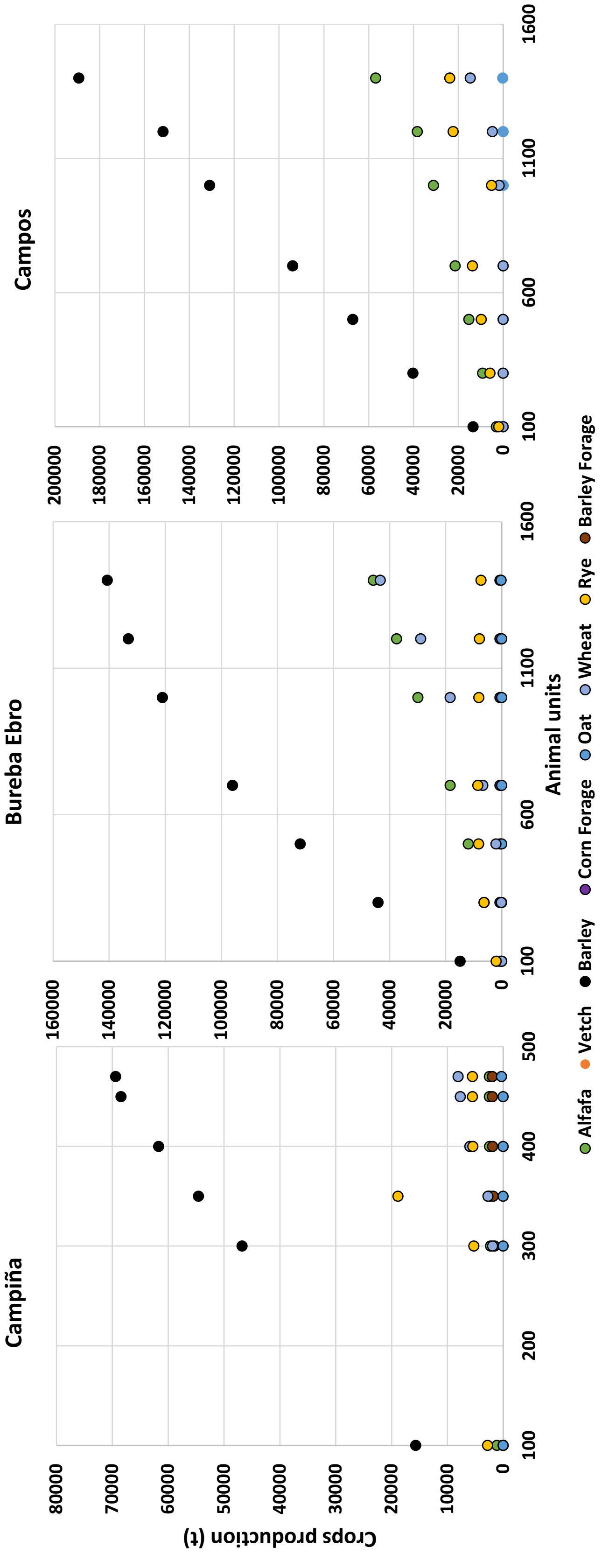


Fig. 5. Crop production as a function of the number of animals for the three best locations.

de Aragon’. However, ‘Monegros' is a district with a lower yield (3.82 times) in barley straw than ‘Bureba-Ebro’ (2.8 t/ha vs 0.73 t/ha), so the cost of production would increase (as it would require more cultivation area) and income would decrease (as there would be less grain to sell).

‘Caporroso’, ‘Torralba de Aragon’, and ’Noviercas' are 3 examples of intensive livestock farms decoupled from crop systems. However, it has been demonstrated in previous works (Taifouris and Martin, 2021), that the integrated development of both sectors can reduce the environmental impact by 65% (compared to the uncoupled systems). This impact can be further reduced by considering the environmental properties of the place where it is implemented, as is done in the prescreening stage of this work. This would contribute to reducing the negative image that these facilities have (Armestre, 2021) due to the improper treatment of waste and animals.

