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A Dynamic Evaluation of the Use of Natural Resources in Crop Rotation in Family Farming Production Units

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Abstract: A total of 35.4% of the earth's surface is used for agriculture, and 32.7% of it for crops. Agricultural activity uses 70% of the world's freshwater, and due to the intensive use of agrochemical inputs and energy, a high percentage of greenhouse gas emissions, pollution, and waste are generated. With the increase in population and fluctuating consumption trends, it is necessary to increase crop production and productivity to meet present and future demands. A relevant factor for the analysis of the production of agricultural goods is the size of the productive unit since about 84% is less than 2 ha in size and distributed over 12% of arable land; however, it is important to highlight other factors, such as the availability of family labour, crop diversification and the development of other agricultural activities that have a lower use of insecticides, pesticides, and chemical fertilisers compared to industrial crops. Therefore, food is produced, providing social and ecological benefits. Thus, a dynamic simulation is presented to evaluate the use of natural resources in developing different rotations of transient and permanent crops in a municipality in Colombia. This study assesses the impact on land use, soil degradation due to crop development, and the total water footprint associated with each rotation.

Keywords: natural resources; agricultural; system dynamics

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1. Introduction

One of the key variables in the production of agricultural goods is the size of the productive unit; about 84% of agricultural production units (APUs) in the world are less than 2 ha in size and distributed over 12% of arable land, and authors such as Vincent Ricciardi have found even higher yields in this type of PUs, highlighting factors such as the availability of family labour, crop diversification, and other agricultural activities that have a lower use of insecticides compared to industrial crops [1]. These factors allow food to be produced, providing social and ecological benefits [2].

Within agricultural activities, different models have been designed over time that make the decision-making process more agile, taking into account the needs of different actors in production chains, as well as the objectives of each of these activities, which range from the identification and characterisation of producers to the development of sustainable agricultural systems while taking into account food security, territorial development, the reduction in carbon emissions, energy efficiency, and the conservation and sustainable use of natural resources, among others [3,4].

It is important to understand the context in which these models are applied. Considering the distribution of agricultural production units and the types of crops grown there, this review is focused on the characteristics of production units with a concentration of smallholders (less than 10 ha) which are likely to be family farmed.

Family farming is a mode of agricultural production managed by a family where family labour predominates. The family and productive activity are linked, evolve together, and combine economic, environmental, social, and cultural aspects [5]. The factors mentioned before directly affect the production and performance of these production units [1].

According to Craviotti, C., some characteristics differentiate family farming, taking into account its diversity and complexity: one characteristic is access to natural resources, especially soil and water resources; a second characteristic is that family labour is the leading human resource of productive units; and finally, the primary income of this population comes from these agricultural activities [6].

The use of natural resources in each productive unit and their characteristics are required to generate different agricultural production chains. All are fundamental in decision making regarding crop planning and programming: physiography, soil, geology, climatology, water resources, forestry, and fauna.

In the case of family farming, since it adapts its production systems to meet the nutritional needs of the people who make up the APU and focuses on diversifying traditional crops, there are diverse ecological niches at the field and landscape levels [1].

The primary resources that are taken into account in the models developed for decision making are soil resources and water resources. Soil resources are natural environments for plant growth. Soil is the final product of the influence of time combined with climate, topography, organisms (flora, fauna, and human beings), and parental materials (rocks and native minerals). Soil can vary according to texture, structure, consistency, colour, and chemical, biological, and physical properties [7].

According to the State of the World's Soil Report (2016), an obstacle is the degradation of landscape caused by poor agricultural practises, water erosion, and landslides. A lack of nutrients and the agrarian inputs necessary for producing food from crops result in low productivity, performance, and efficiency [8].

Therefore, strategies and practises have been proposed to increase food supply and reduce the environmental impact caused by agricultural activities. Latin America and the Caribbean have about 800 million hectares of agricultural potential and are among the wealthiest regions with potentially arable land [8]. In the case of productive units with family farming, due to the small area, many producers have soils with low quality and consequently low productivity; additionally, in Latin America, there is evidence of a decrease in the use of this type of productive units [9].

In Colombia, 39,820,919 hectares of dispersed rural areas is distributed in 322,859 agricultural production units (APUs), of which 51.6% are self-owned, 3.4% are rented, 27.4% are collectively owned, and 1.8% are mixed. A total of 88.4% (95,662 APUs) are predominantly used for agriculture and represent an area of 164,748 ha distributed in APUs of less than 10 ha [10].

For the above reasons, an assessment of the impact of productive chains on natural resources through dynamic simulation, emphasising land and water use in the municipality of Tuta, Boyacá, Colombia, is presented. Furthermore, the effect on these resources derived from the scheduling and sequencing of temporary crops through rotations in various municipality areas distributed across agricultural production units is analysed.

2. Literature Review

According to the literature review considered in this work, modelling through system dynamics can simulate various policies in agricultural supply chains and the effects generated over time by the availability of water resources, changes in land use due to agricultural or livestock production, and their impact on social and economic indicators. The simulation of different scenarios allows for comparing and measuring various indicators depending on the evaluated system, thus aiding in identifying a solution or integrating policies to adapt a productive system [11]. Models applied to agricultural supply chains were found and developed in studies by Vensim [12], Stella [13], and AnyLogic [14], among others.

This review highlights the use of dynamic simulation in the development of models to evaluate agricultural systems, as well as in the analysis of different policies for managing water resources, taking into account the demand and limitations in a specific region. It also emphasises the possibility of using irrigation systems, considering various irrigation methods [11,15], the fluctuation in water availability according to the season and its impact on crops [16], the implementation of cultivation methods to reduce water consumption, the application of pesticides and fertilisers on crops [17], the increase in production under specific resource restriction conditions, such as droughts [18], and the socioeconomic impact on the population under study [19,20].

The literature review mentions some of the research that has been developed, considering different objectives for agricultural supply chains (Table 1).

Table 1. Application of system dynamics in agricultural supply chains.

Location	Scenarios Evaluation	Source
Honduras	Conditions for crop production	[21]
Australia	Management of irrigation systems	[22]
	Energy consumption performance from use of irrigation systems	[15]
Africa	Policies for sustainable use of water resources and agricultural development	[23]
India	Measurement of methane emissions from rice cultivation	[24]
Argentina	Policies on consumption of groundwater, considering economic factors	[16]
Africa	Determining policies for droughts	[11,25]
Indonesia	Analysis of cereal availability for subsequent consumption	[19]
Germany	Identifying effective measures for adaptation to climate change in agricultural sector	[26]
Malawi and South Africa	Evaluating efficiency of invasive and parasitic weed control policies in smallholder crops	[17]
Vietnam	Evaluating impact of land use changes	[18]
China	Evaluating factors of land management, disasters, pollution, and poverty in sustainable agriculture system	[20]

Regarding the models studied, the main variables were identified and classified according to the natural resources used and the effects generated by the development of agricultural supply chains, as shown in Table 2.

Table 2. Variables in the system dynamics models from the literature review.

Classification	Variable	Source
Soil resource	Agricultural area	[14,27–31]
	Land use pattern	[13,14,28,29]
	Crop area change rate	[29]
	Unused area	[30]
	Built-up area	[30]
	Cover type	[28,32,33]
	Total area	[32]
	Soil slope	[27]
	Eroded or degraded soil area	[28,34]
	Irrigation area	[29]
Water resource	Supply/demand	[28]
	Per capita, industrial, and agricultural consumption	[31]
	Water scarcity	[28]
	Water balance (green, blue, and grey)	[14,34,35]
	Water flow in soil	[35]
	Solute transport	[35]
	Precipitation, streamflow, and groundwater	[13,14,36–38]
Emissions or others	Residual fertiliser emissions	[35,39]
	Nitrogen intensity per unit of GDP	[36]

According to this review, research was found where system dynamics were integrated with a stochastic programming model to carry out the management of irrigation systems in an agricultural ecological system [29].

The application of system dynamics for land use planning has been observed not only in the planning of agricultural activities but also in urban land use, primarily considering the fluctuation in GDP, population, urban development, and the rate of urbanisation [37].

3. Materials and Methods

The municipality and the supply chains were characterised based on the literature review and the need to assess the impact of developing assigned and scheduled permanent and transitional crops in productive units. This review allowed for identifying interrelated variables and elements representing the studied system.

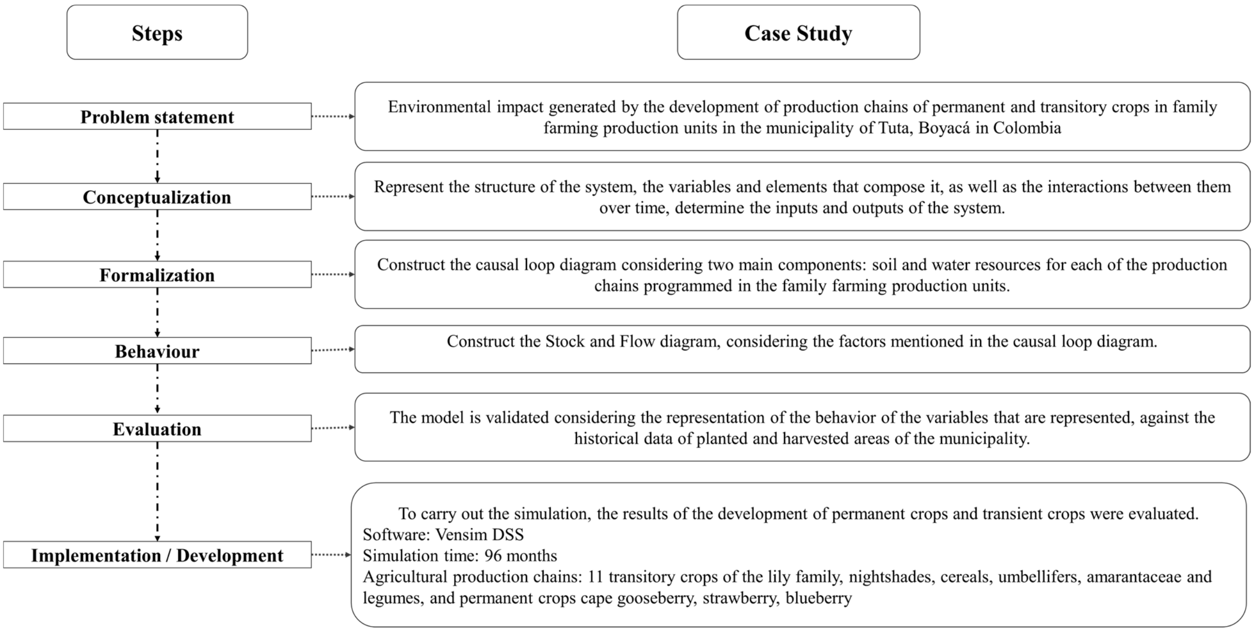
Subsequently, an influence diagram was created, showing the variables and relationships analysed regarding natural resources, agricultural supply chains, and productive units.

Once the variables and relationships to be studied were formalised, a flow and level diagram was designed, where the level variables, flow variables, and the parameters or rates necessary to analyse the system's behaviour were classified.

