Sustainable Nutrient Management in a Typical Uruguayan Dairy Farm through Nutrient Budget and Modelling

Submitted in fulfillment of the requirements for the degree of

Master in Sustainability in Sustainable Regional Development

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ABSTRACT - Uruguayan dairy production is fundamental for this country and is under scrutiny due to the environmental impacts that it causes. The impacts are primarily the result of inefficient management practices, which lead to excessive use of nutrients – mainly nitrogen and phosphorus - and their surplus flow into the environment affecting rivers, groundwater and soil. In this context, this thesis aimed to generate new knowledge for informing the Uruguayan dairy sector to achieve a more sustainable production by understanding which farming management practices maximise nutrient efficiency and reduce environmental damage. It also aimed to contribute to the strategic planning of the Uruguayan Government for achieving a sustainable dairy farm production system.

The thesis implemented a multi-methodological approach to the case study of a typical Uruguayan dairy farm through the application of the *Nutrient Budget Method* and an agent-based model called *Nitrogen Phosphorous Management* (NPM). The combined results from their application demonstrated that, along with the use of correct management practices, it is possible to be more efficient in nutrient use and, in this way, dairy production systems can be less dependent on nutrient inputs.

The main findings indicated that nitrogen biological fixation, pastoral diets, cows' stocking rate and phosphorous accumulation in soils are key management variables that affect nutrient efficiency and environmental impacts. Furthermore, it was concluded that the presentation and discussion of important research outcomes in a *collective learning* approach between researchers and farmers improves their understanding of environmentally-friendly practices as well as enhance their essential roles as sustainable managers, on behalf of society, of finite natural resources.

Keywords: Agent-based Modelling, Dairy Farmers, Nutrient Budget, Nutrient Efficiency, Sustainable Development

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GLOSSARY

Adaptation: ´The process of adjustment to actual or expected climate and its effects...In some natural systems, human intervention may facilitate adjustment to expected climate and its effects´ (IPCC, 2014).

Agent-Based Model: ´This model is an appropriate tool to be used in systems composed of autonomous ´agents´ that interact with each other and their environment, differ from each other and over space and time´ (Railsback and Grimm 2019).

Circular Economy: ´A model of economic, social, and environmental way of producing and consuming that eliminates the concept of waste. It is proposed as opposite as the model of linear economy, in which industrialized food systems are based´ (Ellen MacArthur Foundation, 2013).

Climate Change: ´A change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods´ (UNFCCC, 1992).

Collective Learning: ´Model based on open learning among diverse interests that can improve communication and achieve lasting system change´ (Brown and Lambert 2012).

Dairy Farm Effluent: ´All material (solid or liquid) that has been in contact with animal manure and is destined for storage or application to land. This includes the manure itself (i.e., faeces and urine) as well as any wash-water, bedding material, feed, milk, etc. that is mixed with it´ (Dairy NZ 2015).

Efficiency: ´Efficiency is perceived as maximising products with the minimum possible use of external subsidies´ (Llanos et al. 2013).

Environmental impact: ´Any change to the environment, whether adverse or beneficial, wholly or partially resulting from an organization's activities, products or services´ (FAO 2018a).

Eutrophication: ´Over-enrichment of water by nutrients such as nitrogen and phosphorus. It is one of the leading causes of water quality impairment. The two most acute symptoms of eutrophication are hypoxia (or oxygen depletion) and harmful algal blooms´ (IPCC 2014).

Excreta: ´Waste expelled from the body: faeces plus urine´ (Pain and Menzi 2011 cited by FAO 2018a).

Footprint: ´Metrics used to report life cycle assessment results addressing an area of concern´ (Ridoutt et al., 2016 cited by FAO 2018a).

Hard System Thinking (HST): ´HST approaches are goal-orientated in tackling structured problems, mainly in the physical field, where defined objectives and constraints exist and the significant variables are generally quantifiable´ (Sposito 2021).

Input: ´Product, material or energy flow that enters a unit process´ (FAO 2018a).

Land Use: ´The total arrangements, activities, and inputs undertaken in a certain land cover type. The term land use is also used in the sense of the social and economic purposes for which land is managed´ (IPCC, 2014).

Livestock: ´Domesticated terrestrial animals that are raised to provide a diverse array of goods and services such as traction, meat, milk, eggs, hides, fibres and feathers´ (FAO, 2018b).