3.2. *Multi-objective techno-economic analysis*

Once the size and location are fixed, the Pareto curve corresponding to the size of 1000 initial animals for the”Bureba Ebro” location is analyzed. This curve could be analyzed directly in Fig. 4, however, the limits used to normalize the environmental impact indexes (see Section 2.3) must be updated, since they were calculated considering different farm sizes (the minimum values of each index corresponded to the smallest sizes and the maximum values to the largest sizes). For this new Pareto curve, the values of the composite index consider only scenarios of a farm of 1000 initial animals. The minimum values of GWP, Eui, and WF correspond to the scenarios that minimize each of these indices, while the maximum values correspond to the scenario in which profit is maximized, without considering the environmental impact. These values are shown in Table S.4 of the supplementary material. For this reason, the values of the composite index are different from those shown in Fig. 4. The new Pareto curve is shown in Fig. 6. 3 scenarios of interest are highlighted. First, a scenario is considered where no environmental constraint is introduced in the model, resulting in the economic optimum. A second scenario that minimizes the environmental impact of the economic activity is evaluated. Finally, the scenario that best balances the two objectives is also considered. A techno-economic study is carried out for each scenario and the results are presented in Fig. 7.

The profits of the economic, multi-objective, and eco-friendly scenarios are 4.9 M€, 4.7 M€, and 2.7 M€, respectively. While the composite indexes are 1, 0.65, and 0.3 for the economic, multi-objective, and eco-friendly scenarios, respectively. Between the economic and multi-objective cases, the composite index drops 35%, while the profit only drops 0.22 M€ (4.4% lower). Nevertheless, if the multi-objective scenario is compared with the eco-friendly case, the composite index drops 0.35, but the profit drops 2.03 M€. For this reason, the multi-objective scenario is postulated as a trade-off between economic and environmental objectives.

Concerning income, all scenarios show a higher income from crop sales than from meat sales (see Fig. 7a). This means that cropping is the most profitable economic activity. Nevertheless, the central activity is sought to be the livestock and, therefore, the commercial management of crops is limited and oriented to animal feed. The income from the sale of power produced using the biogas generated from waste treatment has not been included in Fig. 7a because it represents less than 0.05% of the total income in all scenarios.

Regarding costs, the most important are fertilizer costs, crop costs (which include tillage, sowing, and harvesting), and waste treatment costs. The cost of the water used as feed is especially low because water is cheap. This is because hydrological plans (Ministerio para la transición ecológica y reto demográfico, 2021) have been used to estimate the cost of using water from an existing water source (rivers, lakes, etc.). It can be seen that the cost of waste treatment is similar in the three cases (over 2.5 M€). This is due to the fact that this cost is estimated based on the amount of waste generated. Although its composition varies from one scenario to another, its amount is similar.

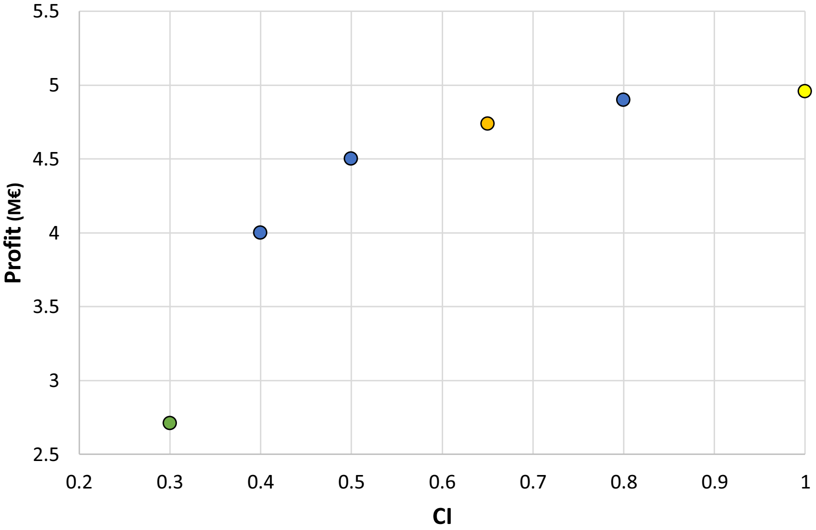


Fig. 6. Relation between composite index and profit (Economic:yellow, Multi-objective:orange; Ecofriendly:green). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Another important result is the comparison between the cost of meat production and the consumer benefit (CB). The CB is 1 kg of consumed, boneless, edible beef and is calculated corresponding to 29% of the live weight (Asem-Hiablie et al., 2019). In the course of the 20 years of operation of the farm, 5305 tons of meat are generated, considering both yearlings and cows slaughtered. The CB is 1538 tons. The cost of meat production is 8.87 €/CB (of which 1.61 €/CB corresponds to the cost of waste treatment) for the multi-objective case. This cost is similar to the selling price of meat in Spain (9.84 €/CB (Statista, 2021)). Nevertheless, this price includes other economic items, such as packaging, transportation, and profit margin, which are not considered in this work. However, the meat cost of this work can be reduced, if it is considered the income from the crops sold, down to 1.51 €/CB.