The model was validated based on the behaviour of the represented variables and its comparison with historical data.

Finally, simulations of different scenarios were performed. These included variations in the rotations of transitional crops and the planning of changes in land allocated to permanent crops in the municipality.

The steps identified in Figure 1 defined the route for designing and developing the dynamic simulation model proposed by Sterman [38].



Environmental impact generated by the development of production chains of permanent and transitory crops in family farming production units in the municipality of Tuta, Boyacá in Colombia

Represent the structure of the system, the variables and elements that compose it, as well as the interactions between them over time, determine the inputs and outputs of the system.

Construct the causal loop diagram considering two main components: soil and water resources for each of the production chains programmed in the family farming production units.

Construct the Stock and Flow diagram, considering the factors mentioned in the causal loop diagram.

The model is validated considering the representation of the behavior of the variables that are represented, against the historical data of planted and harvested areas of the municipality.

To carry out the simulation, the results of the development of permanent crops and transient crops were evaluated.
Software: Vensim DSS
Simulation time: 96 months
Agricultural production chains: 11 transitory crops of the lily family, nightshades, cereals, umbellifers, amarantaceae and legumes, and permanent crops cape gooseberry, strawberry, blueberry

Figure 1. Methodological approach adapted from [39].

3.1. Problem Statement

To apply this methodology, the case study of Tuta, in the central province of the department of Boyacá, located 26 km from Tunja and covering an area of 15,977 hectares, is used. It has a population of 8461 inhabitants, of which 71.65% reside in the rural area, and 3861 agricultural productive units (Figure 2) [40].

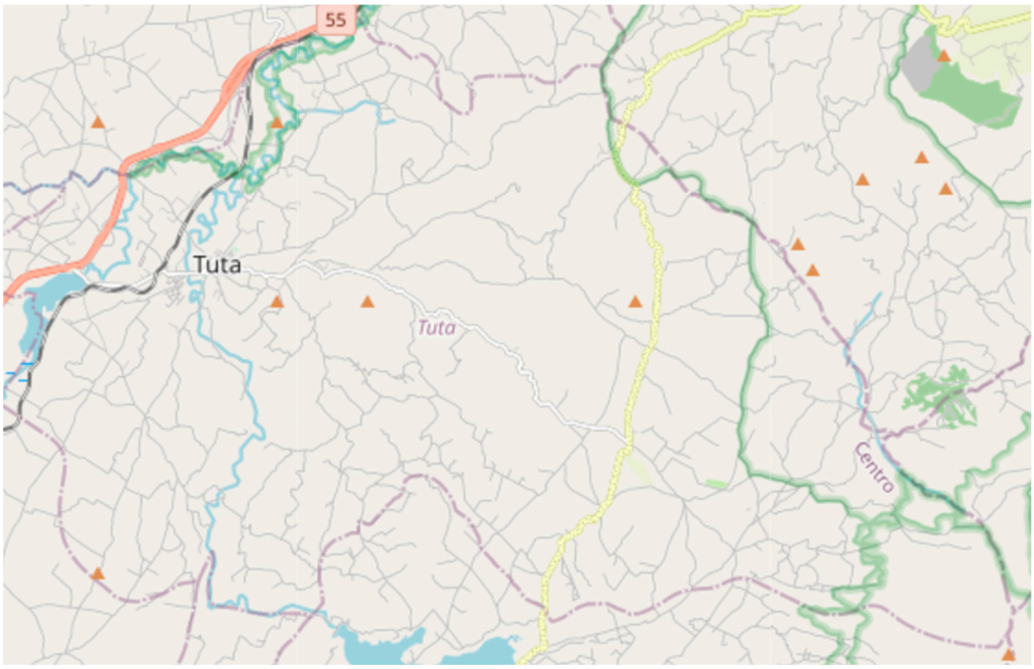


Figure 2. A map of the municipality of Tuta, Boyacá, Colombia [40]. "License: OpenStreetMap$^{®}$ is open data, licensed under the Open Data Commons Open Database License (ODbL) by the OpenStreetMap Foundation (OSMF). You are free to copy, distribute, transmit, and adapt our data, as long as you credit OpenStreetMap and its contributors. If you alter or build upon our data, you may distribute the result only under the same license. The full legal code explains your rights and responsibilities".

Due to the climatic characteristics, the topography, and the soil of the municipality, which has an agricultural and forestry vocation, in the national agricultural census, 3280 hectares is registered for agricultural use, of which 2165 hectares is planted with deciduous fruit trees and others, with the productive chains of potatoes, blackberries, peas, and tomatoes being the crops with the highest participation in terms of land use [40].

In productive units where it has medium or low suitability for use in agricultural activities, erosion may occur, as well as the contamination of natural resources; invasion by the population of areas that require conservation and protection since there is sub-Andean paramo (305 ha); areas with natural forest (1116 ha); peripheral areas of sources of streams, rivers, or springs; areas with infiltrations of aquifer recharge; and strips of springs that supply the aqueduct of the municipality [10].

Regarding the risks caused by natural phenomena and the activities of the rural population that take place in the municipality, there is a risk of drought due to the insufficiency of water resources, which also causes a risk of frost, especially in areas devoid of trees or abusive vegetation for the protection of crops; this reduces agricultural production and consequently causes losses for producers and an impact at the social level because of a reduction in sources of employment for the development of the same activities [40].

3.2. Conceptualization

The relevant inputs and parameters to be considered within the system of production of agricultural goods in family farming productive units are presented in Figure 3; the elements that make up the system are considered not only from the perspective of the productive unit but also from the perspective of a rural environment and its sociodemographic conditions, and the availability and use of natural resources are also taken into account. Once the simulation is carried out, it is expected that with the result, it will analyse the behaviour of each of the variables raised in the outputs, taking into account the demand for agricultural goods in a national environment and self-consumption, as well as the effects on the natural resources used for the development of the proposed crops.

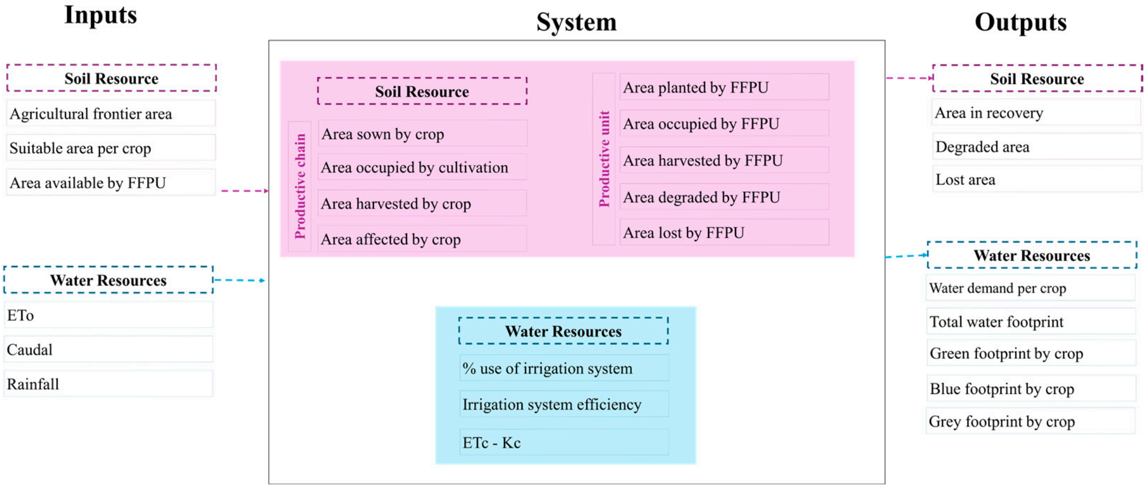


Figure 3. System representation.

3.3. Formalisation

The causal loop diagram represents the agricultural crop production system in productive units of family farming. The literature review was considered and divided into two sections, each referring to the use of natural resources, specifically soil water.

The first section (Figure 4) represents the variables and relationships of the soil resource, where seven negative feedback or balance loops and five positive feedback or reinforcement loops can mainly be observed.

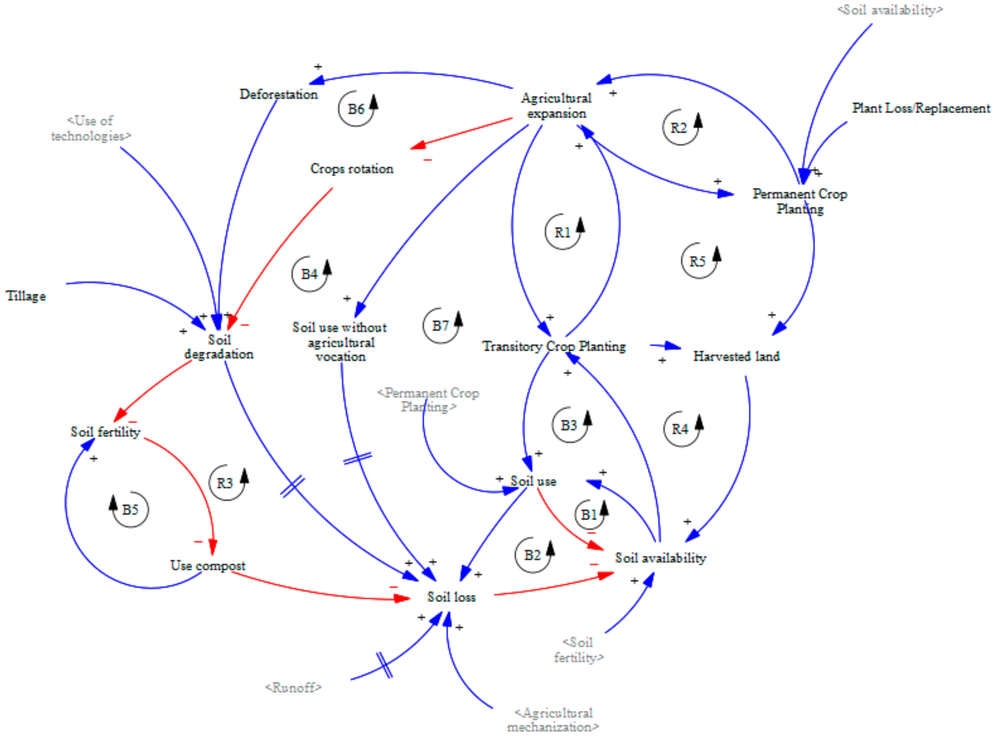


Figure 4. Causal loop diagram of soil resources.

In the second section (Figure 5), the variables and relationships of water resources are represented, where three negative feedback or balance loops and four positive feedback or reinforcement loops can mainly be observed.