Mitigation: ´An anthropogenic intervention to reduce the sources or enhance the sinks of greenhouse gases (GHGs)´ (IPCC, 2014).

Multi Methodology: ´The combinations of methodologies (possibly from different paradigms) and methods together in a single intervention´ (Jackson, 2019).

Output: ´Product, material or energy flow that leaves a unit process´ (FAO 2018a).

Paradigm: ´A set of theories, concepts, methodologies, and methods in relation to a specific field´ (Sposito, 2020b).

Planetary boundaries: ´Planetary boundaries within which we expect that humanity can operate safely. Transgressing one or more planetary boundaries may be deleterious or even catastrophic due to the risk of crossing thresholds that will trigger non-linear, abrupt environmental change within continental- to planetary-scale systems´ (Rockström et al. 2009).

Production system: ´The scale, purpose and nature of the farming enterprise´ (FAO, 2018a).

Resilience: ´The capacity of social, economic and environmental systems to cope with a hazardous event or trend or disturbance, responding or reorganizing in ways that maintain their essential function, identity, and structure, while also maintaining the capacity for adaptation, learning, and transformation´ (IPCC, 2014).

Risk: ´The potential for consequences where something of value is at stake and where the outcome is uncertain, recognizing the diversity of values. Risk is often represented as probability or likelihood of occurrence of hazardous events or trends multiplied by the impacts if these events or trends occur´ (IPCC, 2014).

Soft System Methodology (SSM): ´An epistemology which enables you to learn your way to taking action to improve a problematical situation or a wicked situation´ (Checkland, 1981).

Sustainable Development: ´The ability to make development sustainable to ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs´ (WCED, 1987).

System approach: ´Approach that considers the production variables and system components in a holistic way´ (Sposito 2021).

Uncertainty: ´A state of incomplete knowledge that can result from a lack of information or from disagreement about what is known or even knowable´ (IPCC, 2014).

Vulnerability: ´The propensity or predisposition to be adversely affected ´ (IPCC, 2014).

LIST OF ABBREVIATIONS

Initials	Meaning
BNF	Biological Nitrogen Fixation
CH_4	Methane
CO_2	Carbon Dioxide
CONAPROLE	National Cooperative of Milk Producers
DIEA	Office of Agricultural Statistics
DM	Dry matter
FAGRO	Faculty of Agronomy
FAO	Food and Agriculture Organization of the United Nations
GHGs	Greenhouse Gases
GIS	Geographic Information System
Ha	Hectare
HST	Hard Systems Thinking
INALE	National Milk Institute
INIA	National Institute of Agricultural Research
IPA	Agricultural Plan Institute
IPCC	Intergovernmental Panel on Climate Change
Kg	Kilogram
L	Litres
MA	Ministry of Environment of Uruguay
MGAP	Ministry of Agriculture, Livestock and Fisheries of Uruguay
MUN	Milk Urea Nitrogen
MVOTMA	Ministry of Housing, Territorial Planning, and the Environment of Uruguay
N	Nitrogen
NO	Nitrogen Oxide
NO_3	Nitrate
NBF	Nitrogen Biological Fixation
NPM	Nitrogen Phosphorous Management Model
NUE	Nitrogen Use Efficiency
N_2O	Nitrous Oxide
P	Phosphorous
PO_4^{3-}	Phosphate
PUE	Phosphorous Use Efficiency
PPM	Parts Per Million
SSM	Soft Systems Methodologies
UDELAR	University of the Republic, Uruguay
VM	Milking and Dry cows
VO	Milking cows
WECD	World Commission on the Environment and Development

CHAPTER 1: INTRODUCTION

This chapter explains the research background and the problematic situation under study. It includes the thesis' aims and research questions, which are followed by the expected outcomes. Finally, a diagram of the thesis structure is included.

1.1. Research Context

A significant volume of international research has been published on the agriculture impacts in natural resources, particularly water systems, and biodiversity in current circumstances as well as in unfolding climatic changes (Moss 2008, Tubiello et al. 2015, Darré et al. 2021).

The international efforts have resulted in multiple national policies to meet agreed standards for mitigating the environmental impacts of food and fibre production (IPCC et al. 2015). Therefore, objectively quantifying the environmental impacts of agriculture is a fundamental requirement in research and protocols for the management of commercial production systems (Tubiello et al. 2015).