The decrease in profit between the economic and the multi-objective scenarios is due to the decrease in the amount of barley straw (see Fig. 7b), which is replaced by other crops with higher yields (larger amount per hectare), such as alfalfa and vetch, to reduce the cultivated area, and therefore, the consumption of fertilizer. In addition, a significant amount of the barley grain produced (which was destined for the food market in the economic scenario) is also devoted to animal feed, reducing the need for wheat or barley straw, as it can be seen in Fig. 7b. Nevertheless, these changes do not only reduce the environmental impact of the facility (19% lower in GPW and 17% lower in EUi) but also the amount of barley grain available for sale, and thus, the income from crops. However, this is mitigated by economic savings in fertilization, labor, and soil costs since the total cultivated area is 10% lower. When comparing the multi-objective scenario with the eco-friendly scenario, it is observed, in Fig. 7a, that the economic savings in fertilizer do no longer compensate for the reduction in income from crop sales. In this case, it is very difficult to further reduce the area needed through changes in the selection of the crops. Therefore, efforts are concentrated on increasing the amount of barley grains devoted to animal feed by 2.79 times compared to the multi-objective scenario, as it can be seen in Fig. 7b. This allows a 6% reduction in the total cultivated area since the amount of alfalfa, barley straw, and rye are reduced but causes a sharp drop in profits. The reduction in environmental impact is concentrated on reducing GPW by 15% and Eui by 25% as it can be seen in Fig. 7c.

Regarding the environmental impact indexes, it can be observed that the WF is similar in the three scenarios (see Fig. 7c), with the use of rainwater (green water footprint) being much higher than the artificial input from rivers, lakes, and groundwater sources (blue water footprint). This is because irrigated crops are not used in any of the 3 scenarios. While the green water footprint of the facility is slightly higher (9370 m^3/t vs 8849 m^3/t) than what can be found in the literature, the blue water footprint is much lower (Mekonnen and Hoekstra, 2012). Nevertheless, the water footprint depends on the technology and weather of the countries since there are some countries, such as Brazil or China, that can have a water footprint larger than 8000m^3 per kilogram of meat, while that others like the United State or the Netherlands does not exceed 5000 m^3/kg (Gerbens-Leenes et al., 2013). Finally, with respect to GWP, it is observed that the results obtained in the eco-friendly, multi-objective, and economic scenarios (1.96, 2.31 and 2.85 kgCO_2/kg live weight, respectively) are slightly lower than those reported by the literature (Roop et al., 2014; Pelletier et al., 2010). According to these work, GWP varies from 3.47 kgCO_2/kg live weight to 5.59 kgCO_2/kg live weight depending on the type of crop, the type of animal, as well as the age, and weight at the time of slaughter. The numerical data of this Section can be consulted in Table S.7 of the supplementary material.

Finally, analyzing the nutrient balance, it is determined that, for the multi-objective case, it is possible to recover the 26.2% of nitrogen and 62% of potassium necessary for crop growth. The nutrient requirement of the multi-objective scenario is 12% less than in the economic scenario. Whereas, if this scenario is compared to the eco-friendly scenario, the nutrient requirement is 15.7% higher.

3.3. Animal and crop distribution for the multi-objective scenario

The distribution of animals through the farm operation is analyzed together with the percentage of each crop needed per year. This study is shown in Fig. 8. The joint representation of animals (Fig. 8a) and crop distribution (Fig. 8b) allows relating changes in crops to the number and age of the animals along the life cycle of the farm.