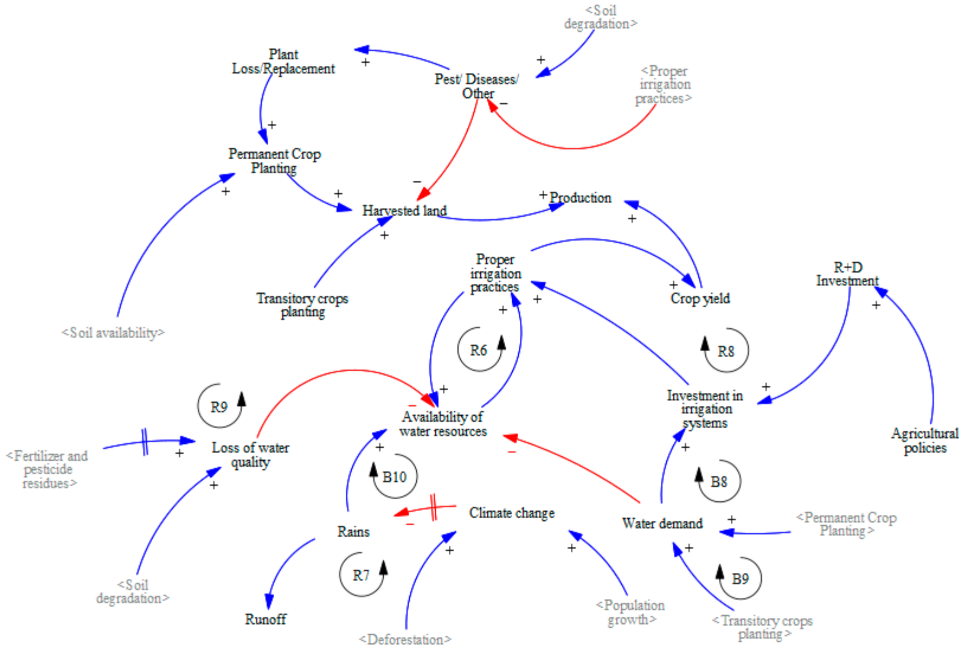


Figure 5. Causal loop diagram of water resources.

3.4. Behaviour

After developing the methodology, the causal loop diagram transitions into a stock and flow diagram created using Vensim® PLE Version 10.2.2. software. The components of each section included in the causal loop diagram are clearly defined. In this case, two elements are identified: variables, which represent components that fluctuate over time, and data, which consist of parameters or rates.

Likewise, the model classifies variables into level variables and flow variables. Level variables represent key components of the system and depend on the input and output flow variables, which are controlled based on the unit of time. Flow variables typically depend on parameters or rates. During model development, auxiliary variables may be included to enhance the visualisation of the system's flow behaviour [41].

The following sections define the stock and flow diagram and its components.

The system representation includes three levels within the soil resource subsystem. The first level (Figure 6), called soil, represents the total land available in the municipality for agricultural activities, including livestock, transitory crops, and permanent crops. Although soil is a finite resource, it can recover when not used, provided that efforts are made to restore it after losses caused by overuse, resource mismanagement, pollution, compaction, or other factors. Proper use of the soil is essential to prevent productivity decline, reduce crop yield potential, degradation, and loss of nutrients and organic inputs [42].

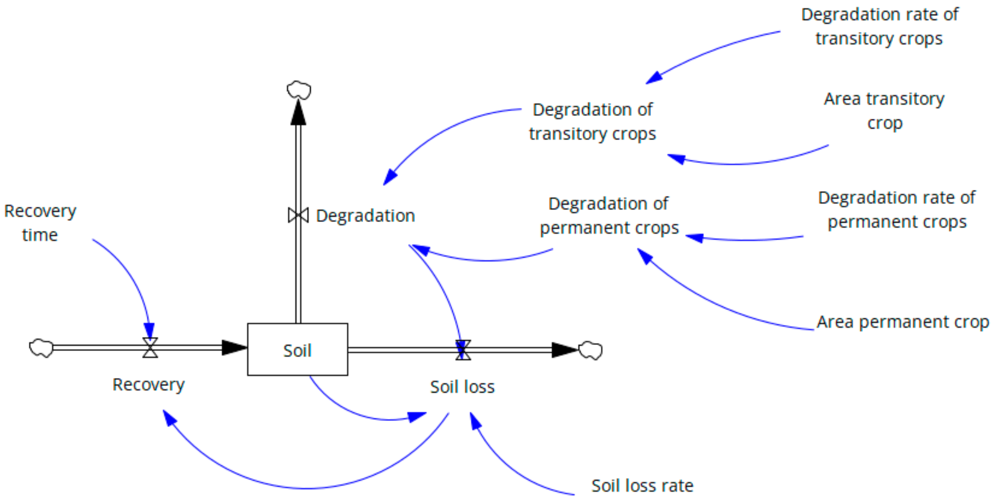


Figure 6. Stock and flow diagram of soil resources. Level 1: soil.

Table 3 lists the variables, names, and equations for the agricultural soil level, while Table 4 presents the parameters.

Table 3. Classification and equation for level 1 of agricultural soil.

Name	Type *	Equation
Soil	L	Recovery − Degradation − Soil Loss
Recovery	F	Soil Loss/(Recovery time × 12)
Degradation	F	Degradation permanente crops + Degradation transitory crops
Soil loss	F	min(Degradation × Soil loss rate, Soil)
Degradation of transitory crops	A	Area occupied transitory crop × Degradation rate of transitory crop
Degradation of permanent crops	A	Area occupied permanent crop × Degradation rate of permanent crop

* Variable type: L—Level; F—Flow; A—Auxiliary.

Table 4. Information on the parameters for level 1 of agricultural soil.

Parameter	Value	Unit of Measurement	Source
Recovery time	20–40	Years	[43]
Degradation rate of transitory crops	1.1	Percentage	[44]
Degradation rate of permanent crops	0.5	Percentage	
Soil loss rate	1	Percentage/annually	[45]

The second level, the area occupied by a transitory crop (Figure 7), represents each crop's land in the municipality. The planting process determines this level, allocating an area for the germination of each crop based on the pre-established programme. Losses due to diseases, pests, or climatic conditions reduce this level, as does the area harvested after completing the phenological cycle to produce the agricultural good, which aligns with the programme. This process applies to each of the crops under consideration.

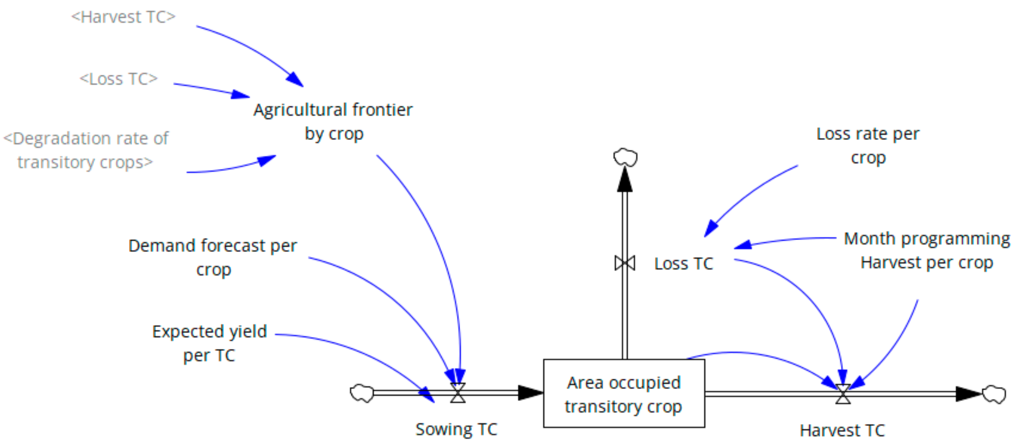


Figure 7. Stock and flow diagram of soil resources. Level 2: area occupied by transitory crop.

The third level, the area occupied by a permanent crop (Figure 8), represents the land in the municipality occupied by each crop and is influenced by planting. This level vacates as diseases, pests, and/or natural events cause the crop area to be lost. Farmers harvest permanent crops once the production time is completed. These crops continue to occupy the area while waiting for the product development process to restart, allowing the harvest cycle to repeat after a certain period. These cycles depend on agroclimatic conditions, the production unit, and the cycles of each crop. In the application case, we replicated this level for each permanent crop considered in the case study.

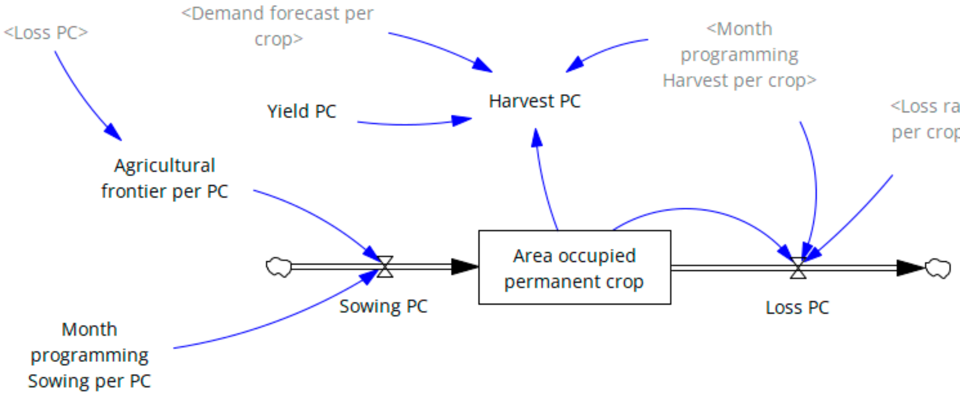


Figure 8. Stock and flow diagram of soil resources. Level 3: area occupied by permanent crop.

Table 5 provides the types of variables, names, and equations for level 2 (the area occupied by a transitory crop) and level 3 (the area occupied by permanent crops).

Table 5. Classifications and equations for levels 2 and 3.

Name	Type *	Equation
Area occupied by transitory crop	L	$\text{Sowing TC} - \text{Harvest TC} - \text{Loss TC}$
Sowing of transitory crop	F	$\text{IF THEN ELSE}\left(\text{Month programming sowing TC} = \text{n}, \min\left(\text{Suitable area TC}, \frac{\text{Demand Forecast TC}}{\text{Expected Yield TC}}\right), 0\right)$
Harvest of transitory crop	F	$\text{IF THEN ELSE}(\text{Month programming harvest TC} = \text{n}, \ \text{Area occupied TC} - \text{Loss TC}, 0)$
Loss of transitory crop	F	$\text{IF THEN ELSE}(\text{Month programming harvest TC} = \text{n}, \text{Area occupied TC} \times \text{Loss rate per crop}, 0)$
Agriculture frontier for transitory crop (TC)	A	$\text{Inicial agriculture frontier TC} - ((\text{Loss TC} + \text{Harvest TC}) \times \text{Degradation rate of transitory crop})$
Area of permanent crop	L	$\text{Sowing PC} - \text{Loss TC}$
Loss of permanent crop	F	$\text{IF THEN ELSE}(\text{Month programming harvest PC} = \text{n}, \text{Area occupied PC} \times \text{Loss rate per crop}, 0)$
Harvest of permanent crop	A	$\text{IF THEN ELSE}\left(\text{Area occupied PC} - \text{Loss PC} > 0, \min\left(\text{Month programming harvest PC}, \frac{\text{Demand Forecast TC}}{\text{Expected Yield TC}}\right), 0\right)$

* Variable type: L—Level; F—Flow; A—Auxiliary.