Uruguay, in South America, is primarily an agricultural-based country. Their extension is 176.000 km2, where approximately 160.000 km2 are good soils for potential agricultural utilization (INE 2011). The country has moderate temperatures and a good regime of precipitations. It is thus an interesting developing country to assess the different environmental effects caused by agriculture as well as examine feasible solutions to improve the perceived problematic situations.

The following figure shows the location of Uruguay in South America.

Figure 1. Map of Uruguay in South America.

Source: elaborated by the author, adapted from Google Maps (2021).

One of the principal agricultural sectors in Uruguay is the dairy industry, which involves 3,300 dairy farmers with an annual production of 2,200 million litres of milk (INALE 2021). The dairy industry is also essential for this country due to the labour involved and the national and regional/rural income it generates. Thirty per cent (30%) of industrialized milk is for internal consumption and seventy per cent (70%) is destined for export, making Uruguay the seventh-largest milk exporter in the world (INALE 2021). Figure 2 shows the main economic indicators of agriculture, in general, and dairy, in particular.

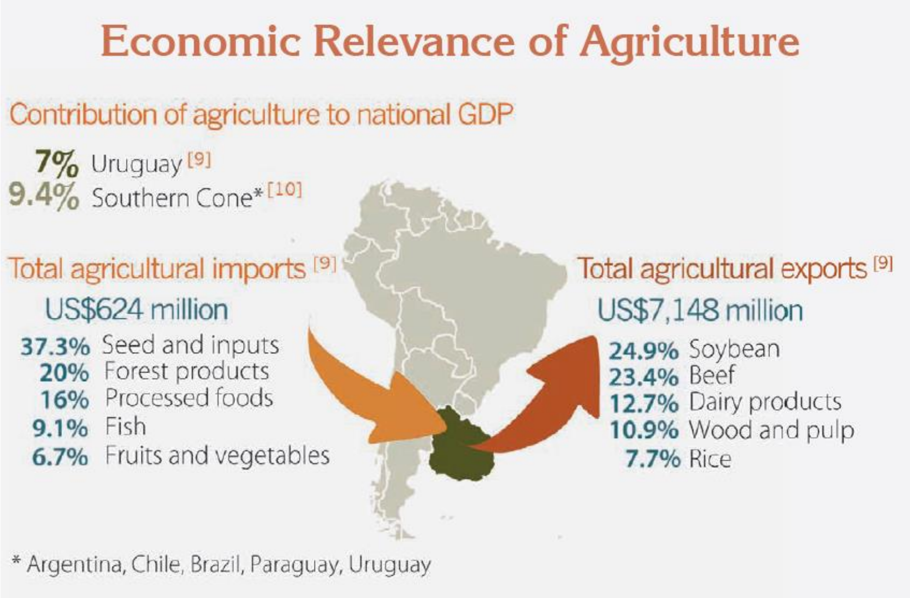


Figure 2. Economic relevance of Uruguayan agriculture.

Source: World Bank and CIAT (2015 p. 2).

The quantification of the environmental impacts at a national geographic level must take into account the specific characteristics of agriculture and the whole production context in the country of concern (IPCC 2019a). According to the Ministry of the Environment of Uruguay (MA 2020), the largest contributor to greenhouse gases (GHGs) in Uruguay is the agricultural sector and the gases with the major contribution are nitrous oxide and methane. Especially in dairy farms, the carbon footprint is dominated by the agricultural production phase, with methane emissions coming mainly from the food fermentation that occurs in the rumen and nitrous oxide emissions from nitrogen (N) excretion in urine and the application of N-based fertilizers (Lizarralde 2013).

Similarly, it is necessary to evaluate nutrients export from dairy farms to other ecosystems such as watercourses (Tayyab and McLean 2015). The environmental impact of dairy farms is a major contributor to river eutrophication; for example in the Santa Lucía River Basin of Uruguay (Aubriot et al. 2017). This large basin is the main source of drinking water in this country and their contamination is partly associated with the historical presence of dairy farms in its catchment since it is a predominant region of dairy production (Aubriot et al. 2017).