First, during year 1 there are no animals on the farm, so the crop distribution in year 2 is grown, harvested, and stored during year 1 to feed the animals in year 2. Therefore, the crop distribution shown in Fig. 8b of a specific year corresponds to the feed needed for the animals of that year yet is planted and harvested in the previous year. Thus, the crop and animal distributions can be directly compared year by year. It is observed that in the first years (i.e., years 2 and 3), almost 50% of the crops are concentrated (wheat and barley grains). This is due to the type of animals during theses years are only yearlings (12- month-old) and young cows. They need more concentrate than forage because the dry matter intake (DMI) of this kind of animals is low and needs more

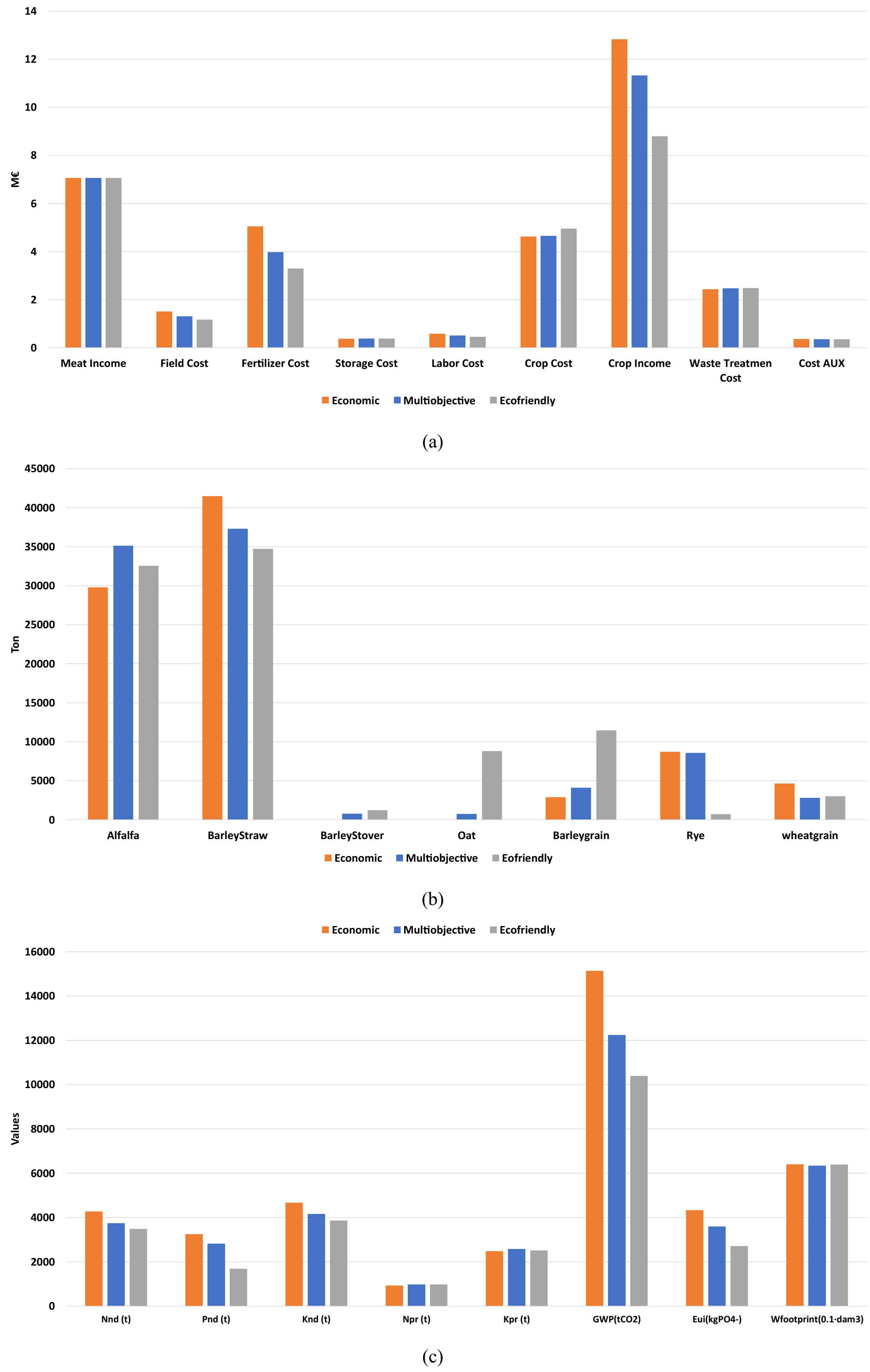
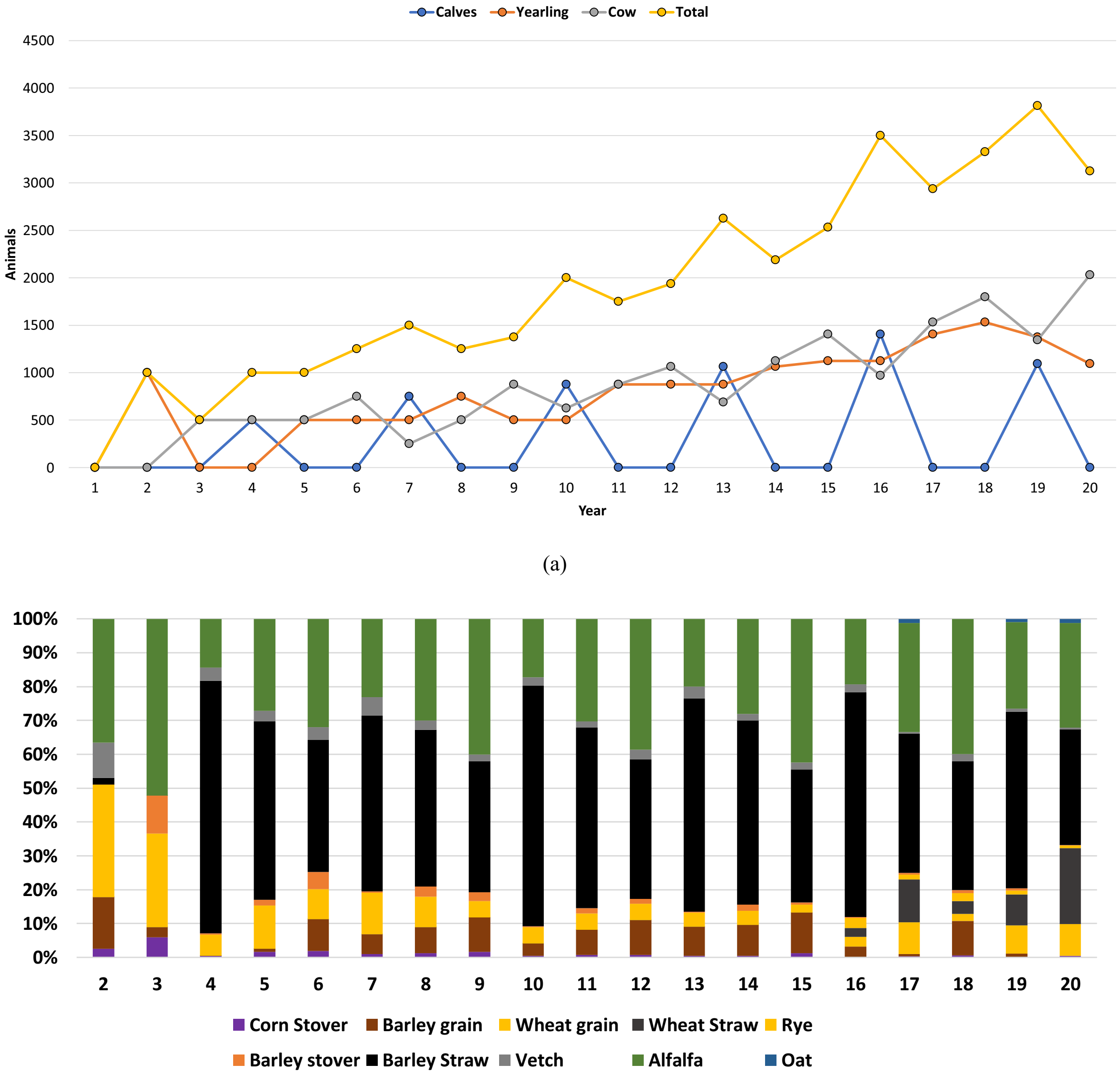