Historical data from Table 6 were considered for the parameter of expected yield for each transitory and permanent crop. Yield is the tonnes of the product obtained per hectare of the harvested crop [46]. The difference between the planted and harvested areas per unit of time is estimated based on the loss rate. For this, the average losses relative to the planted area were considered. The yield and loss rates were based on historical data from the municipality of Tuta, Boyacá, between 2006 and 2023 [47].

Table 6. Yield parameters and crop loss rates in the municipality.

Crop	Yield Tonnes per ha	Percentage % of Loss Rate per Crop
Bulb onion	12.0–25.5	6.3
Potato	12.0–25.5	6.3
Wheat	1.5–2.0	10
Oat	1.5–2.0	2.3
Maize	2.0	29.0
Coriander	9.0–15.0	0.0
Barley	1.5–2.0	20.6
Quinoa	1.6–2.5	9.6
Carrot	17.0–25.0	4.1
Pea	2–1.8	14.1
Bean	1.5–1.93	6.3
Cape gooseberry	12.0	20.8
Strawberry	13.0–20.0	11.5
Blueberry	8.0–12.0	22.3

Source: [47].

Regarding the initial value of the agricultural frontier by crop, for temporary crops such as bulb onion and potato, there is an area of 10,871 ha; for maize, there is 10,853 ha [47,48]; and for other temporary crops, there is 5244 ha, considering the potential value of the Agricultural Production Units (APU) [49]. Meanwhile, there is an area of 10,618 ha for permanent crops for strawberries and 820 ha for blueberries and cape gooseberries [49].

In the municipality of Tuta, a meticulous process was undertaken by local researchers to identify and classify homogeneous physical units based on soil conditions. Following the methodology for calculating the family agricultural unit, this process was defined based on the soil's potential value (Table 7). The thoroughness of this classification, which considered climatic conditions and, at the edaphic level, factors such as workability, rooting conditions, the availability of moisture, oxygen, nutrients, toxicity due to salts, sodium and/or aluminium, and susceptibility to soil loss [49], should instil confidence regarding the data presented.

Table 7. The classification and potential value of the soil in the municipality of Tuta.

Class	Assessment	Hectares	Percentage
03	Good	3	0.0%
06	Medium	817	5.0%
07	Medium to Fair	1198	7.3%
08	Fair	3226	19.6%
09	Fair to Poor	6258	38.0%
10	Poor	624	3.8%
11	Poor to Very Poor	505	3.6%

Source: [48,49].

Two levels are proposed to analyse the effect of using water resources. At level 4 (Figure 9), we consider water flow from sources such as rivers, streams, springs, and rainfall. In contrast, surface water extraction depends on the population's water demand and the need for agricultural activities, such as livestock farming and cultivating transitory and permanent crops in the region.

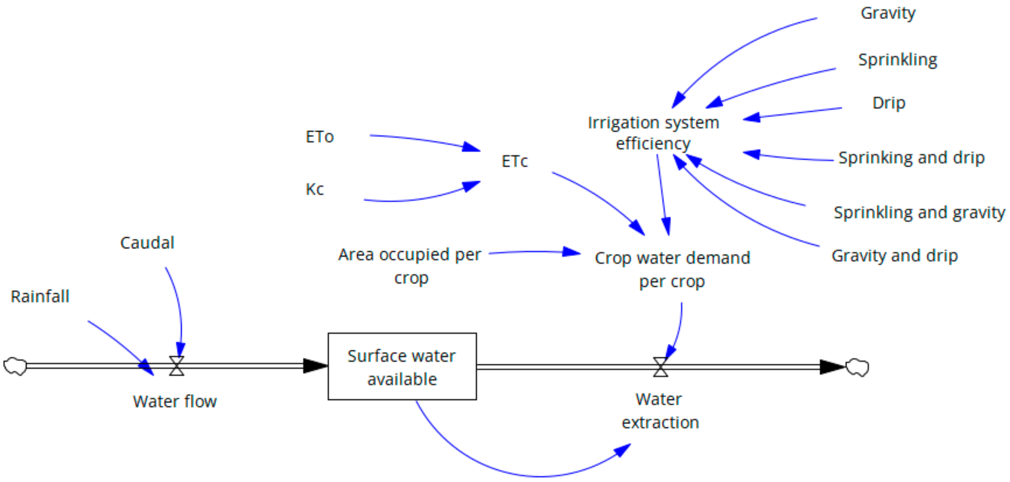


Figure 9. Stock and flow diagram of water resources. Level 4: surface water available.

The types of variables, names, and equations for level 4 are presented in Table 8.

Agriculture is an economic activity that requires approximately 70% of the world's freshwater [50]. Colombia has two rainy seasons throughout the year, providing 21.6% of the water, while 44.4% comes from rivers, streams, or other sources.

Furthermore, 54.7% of the productive units in the census faced difficulties in accessing water. Only 1.4% of the agricultural production units (APUs) have access to irrigation districts; 15.7% to wells, cisterns, or reservoirs; and 21% to the water supply network [51].

Table 8. Classifications and equations for level 4.

Name	Type *	Equation
Surface water available	L	Water flow − Water extraction
Water flow	F	Rainfall + Caudal
Water extraction	F	$\sum$Crop water demand per crop
Crop water demand per crop	A	Area occupied per crop × ETc × Irrigation system efficiency

* Variable type: L—Level; F—Flow; A—Auxiliary.

This infrastructure ensures access to water during agricultural activities, enabling efficient resource use and increasing crop yields when supplied adequately throughout the different stages of crop development [50]. It supports the achievement of Sustainable Development Goal 6, which focuses on reducing water consumption in food production [52].

According to the National Agricultural Census, the department of Boyacá shows the percentage of irrigation system usage according to some of the production chains considered in the simulation, as presented in Table 9.

Table 9. Use of irrigation system by crop.

Crop	Irrigation System			
	Drip	Sprinkler	Gravity	Manual
	%	%	%	%
Pea	0.5	88.9	1.2	9
Barley	-	83.6	-	16.4
Bulb onion	0.4	93.9	1.7	2.0
Bean	1.8	80.0	6.3	10.1
Maize	2.2	85.7	5.3	6.6
Potato	0.3	80.9	13.6	4.1
Wheat	-	52.8	2.4	44.8
Carrot	-	98.3	1.7	-
Strawberry	92.9	6.5	-	0.5
Cape gooseberry	59.3	29.4	15.5	4.8

Source: [53].

The irrigation system’s efficiency must be considered to determine the actual water consumption of each production chain [54]. This way, the actual consumption value can be found according to the type of irrigation district used (Table 10).

Table 10. Efficiency according to the irrigation system.

Irrigation Type	Efficiency (%)
Sprinkler	75
Gravity	50
Drip	90
Sprinkler and gravity	60
Sprinkler and drip	75
No information	50
No irrigation district	60

Source: [55].

Regarding the municipality, three potential areas are identified based on the physical component of land suitability for irrigation purposes. The first type, which accounts for 0.4% (61 ha), includes potential irrigable areas with specific requirements for surface irrigation. The second type represents 2.9% (483 ha) with specifications for specialised irrigation. The third type represents 4.3% (714 ha) of high-efficiency pressurised irrigation systems [48]. In type 1 and 2 lands, irrigation methods such as sprinkler, micro-sprinkler, and drip irrigation are recommended, as the soil texture may pose a water erosion risk. For type 3 lands, the previously mentioned methods can be used depending on the crop, provided the slopes do not exceed 20%. Conventional sprinklers can be used for slopes between 20% and 35%, and drip irrigation can be used for perennial crops, even on slopes of up to 45% [56].

Regarding the sustainable use of soil resources in rural areas, biodiversity conservation, and the ecosystem component, an area with a high potential with a size of 1257 ha (7.6%) was recorded. In this same area, surface water resources had low availability and were underregulated. Concerning the need for the same resource, a high need was recorded in 4.7% (774 ha) and a moderate need in 2.9% (483 ha) of the area [51,57].

In level 5 (Figure 10), the aim is to determine the water consumption in the production of the agricultural chains under study. The volume of freshwater required for the development of each agricultural product was calculated [58,59]. According to Figure 10, the total water footprint is the sum of the green, grey, and blue water footprints generated by developing the agricultural production chains included in the simulation.

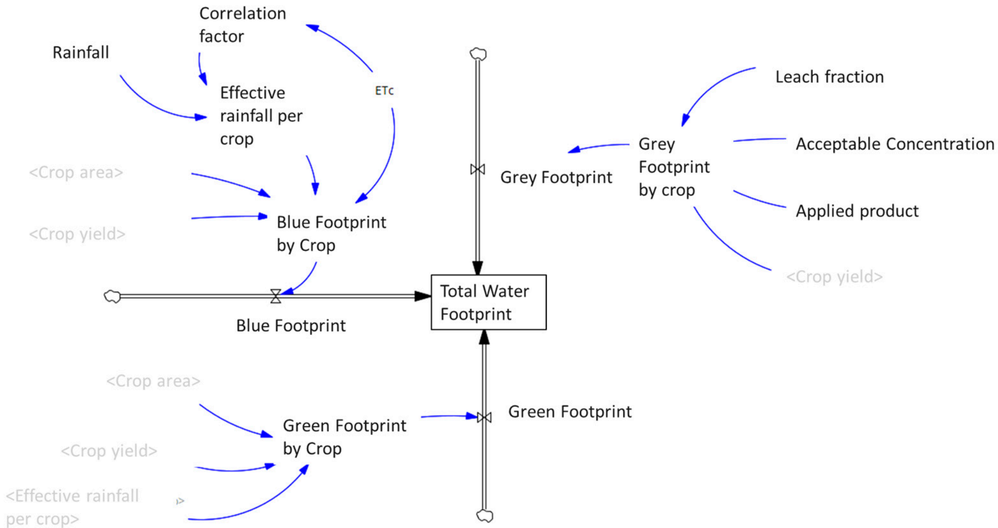


Figure 10. Stock and flow diagram of water resources. Level 5: total water footprint.

The types of variables, names, and equations for level 5 are presented in Table 11.

Table 11. Classification and equation for level 5.

Name	Type *	Equation	Source
Total water footprint	L	Blue footprint + Green footprint + Grey footprint	
Blue footprint	F	$\frac{\text{ETc}-\text{Effective rainfall per crop}}{\text{Crop yield}}$	[57]
Green footprint	F	$\frac{\text{Effective rainfall per crop}}{\text{Crop yield}}$	[54]
Grey footprint	F	$\frac{\frac{\left(\frac{\text{kg}}{\text{ha}}\ \text{applied product}\right)\times\text{Leach fraction}}{\text{Acceptable concentration}}}{\text{Crop yield}}$	[58]
ETc	A	$\text{ETc} = \text{ETo} \times \text{Kc}$	[54]
Effective rainfall per crop	A	$\text{Pp} \times \text{Correction factor}$	[59]

* Variable type: L—Level; F—Flow; A—Auxiliary.