An agroecosystem sustainability approach seems to be an appropriate tool to address the nutrients environmental impact of dairy farms in order to achieve a robust ecological foundation, using the ecosystem knowledge inherent to agroecology (Gliessman 2004). Furthermore, this approach considers the production variables and system components in a holistic way (Sposito 2021). The complexity of the management practices interacting with the diversity of soil type, topography, climate, and hydrology generates a substantial spatial and temporal variation in nutrient pollution, making necessary a national-level evaluation (Cherry et al. 2008).

Moreover, Rockström et al. (2009, p.1) stated that at a global scale, there are high-risk zones for the *Planetary Boundaries* – limits within which expect that humanity can operate safely - in the biogeochemical cycles of N and phosphorous (P) because of the growth of fertilizers' use in modern agriculture. This means that the agricultural intensification through the subsidy of production systems with external nutrients inputs must be both questioned and evaluated. Because of this, it is essential to understand the structural and functional relations between different components of agricultural production systems.

According to Lizarralde and Astigarraga (2014), when the production efficiency increases - for example, when animal production augments with the same number of external inputs - the environmental impact due to N and P surplus as well as their carbon footprint tend to decrease. Therefore, farm-scale analysis and the quantification of the management practices are essential for achieving farms with efficient nutrient utilization and reductions in their negative environmental impacts.

Several researchers, such as Carbó (2011) and Gourley et al. (2012), consider that nutrient budget analysis enables to adjust the agriculture management practices in order to reducing nutrients losses to the environment and improve the monetary margins accruing to farmers. *Nutrient Budget* is a method to evaluate a farm's nutrient performance (see Section 2.6). In addition to supporting farmers' nutrient management decisions, the budgets can be valuable for informing policy-making and as regulatory tools in themselves (Gourley et al. 2007).

It is considered then that there is a necessity for prioritizing and focusing research on measures for mitigating N loss to enhance environmental and agricultural sustainability (Zhang and Yu 2020). Similarly, Sharpley et al. (2015) stated that further research is required through modelling the phosphorus losses to water systems.

According to Railsback and Grimm 2019, *Agent-Based Modelling* (ABM) is a very useful instrument (or tool) for representing complex agroecosystem possibilities and finding solutions related to environmental problematic situations (see Section 2.7). This means that the evaluation of environmental contamination by nutrients and agriculture practices can be appropriately made by ABM. The system´s approach of ABM is especially convenient because farm nutrient pollution is a complex problem with many agents involved, and ABM further enables modelling in geographic *space and time*.

To conclude the outline of the problematic situation caused by current agricultural practices in Uruguay (and in similar countries), this thesis' approach is considered important to this country in its expected contribution to achieving sustainable dairy farm production. According to the literature briefly described above and comprehensively covered in Chapter 2, there is a compelling needed to evaluating the management practices in dairy farms to reduce nutrient contamination to the environment. In particular, this thesis intends to contribute to the understanding of what a sustainable dairy farm approach is through nutrient budgets and ABM modelling.

1.2. Research Aims and Research Questions

In the above context, this thesis aims to generate new knowledge for informing the Uruguayan dairy sector to achieve a more sustainable production by comprehending which farming management practices maximise nutrient efficiency and reduce environmental damage. It also aims to contribute to the strategic planning of the Uruguayan Government to achieve sustainable dairy farm production across the country.

The research focuses, in particular, on understanding which farming management practices maximise nitrogen (N) and phosphorous (P) utilisation efficiency to reduce losses, and negative environmental impacts, to the environment. The approach is based on a case study involving a typical dairy farm within the national productive, socio-ecological, and economic Uruguayan context.

The following research questions guide the research.

Research Question 1 (RQ 1) - How can the current Uruguayan dairy farm configuration be transformed to be more sustainable?

Research Question 2 (RQ 2) - Which are the dairy farm management practices that reduce nutrient pollution?

Research Question 3 (RQ 3) - Which management scenarios maximize nutrient efficiency and, at the same time, minimize the nutrient losses to the environment?

Research Question 4 (RQ 4) - Can Agent-based Modelling (ABM) spatialize the nutrient dynamics of a dairy farm?

In addition, this research intends to assist farmers in their decision-making by developing different research outcomes and analysing and discussing them with farmers in a *collective learning* approach. It is considered that this would contribute to the improvement of farmers' understanding of environmentally friendly practices as well as enhancing their role as managers, on behalf of society, of finite natural resources.