Fig. 7. Tecno-economic analysis for economic, multi-objective and eco-friendly scenarios. (a) Economic analysis (b) Analysis of crop production for animal feed (c) Environmental analysis and nutrient balance (Nd:needed and Rc:recovered).



(a)

(b)

Fig. 8. Animal (a) and crop distribution (b) along the life cycle of the farm.

energetic ingredients.

Between years 4 and 6, the main changes affect the barley straw and alfalfa fraction. This year 4, there are cows and calves, yet the largest proportion of the total DMI belongs to cows. In this year, cows are 48-month-old and at this age, the energy requirements are lower. For this reason, the fraction of barley straw is much higher than that of alfalfa since its NEMA is lower than the NEMA of alfalfa (0.6 Mcal/kg vs 1.24 Mcal/kg). Nevertheless, from year 5, the population of yearlings is older which affects crop distribution. Cows start eating less feed and yearlings more. In addition, yearlings need more energetic forage than cows. As a result, the fraction of alfalfa is larger than in year 4. In year 6, both yearlings and cows continue to grow and, consequently, cows have a lower DMI, and yearlings have a higher DMI. This results in a larger fraction of alfalfa in the crop distribution for the same reason as the previous year.

However, there is a change in trend in year 7. The number of cows decreases, yearlings are older, and the number of calves increases. In this situation, the DMI is adjusted for the needs of the yearling. However, these yearlings are older and require less energy, increasing the fraction of barley straw, restarting the loop (see Fig. 8b). It is possible to see 5 crop distribution periods since the animal distribution is cyclical every 3 years. Nevertheless, in the two last years (i.e. years 19 and 20), due to the beginning of the dismantling process of the farm, the distribution of animals changes, which slightly breaks the periods, significantly increasing the amount of wheat straw. This is due to the abrupt drop in the number of yearlings. These results are consistent with previous work (Taifouris and Martin, 2021).

4. Conclusion

This work presents a methodology for the simultaneous design of products, processes, and location for an integrated system of intensive livestock and crop management, which consists of a two-step procedure. Following this methodology it is possible to systematically select the best feed formula (and with it the necessary crops year by year), establish the raw materials and products obtained from the waste treatment and design the nutrient recovery process, as well as determine the best possible location and size, all from an economic and environmental points of view. For this purpose, a multi-objective and multi-period optimization model (MILP) is formulated and applied to a case study in Spain.

From the results of the prescreening stage, 42% of the initial locations available do not meet the environmental constraints, demonstrating the importance of carrying out a preliminary analysis to study the viability of the locations considered.

The results of the multi-objective approach show that the optimal location is closely related to the size of the farm, finding the best value of 1000 initial animals in the agricultural district of 'Bureba-Ebro', from economic and environmental points of view. The profit achieved with this selection is 2.78 times higher than the second-best option, 'Campos'. This demonstrates the importance of considering location and farm design simultaneously.

Once the facilities are placed in Bureba-Ebro and its size is fixed to 1000 initial animals, the selection of the crops (type and quantity) necessary to satisfy the nutritional needs of the animals is analyzed, readjusting the composite environmental impact index and proposing 3 scenarios, economic, multi-objective and eco-friendly. This study shows that, when comparing the multi-objective scenario with the economic scenario, a very significant reduction of the environmental impact (35%) of intensive livestock farming is possible by selecting crops with a higher yield per hectare (alfalfa and vetch) and orienting the production of barley grains to animal feed instead of sending them to the market. This reduces the total crop area, and therefore, the total nutrient consumption (12%). However, this also implies a reduction in profits (4.4%) that can be compensated by incentive policies oriented to the creation of sustainable processes (Martín-Hernández et al., 2022). Since crop yields depend on the location of the facilities, the consideration of location in this type of problem is key for holistic optimization.

It is important to highlight that the most profitable economic activity is crop production (representing between 55% and 65% of total revenues depending on the scenario considered). This opens the possibility of devoting this type of integration to crop production, with meat being a by-product of the facility, and comparing it to the approach presented in this work. In addition, power production through biogas does not represent an important source of income and the most important costs are those associated with crops (34.10%), fertilizer (29.11%), and waste treatment (18.13%) in the multi-objective scenario. Finally, it is possible to reduce the cost to produce meat by 82.9% by considering the incomes of the crops as a method of reducing costs.

Regarding crop distribution, it should be noted that, except for the first years, the most important crops are Alfalfa and Barley (straw). The variation in the fraction of each of these two crops depended on the number, age, and type of animals predominant each year, forming a total of 5 loops where the crop distribution is repeated with the animal distribution.

Declaration of Competing Interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.agsy.2022.103517.

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