It is essential to consider some definitions regarding the different types of footprints. The blue water footprint calculates the water consumption of surface water [57]. The green water footprint refers to the water consumed from adequate precipitation (Ppeff). If this exceeds crop evapotranspiration (ETc), it is assumed that the green footprint equals ETc [54].

Finally, the greywater footprint is calculated based on the freshwater required to dilute the contaminated water discharges during crop development until the quality standards are met. These standards may vary according to current regulations and the subsequent resource use, particularly for human consumption, considering agricultural inputs such as pesticides, herbicides, and fertilisers.

In this case, the chemical applied depends on the crop and its nutritional requirements. Only the nitrogen dosage was considered, as shown in Table 12. The leaching factor is 10% [60], and the maximum allowed concentration in the aquifer is 10 mg/L [61].

A critical definition of level 5 is crop evapotranspiration (ETc), which refers to the actual consumption of productive units according to the crop's demand, irrigation conditions, and climatic conditions [62].

It should be known that the reference crop evapotranspiration (ETo) (Table 13) is essential for reference evapotranspiration (ETo), which allows for the volume and frequency of irrigation to be adjusted according to the crop's water requirements, minimising resource waste [63]. This knowledge also helps increase yield, maintain stability overt the years, and achieve the optimal quality of the harvested product [54].

Table 12. Parameter: nitrogen applied per production chain.

Crop	Nitrogen	Source
	kg/ha	
Pea	357	[64]
Bean	152	[64]
Oat	50	[65]
Barley	15–20	[66]
Bulb onion	100	[67]
Coriander	60	[68]
Strawberry	100	[69]
Maize	70–105	[70]
Potato	110	[71]
Quinoa	225	[72]
Wheat	187.5	[73]
Carrot	90	[74]
Cape gooseberry	300	[75]

Table 13. Monthly reference evapotranspiration (ETo) of municipality of Tuta.

Month	ETo	Rain	Eff Rain
	mm/day	mm	mm
1	3.04	69.7	61.9
2	3.29	26.7	25.6
3	3.21	120.2	97.1
4	3.01	132.1	104.2
5	2.83	89.4	76.6
6	2.72	68.2	60.8
7	2.76	47.1	43.6
8	2.88	67.2	60.0
9	2.98	35.4	33.4
10	2.90	108.8	89.9
11	2.85	51.6	47.3
12	2.96	74.7	65.8

Source: [76].

The crop's unique coefficient (Kc) measures the difference between soil evaporation and the crop's transpiration rate. This value can fluctuate according to changes in the availability of water resources, whether from precipitation or irrigation systems. This coefficient is used in the planning and design stages of irrigation systems. Information regarding the crop's requirements, according to its development stage, is also provided in Table 14 [77].

Table 14. Unique crop coefficient (Kc) by development stage per crop.

Crop	Stage		
	Initial	Mid	Final
Pea	0.5	1.15	1.10
Oat	0.3	1.15	0.25
Barley	0.3	1.15	0.25
Bulb onion	0.7	1	1
Coriander	0.7	1.05	0.95
Bean	0.5	1.05	0.9
Maize	0.3	1.20	0.60
Potato	0.5	1.15	0.75
Quinoa	0.3	1.15	0.4
Wheat	0.4	1.15	0.25–0.4
Carrot	0.7	1.05	0.95
Blueberry	0.2	1	0.4
Strawberry	0.4	0.85	0.75
Cape gooseberry	0.6	1.15	0.8

Source: [77].

Adequate precipitation ($Ppeff$) [59] is calculated from the actual average monthly precipitation (Pp), taking into account the meteorological data from IDEAM [77] and the correction factor, which indicates the efficiency of precipitation in developing crops.

The correction factor depends on the value of ETc, as shown in Table 15.

Table 15. Correction factor according to ETc.

ETc Month	Correction Factor
<3	0.65
3–5	0.76
5–7	0.90
>7	0.98

Source: [78].

Considering the equations and parameters mentioned, the simulation process is carried out for the system analysis.

4. Results and Discussion

4.1. Evaluation

For the model's evaluation process, the productive chains shown in Table 16 were considered, understanding that the municipality has its agricultural vocation and the potential for developing these productive chains. However, the transitory crops were assigned in rotations and sequenced in productive units with a programming model by goals. We also took into account production between 2019 and 2023 and the performance recorded in the municipality in 2023 [79].

On the other hand, for the validation of the model, in the case of permanent and transitory crops, the variation observed between 2019 and 2023 in municipal agricultural evaluations was considered [80]. As in the case of sowing and harvesting, historical data were considered each month of the year, as shown in Figures 11–13, which compare the simulation results with the reality of some crops considered in the model.

Table 16. The types of crops considered in the model and developed in Tuta.

Crop	Type of Crop	Family Crop	Production Between 2019 and 2023 Tonnes	Yield 2023 Tonnes per ha
Bulb onion	transitory	Liliaceae	26,840	32
Potato (all varieties)	transitory	Solanaceae	17,520	25
Wheat	transitory	Cereals	258	2.7
Oat	transitory	Cereals	719	2
Maize	transitory	Cereals	172	1
Coriander	transitory	Apiaceae	99	11
Barley	transitory	Cereals	322	2
Quinoa	transitory	Amaranthaceae	236	2.5
Carrot	transitory	Apiaceae	184	25
Pea	transitory	Fabaceae	91	1.4
Bean	transitory	Fabaceae	40	1.5
Gooseberry	permanent	Fruit plants	174	12
Strawberry	permanent	Fruit plants	3886	20
Blueberry	permanent	Fruit plants	174	12
		Source	[77]	

Figure 11. Model validation (potato crop—simulated vs. real).

Figure 12. Model validation (gooseberry crop—simulated vs. real).

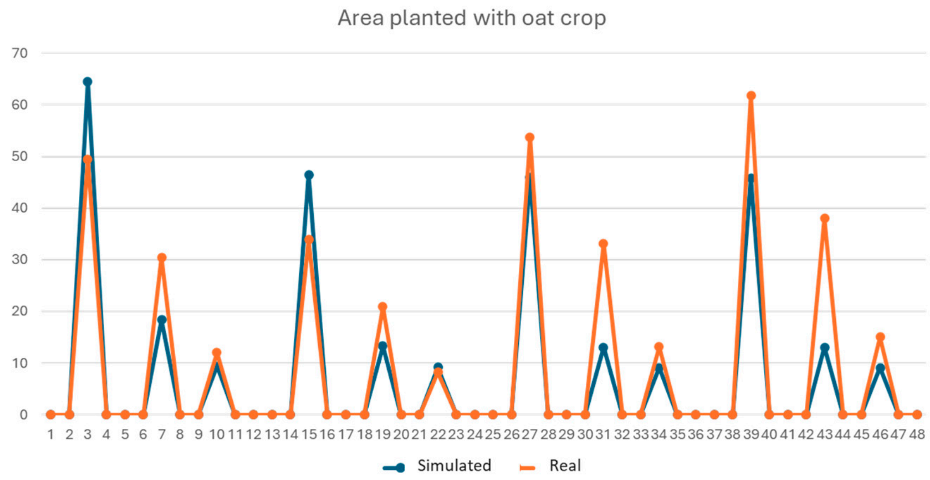


Figure 13. Model validation (oat crop—simulated vs. real).

4.2. Utilisation/Development

A case was considered for developing the simulation, carried out over a 96-month time horizon using the Vensim® PLE Version 10.2.2. software.

The rotations and crops that were assigned to some productive units fluctuate according to size; therefore; in the simulation, the data were disaggregated to analyse the information in a general way from the soil section of the case study, which would make up the total production in the municipality of each of the agricultural goods mentioned there and the impact they generate on the resources available for the development of each product. The second part, from each of the productive units of family farming and the respective rotation or crop, identifies the behaviour of the different variables, such as soil degradation in productive units where a rotation is selected and the total water footprint.

The municipality's agricultural frontier for the simulation of transitional crops is 3986 hectares, considering the type of soil classified between good, medium, and regular. Regarding permanent crops, the initial planted area of each of the productive chains in the municipality was considered, and the maximum area for occupation is 714 hectares for permanent crops and 544 hectares for the development of other fruit trees, considering the classification according to the irrigation system.

Figure 14 shows the allocation and scheduling of crops.

Transitional crop rotation

<table>
<tr><th></th><th colspan="28">Months</th><th colspan="2">Assignment</th></tr>
<tr><th></th><th>1</th><th>2</th><th>3</th><th>4</th><th>5</th><th>6</th><th>7</th><th>8</th><th>9</th><th>10</th><th>11</th><th>12</th><th>13</th><th>14</th><th>15</th><th>16</th><th>17</th><th>18</th><th>19</th><th>20</th><th>21</th><th>22</th><th>23</th><th>24</th><th>25</th><th>26</th><th>27</th><th>28</th><th>Total FFPU</th><th>Total land</th></tr>
<tr><td>1</td><td></td><td></td><td></td><td colspan="6">Quinoa</td><td></td><td></td><td></td><td></td><td colspan="5">Oat</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td>10%</td><td>4%</td></tr>
<tr><td>2</td><td colspan="4">Pea</td><td colspan="7">Potato</td><td colspan="5">Bulb onion</td><td colspan="7">Wheat</td><td></td><td></td><td></td><td></td><td></td><td>60%</td><td>77%</td></tr>
<tr><td>3</td><td colspan="5">Barley</td><td></td><td></td><td></td><td></td><td></td><td></td><td colspan="4">Pea</td><td colspan="7">Potato</td><td colspan="4">Carrot</td><td></td><td></td><td>10%</td><td>5%</td></tr>
<tr><td>4</td><td colspan="3">Coriander</td><td colspan="6">Corn</td><td colspan="4">Pea</td><td colspan="7">Potato</td><td colspan="7">Wheat</td><td></td><td>10%</td><td>8%</td></tr>
<tr><td>5</td><td></td><td></td><td></td><td></td><td></td><td colspan="6">Bean</td><td colspan="7">Potato</td><td colspan="4">Carrot</td><td></td><td></td><td></td><td></td><td></td><td></td><td>10%</td><td>5%</td></tr>
</table>

Annual fluctuation in land area sowing for permanent crops

	Year								**Initial land (ha)**
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	
Strawberry	2.2%	2.6%	5.1%	5.0%	2.2 %	2.6%	5.1%	5.0%	70
Cape gooseberry	− 0.6%	− 0.8%	4.8%	− 36.3%	− 0.6%	− 0.8%	4.8%	− 36.3%	3
Blueberry	41.4%	11.6%	14.8%	19.7%	41.4%	11.6%	14.8%	19.7%	15

Figure 14. Crop rotation.

4.3. Results Based on Crop Rotation and Permanent Crops

Three sections were considered for the presentation and analysis of the simulation results. The first focused on analysing land use for each rotation and scheduled permanent crops. The second examined the impact of the development of these crops on water resource consumption. The third addressed the overall impact on land use and water resources from the combined development of the five rotations and three permanent crops in the municipality in which the case study was concerned.