1.3. Expected Outcomes

Taking into consideration the aims described above, the expected outcomes of this research are the following.

- The development of a nutrient budget evaluation of a typical Uruguayan dairy farm. This evaluation should provide sufficient information to be used as a farm decision support tool. Nutrient budgeting focuses on nutrient efficiency and assessment; subsidy (external inputs) rate; estimation of environmental losses, like leaching and volatilization; among other productive and environmental variables.
- The development of the *Nitrogen Phosphorous Management Model* (NPM), an Agent-Based Model. This will permit modelling the impact of agriculture management practices via N and P dynamics in a typical dairy farm. This is very useful for farmers and decision-makers to model different management practices as well as design and assess feasible farm-scale solutions.

- The thesis also includes technical conclusions on the Uruguayan dairy farm context. This information related to sustainable dairy farming and efficient management practices is helpful to apply at a farm and regional/local scales. As a result, it is possible to reduce the losses of nutrients to the environment, maximize dairy production and contribute to the sustainable development of dairy farms.
- The research outcomes can be used to assist the strategic planning of the Uruguayan Government to achieve sustainable dairy farm production. Specifically, they can contribute to nationals plans to reduce the nutrient contamination to waterways and to the goal of greenhouse gas reduction (MGAP 2019; MVOTMA 2019).

The outcomes of the research were presented to a Uruguayan dairy farmers' group in which the case study farmer is a member (and participant at the meetings with the group). As will be discussed, it is possible to promote collective learning and contribute to sustainable development at the farm level with this type of interactions. The research beneficiaries include the dairy farmers, as the research outcomes can improve their knowledge and improve their decision-making. The research can also enhance the knowledge and skills of agricultural technicians and its use as farmers' assistance instruments. Finally, the research is also significant for planners and other researchers in environmental and agricultural planning.

1.4. Thesis Outline

The thesis has been structured in six main chapters as shown in the following table.

Table 1. Thesis outline

1	**Introduction:** This chapter provides the overall research context and framework, including an outline of the research aims, questions, and expected outcomes.
2	**Literature Revie**w: The second chapter summarises the significant theoretical approaches and literature related to dairy farm management practices, emphasising sustainability and nutrient dynamics. It includes several topics and approaches that provide the essential elements that guide and support the analysis of this thesis – especially nutrient budget and modelling.
3	**Research Methodology:** This chapter firstly includes a description of the multi-methodology and the key methods used in the research. Secondly, a description of the Uruguayan dairy farm context and the dairy farm case study is presented. Finally, the nutrient's budgets and the agent-based model Nitrogen Phosphorous Management (NPM) – are explained.
4	**Results:** This chapter presents the results of the research through the application of the methods included in the methodology. Stage 1 of the methodology, *problem formulation* is carried our using a *Rich Picture* method. Results of the Stage 2, *situation and diagnosis* are described through a social-ecological dairy farm framework, the nutrients budgets, and the agent-based model (NPM). Finally, the analysis of management scenarios is presented as a guide to possible *solutions* (Stage 3) to the formulated problem.
5	**Discussion:** This chapter discusses the main findings in the first three methodological stages - *problem formulation, situation and diagnosis, and solutions*, and compare them with other relevant studies. The analysis and discussion are particularly focus on the problem formulated, the nutrient dynamic results, and the collective learning and sustainable dairy farming. The applications of nutrient budget and agent-based model in a farm-scale are also analysed.
6	**Conclusion:** In this final chapter, the *main findings* of the research are firstly summarised. Secondly, the contribution to knowledge is described by reference to the answering of the *Research Questions* posed at the beginning of the study. Thirdly, some research limitations and methodological considerations are mentioned. Further research in the topic and specific directions for improvement are then discussed. The chapter concludes with a personal reflection.

CHAPTER 2: LITERATURE REVIEW

This chapter discusses the main literature underpinning the thesis' research. It includes several topics and approaches that provide the essential elements that guide and support the analysis of this thesis.

Figure 3 depicts the Literature Review framework, representing the main topics, the various approaches that support the research and the relationships between them.