4.3.1. Soil Resource

Rotation 1 (Figure 15) was assigned to 10% of productive units, with the sequencing of quinoa (red line) and oat (blue line) crops. Regarding the available land for this assignment, at the beginning of the simulation, it developed over an area of 159.44 hectares; however, over time, as the productive chains developed and according to the simulation results, by the end of the 8-year time horizon, there was a 0.84% reduction in land with suitable conditions for crop development. The red line in Figure 15 is reflected in the reduced area occupied by quinoa cultivation in month 96 compared to the area initially assigned for the rotation's development (green line).

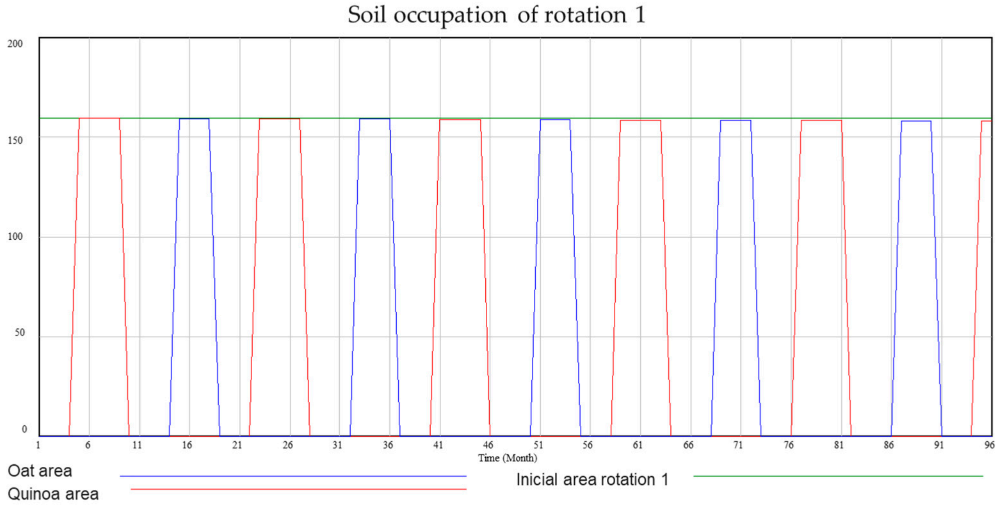


Figure 15. Soil occupation of rotation 1.

In rotation number 2 (Figure 16), where 60% of the productive units cover an area of 3069 hectares, plant pea (green line), bulb onion (grey line), potato (blue line), and wheat (red line) are cultivated. By the end of year 8, 3027 hectares was available for planting, indicating that rotation 2 resulted in a 1.34% degradation and subsequent soil loss. This is evident in the reduction in the area occupied by the wheat crop between months 91 and 96 compared to the area initially assigned for the development of this rotation (black line).

Rotation number 3 (Figure 17) was assigned to 10% of the agricultural productive units and 5% of the area (199.3 ha) of the agricultural frontier, where pea, barley, potato, and carrot are cultivated. By the end of the simulation period, this rotation resulted in a 1.17% loss, meaning the area available for crop development would be 196.9 ha.

Rotation 4 (Figure 18) was scheduled for 8% of the available area, i.e., 318.88 ha (10% of the agricultural productive units), where cilantro, maize, pea, potato, and wheat crops are sequenced. These crops resulted in a soil loss of 1.50% by the end of the simulation period, leaving 313.68 ha available for developing productive chains after the simulation.

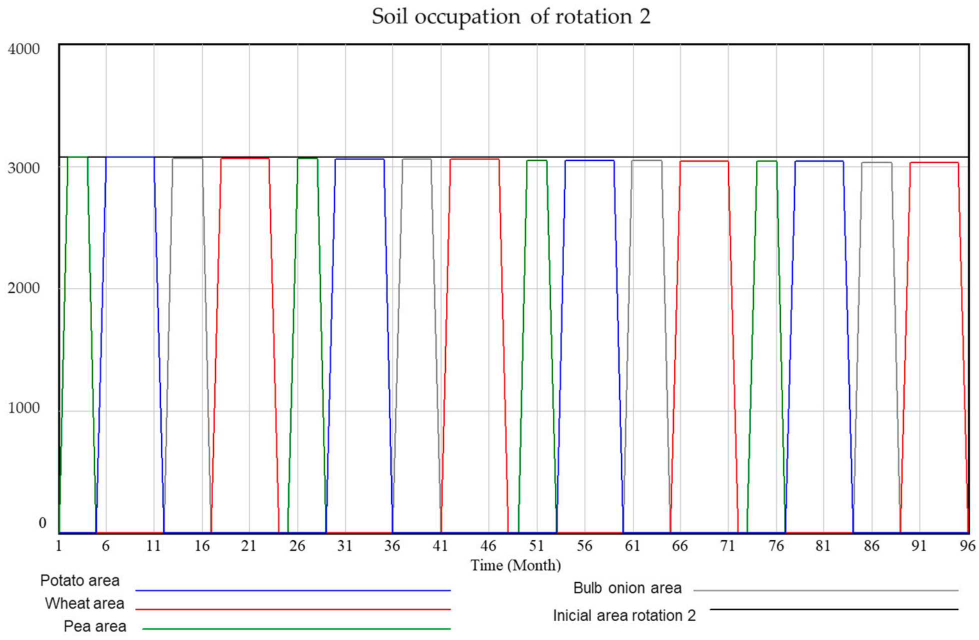


Figure 16. Soil occupation of rotation 2.

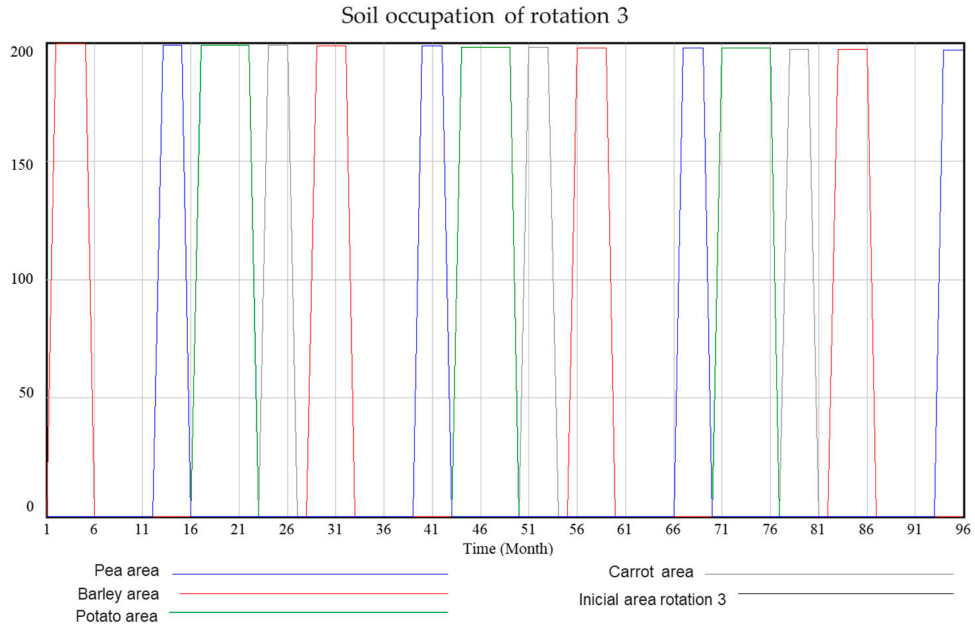


Figure 17. Soil occupation of rotation 3.

Rotation 5 (Figure 19) was assigned 5% of the available area, that is, 199.3 ha (10% of the agricultural productive units), where the sequence of bean, potato, and carrot crops is expected to take place. This results in a 1.01% loss of soil available for cultivation.

Figure 20 shows the soil occupation with respect to permanent crops. Unlike the case of temporary crops, degradation or loss is not compared in the same way; however, an increase in land occupation is observed for the development of these productive chains.

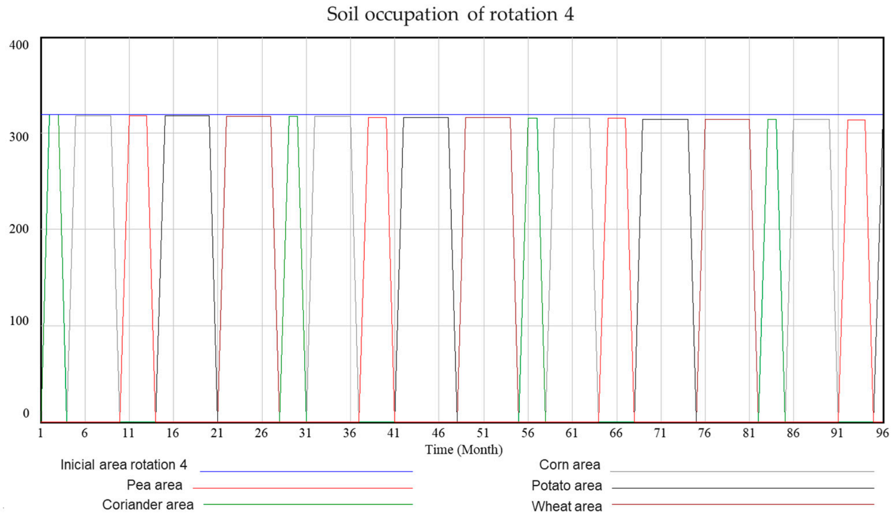


Figure 18. Soil occupation of rotation 4.

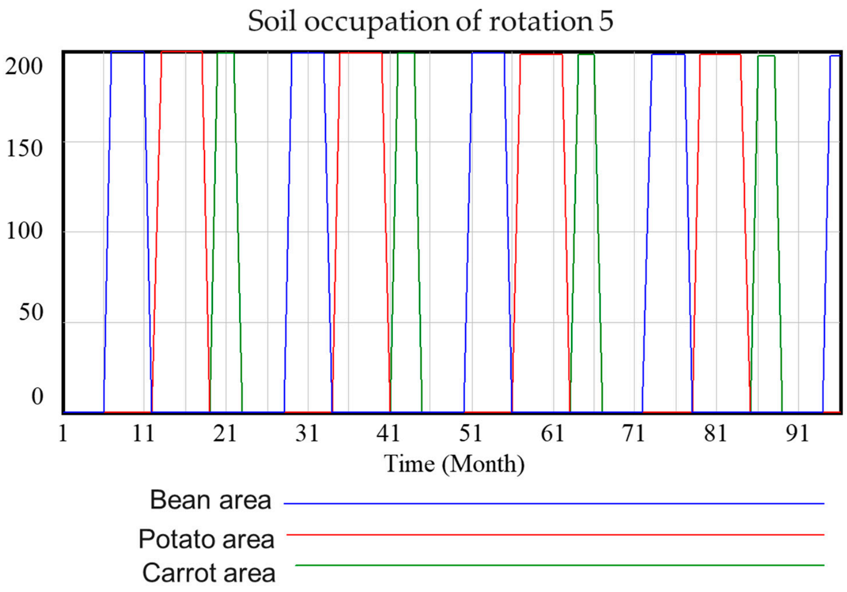


Figure 19. Soil occupation of rotation 5.