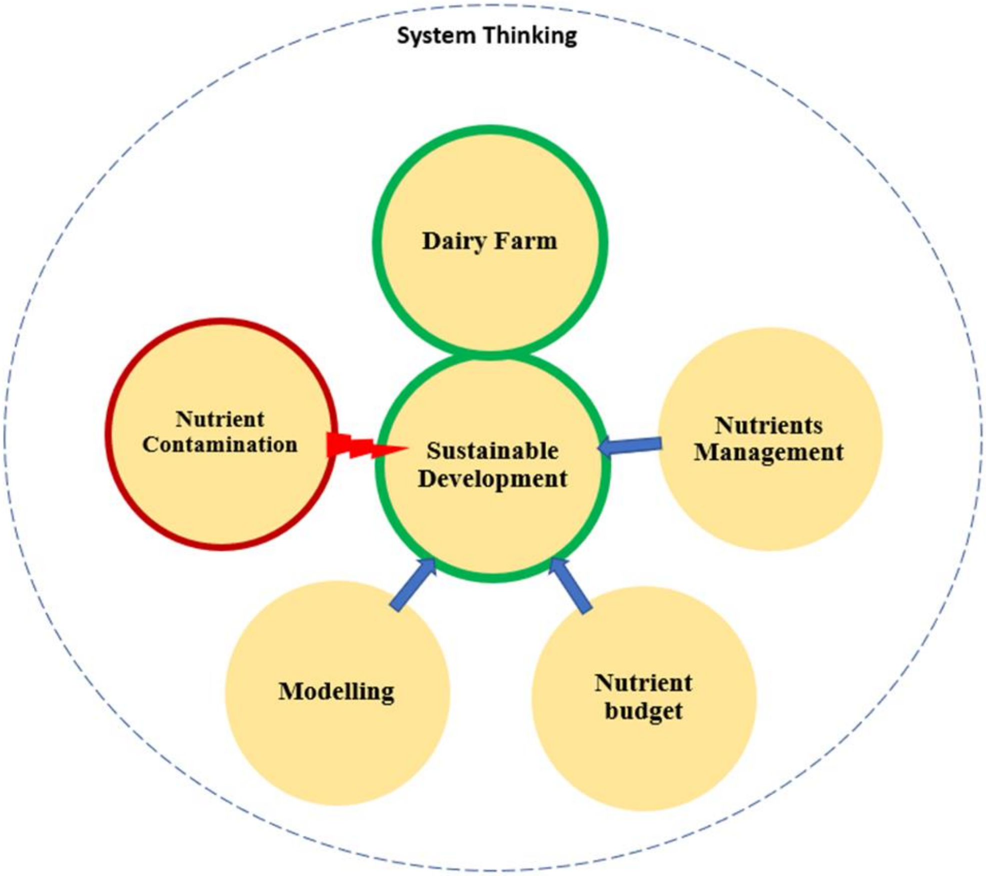


Figure 3. Literature Review Framework.

Source: elaborated by the author.

2.1. Sustainable Development

It is necessary to clarify in general terms what is meant by *sustainability* and *sustainable development*. While the first term refers to the state that a system (i.e.; an economic, social, environmental, or organisational entity) can persist over time, the second term can be defined as the path or framework to achieve sustainability (Sposito 2020a).

In the same line, WCED (1987, p.15) defined sustainable development as the ´development that meets the needs of the present without compromising the ability of future generations to meet their own needs´. The Brundtland Report (WCED, 1987) stressed that economic development is threatened if the natural resources upon which development is based are degraded. It is also stated that economic growth has been not considering the finite resources and the environmental effects on these limited natural resources.

For these reasons, a *holistic approach to sustainable development requires a multi-dimensional perspective focused on four spaces or fields*: *economic, ecologic, organizational, and socio-cultural* (Sposito 2020b). Sustainable development is situated in the intersection of the spaces, as is represented in Figure 4. This significant notion is based on System Thinking and the concept of topological spaces as proposed by the French economist Perroux (Sposito 2020b).

Moreover, this approach highlights that to achieve the sustainable development in the four is essential having a goal or vision for the long term and actions for the short term. According to Sposito (2020a, p. 57), ´the decision-making fields reflect the need for a holistic approach to reconcile socio-cultural, economic, and environmental values and principles for the long-term conservation of the environment and the present and future community's well-being´.