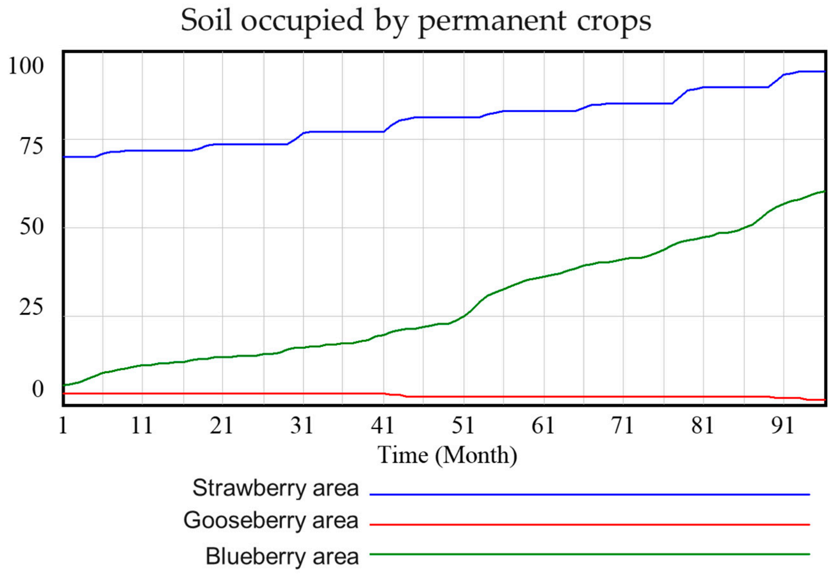


Figure 20. Soil occupied by permanent crops.

4.3.2. Water Resource

Regarding the results by rotation, it is observed that in the first rotation, where the crops of oats and quinoa are sequenced, Figure 21 shows the green, blue, and grey footprints generated by the scheduling of these crops in the municipality. This results in a minimum total water footprint of 1715.17 m^3/ha and a maximum monthly footprint of 3053.17 m^3/ha. A lower demand is evident in the grey footprint, indicating reduced chemical consumption for developing the assigned agricultural production chains. This rotation allows for the development of the production chain, particularly with water demand being met by precipitation (green footprint) and low water consumption for irrigation (blue footprint).

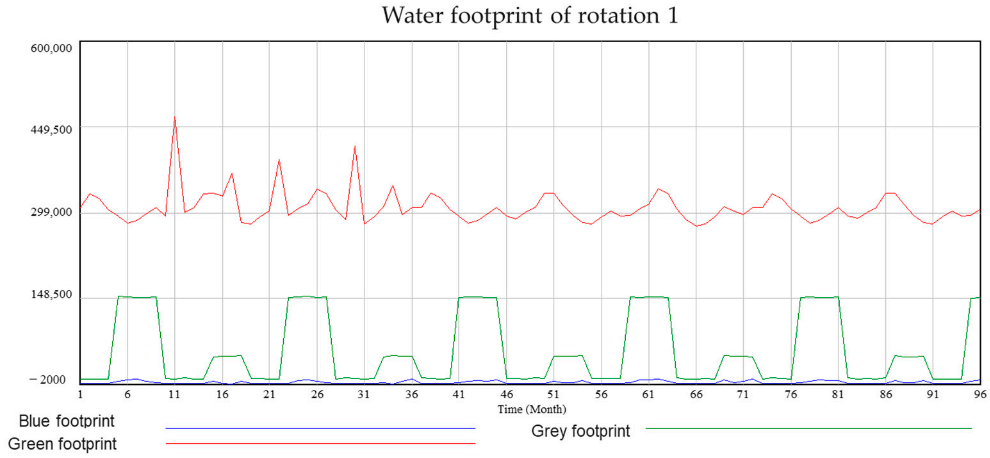


Figure 21. Water footprint of rotation 1 (m^3).

Regarding the water resources in the second rotation, where pea, bulb onion, potato, and wheat crops are scheduled, the water footprint is presented in Figure 22. It shows a significantly higher grey water footprint than green water during several months, especially during the development of the pea and wheat crops. A lower water footprint is also observed in January, May, and December, with a minimum value of 92.7 m^3/ha. Meanwhile, February, March, and April experience higher consumption, with a maximum monthly value of 2796.3 m^3/ha.

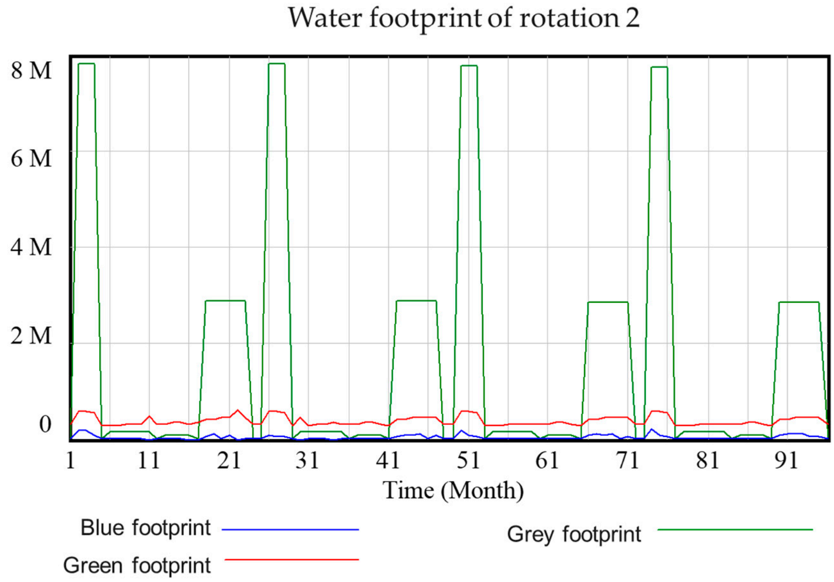


Figure 22. Water footprint of rotation 2 (m^3).

Regarding the water footprint of rotation 3 (Figure 23), where pea, barley, potato, and carrot crops are assigned, a higher volume is observed for the green water footprint. However, in the case of the grey water footprint, during the development of the pea crop and considering the high nitrogen consumption during its growth, a greater demand for the water resource is evident. It is important to determine whether these high fertiliser consumption levels are compensated for by the demand for this component from future crops included in the rotation.

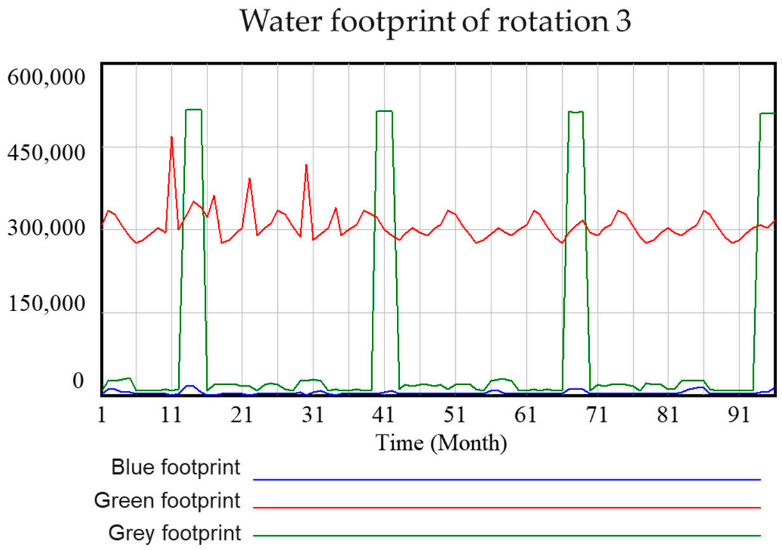


Figure 23. Water footprint of rotation 3 (m^3).

Regarding the water footprint of rotation 4 (Figure 24), where the crops of cilantro, maize, pea, potato, and wheat are assigned, a higher volume is observed for the green water footprint. However, in the case of the grey water footprint, during the development of the pea crop, it exceeds the green footprint considering the high nitrogen consumption during its growth, which results in a greater demand for water resources. Additionally, the impact of the grey footprint, which is close to the values of the green footprint, is generated during the development of the maize and wheat crops.

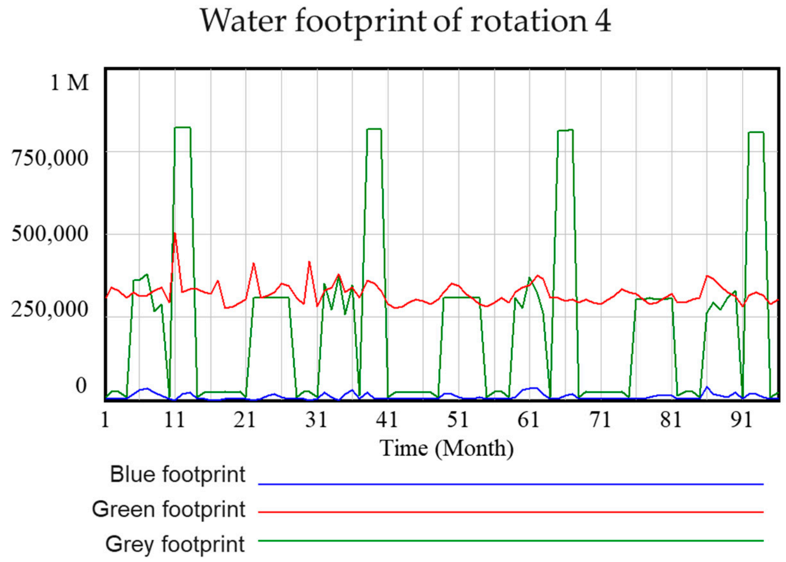


Figure 24. Water footprint of rotation 4 (m^3).

In rotation 5 (Figure 25), the crops of beans, potatoes, and carrots are assigned. The most significant impact occurs in the green water footprint, followed by the grey and blue footprints. Regarding the grey footprint, an increase is observed, especially during the development of the bean crop.

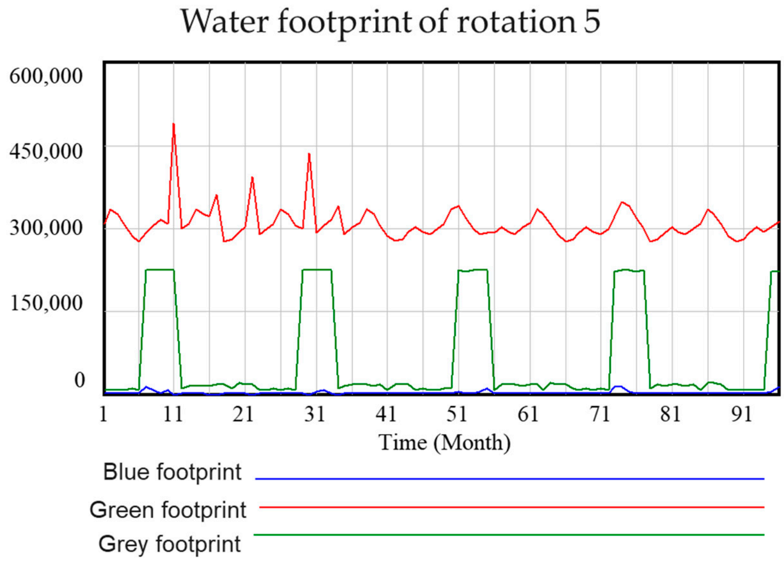


Figure 25. Water footprint of rotation 5 (m^3).