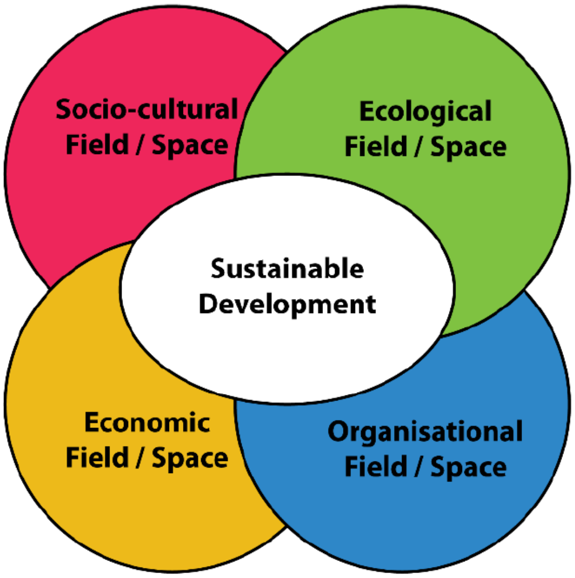


Figure 4. Decision-making spaces for sustainable development.

Source: Sposito (2020b, p.166).

According to Sposito (2020), each of the spaces has a strategic objective - protecting the integrity and resilience of ecosystems (ecological field), improving human welfare (economic field), enriching human development (socio-cultural field) and developing sustainable organisations/institutions (organisational field). Also, the complex systems have direct and indirect drivers of change that operate in that sustainable development spaces, as is summarised in the following figure.

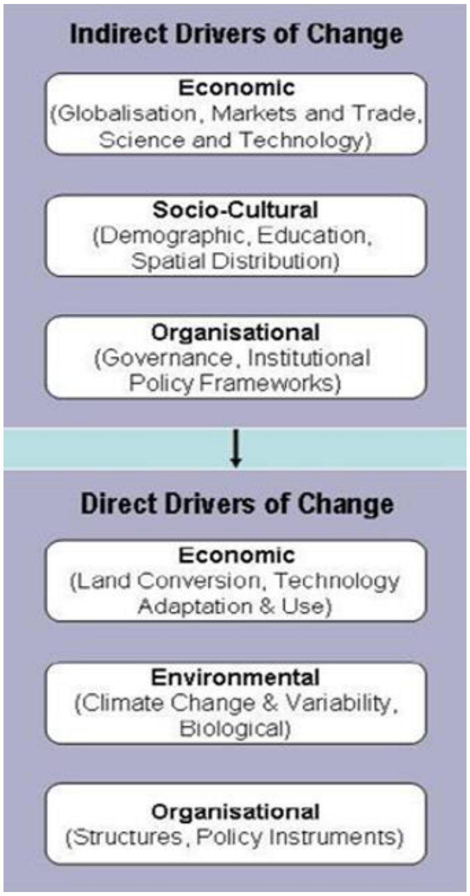


Figure 5. Direct and indirect drivers of change.

Source: Sposito (2020b p. 10).

According to Sposito 2020a, ecologists have developed the concept of *ecological integrity* (general health and resilience of a system) to understand how agroecosystems respond to environmental change. Resilience is defined as ´the capacity of a system to absorb disturbances and sustain and develop its fundamental function, structure, identity and feedbacks through either recovery or reorganisation in another context; that is, its ability to adapt to change´ (Sposito 2020a, p.53). In the same line, Mazzeo et al. (2017a) states that resilient thinking intends to understand the mechanisms that ensure the system's resilience in confronting the drivers of change.

The *multifunctional agriculture* approach considers providing food and conserving natural resources and biodiversity, giving society recreation and tourism, generating employment and economic incomes, and creating a rural culture (Sposito 2020b). Moreover, the multifunctional agriculture concept can be related to environmental, economic, and social capital, as the figure below represents.