In the case of the impact on the water resource (Figure 26) generated by the development of the productive chains of permanent crops, a higher value of the grey footprint is observed until approximately month 60, at which point the impact of the green footprint increases. That impact can be linked to the increase in the area occupied by the blueberry crop. For permanent crops, more efficient irrigation systems are used than temporary crops, resulting in more responsible water resource consumption.

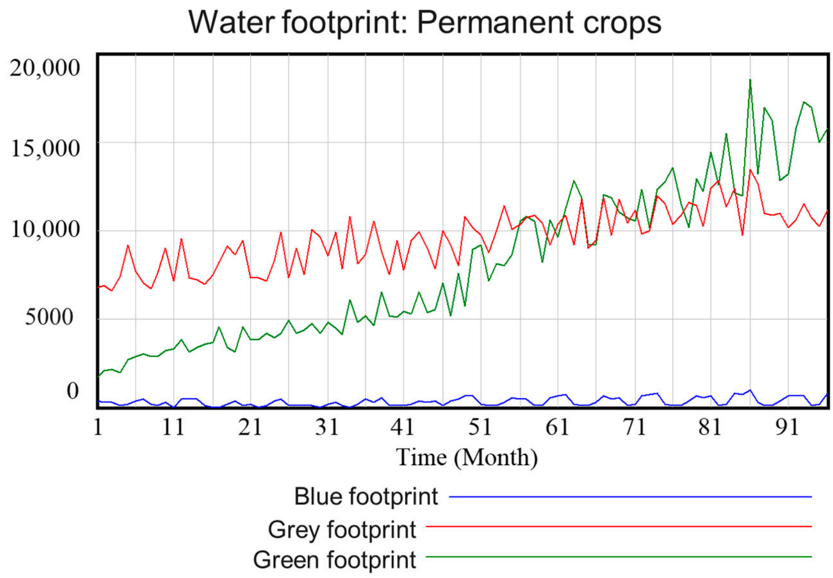


Figure 26. Water footprint of permanent crops (m^3).

4.3.3. Final Results

The scheduling of the previous rotations of temporary and permanent crops impacts the natural resources used. In the simulation of crop scheduling, land occupation is based on the area of suitable land for developing agricultural chains in the municipality. The initial area is 4700 hectares, including the land available for temporary and permanent crops. By the end of year 8 in the simulation, a 1.29% reduction in land is observed compared to the initial value, representing the loss of soil conditions for subsequent use in agricultural activities.

As shown in Figure 27, the green line represents the available land (ha) for crop development in the municipality where the case study is concerned. The red line represents when a temporary crop is planted, occupying an area of land (ha), while the blue line represents the land (ha) occupied by permanent crops.

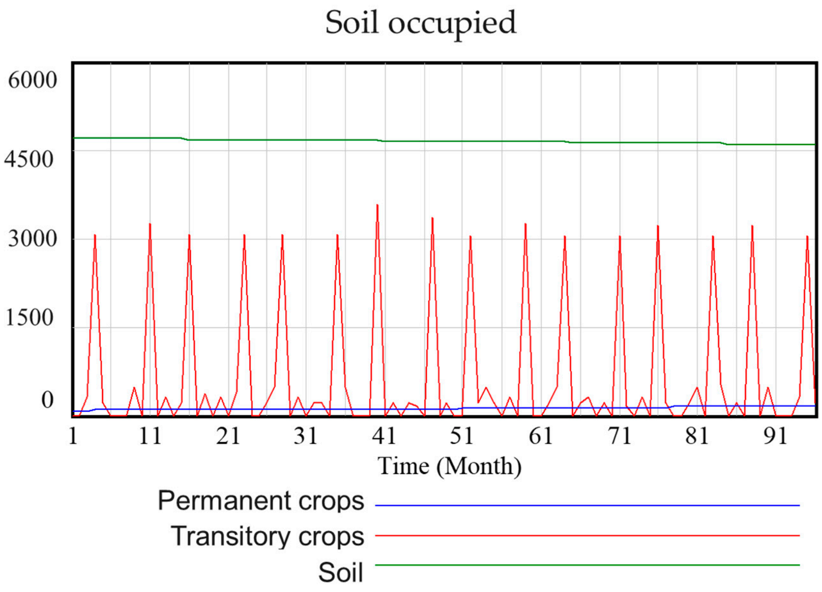


Figure 27. Total soil occupation: permanent and transitory crops.

Regarding the occupation of available land by families of temporary crops, it is observed that throughout the scheduling, the crops can occupy the entire available land without idle periods in the area, which results in a more significant impact on the degradation of available soil. Permanent crops occupy a smaller area; however, the planted area increases over time. Additionally, it is important to consider that permanent crops require more significant investment and development time than temporary crops.

Concerning the water resource, it is important to note that the parameters were calculated for each rotation and the respective scheduled crops (Figure 28). However, in this simulation, it is unclear whether the high fertiliser consumption can be compensated by the demand and requirements of the next crop assigned to the same area.

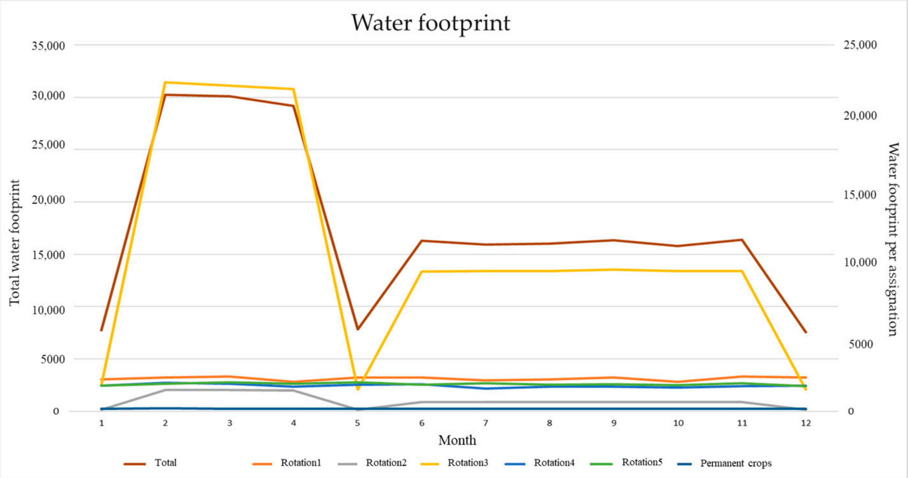


Figure 28. Water footprint per rotations and permanent crops (m^3).

The water footprint shows high freshwater consumption, especially for the dissolution of amendments, fertilisers, and pesticides required to develop agricultural goods. However, these are discharged into the soil or water sources, and it is expected that they meet quality standards for human consumption, which is represented in Figure 29 as the grey footprint. Regarding the water demand for the crop, supplied to the plants by precipitation (green footprint) and irrigation water (blue footprint), the latter is lower than the former.

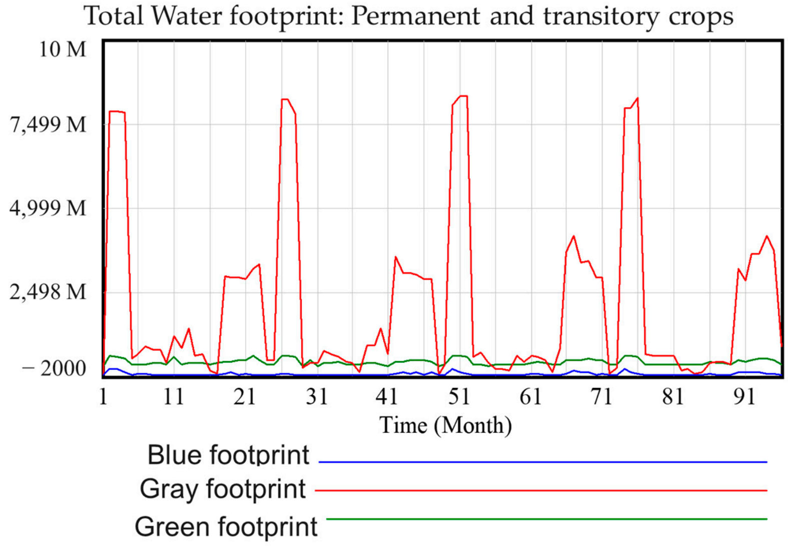


Figure 29. Total water footprint: blue, green, and grey footprints (m^3).

Regarding the total footprint, a more significant impact was found in January, which coincides with the dry season and the risk of frost in the municipality. Likewise, water demand is higher, especially in the first half of the year.

These results are presented for a configuration of possible rotations according to the area's agricultural vocation. However, scenarios can be explored according to demand behaviour and other variables that could be included in the model presented. The proposed model allows for decision making regarding the best use of available natural resources and the coordination of agricultural activities in family farming production units.

5. Conclusions

Through the conceptualisation of the model in the proposed sections and the subsequent dynamic simulation, it was possible to consider and evaluate different important variables in the development of the agricultural production chains of transitory and permanent crops in the case study municipality. The model considered relevant environmental factors such as the soil, degradation, and loss of the same resource; the use of the water resource required for the development of each of the production chains over the time of the simulation; and an analysis regarding the blue, grey, or green water footprint for the development of these crops.

Although crop rotations, which reduce soil degradation and loss, are evaluated in the model, taking into account the conditions of the agricultural frontier of the case study and the suitability of the municipality's soil, the development of agricultural activities affects the soil and water resources, resulting in depletion or pollution. However, the responsible development of agricultural activities is part of the strategies for the conservation of resources over time and for sustainable agriculture.

The tool presented can support decision making in agricultural production units. Evaluating crop rotation scenarios and their impact on natural resources allows stakeholders to anticipate risks and coordinate planning across units. Based on the conditions and suitability of the municipality, this evaluation can improve crop outcomes, promote sustainable agricultural value chains, and serve as a valuable tool for farmers and regulatory bodies.

It is relevant to disseminate research results in an academic field and with the actors that comprise the agricultural production units and the control entities. These tools allow those involved to make informed and responsible decisions, managing natural resources, the workforce, and costs, among other things.

The model could be used in other production chains, municipalities, departments, or case studies; the parameters must be adapted to be appropriate.

In future research, it is important to carry out a more detailed study that takes into account the size of the productive unit within the simulation, which will allow for the evaluation of the costs in detail, the investment and technification per productive unit, and the impact on the performance of each production chain according to the efficiency of the irrigation system used. It would also enable an evaluation of the development of these productive chains in lands with a regular or bad soil type, taking into account said soil, investing in its recovery, and carrying out the adequate development of agricultural practises while taking into account the total area of the agricultural frontier of the municipality.

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