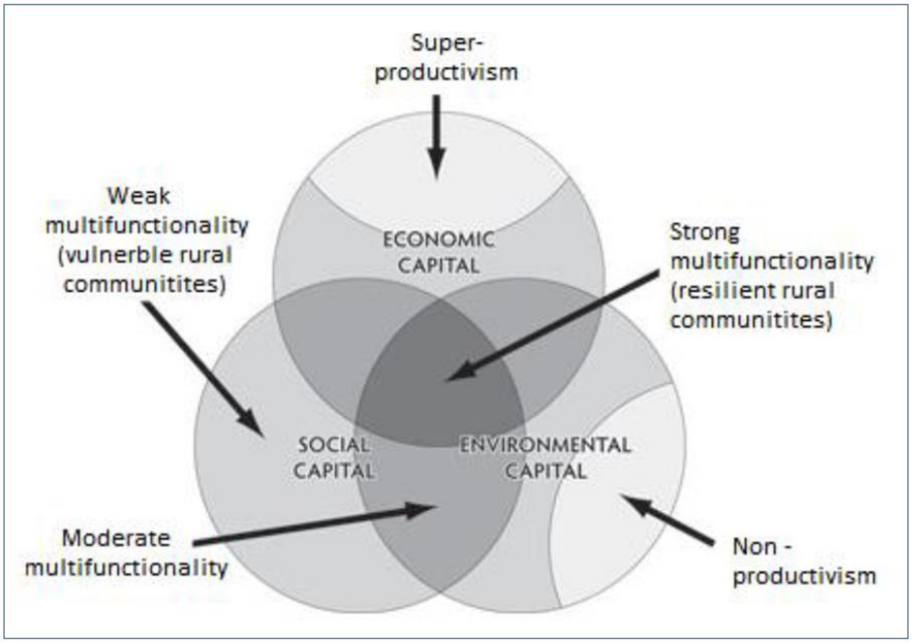


Figure 6. Multifunctional agriculture.

Source: Wilson, (2010, p. 367, cited by Sposito 2020b).

2.2. System Thinking

Modern System Thinking is a discipline which is especially useful in scientific research, planning, and decision-making. During the last five decades, scientists have been moving ´from a traditional reductionist approach to a holistic approach due to the necessity of facing complex problems that are undefined and risky´ (Sposito 2021, p. i).

According to Sposito (2021, p.18), there are two fundamental aspects in the system's idea: ´holism in viewing the reality perceived and systems methodologies to deal with the issues (problems and opportunities) that exist in that perceived reality´. *Holism* is the crucial idea of System Thinking and refers to that the notion that the total is greater than the sum of its parts and cannot be explained only with the nature and constitution of their parts. The other most significant aspect of System Thinking is using a diversity of *systems methodologies* to tackle complex, risky, and uncertain problematic situations. The methodologies are generally structured in well-defined stages, or phases or steps, to ensure the systematic planning, evaluation, and implementation of the actions taken to improve the perceived problematic situation (Sposito 2021).

Another important idea from Systems Thinking is the notion of *multimethodology*. Multimethodology refers to linking different methodologies and methods, probably from different paradigms in a single systemic intervention (Jackson 2019). A multimethodology approach allows ´to address different aspects of problem situations and ensure that technical and practical requirements and stakeholders' interests are given proper consideration´ (Sposito 2021, p. 78).

There are two major forms of System Thinking, *soft and hard*. While soft system approaches are applied to the procedure of dealing with the world, hard system thinking (HST) approaches are goal-oriented to tackle the (physical) world (Sposito 2021).

The process of inquiry in the soft system approaches is ordered as a *learning system*. The most extensive approach used in this group is Peter Checkland's *Soft System Methodology*. It is defined as ´an action-oriented process of inquiry into problematical situations in the everyday world; users learn their way from finding out about the situation to defining/taking action to improve it´ (Checkland and Poulter 2006, p. 22). Furthermore, Checkland's SSM commonly tackles illstructured issues that are difficult to be quantified especially those associated with human-mediated problematic situations (Sposito 2021).

In contrast, HST methodologies are goal-orientated to tackle quantifiable structured problems in the physical field. The use of simulations is common in HST, deploying diverse methods and models.

A systems methodology - and methods (from the focus methodology itself or from other systems methodologies) - is generally used as a *framework* for the analysis of the system of concern and problematic situation(s) in which the system is immersed. There are many methods that can be appropriately deployed from both soft and hard systems thinking according to the uniqueness of the problematic situation, and the people in the situation, to assist in planning and decision making. It is however convenient to apply most than one method to ensuring that the key aspects of the system of interest are holistically understood. Therefore, it is essential for decision-makers and planners to utilise a multimethodological framework (Sposito 2020a).

An example of a SSM method to analyse messy situations is the *Rich Picture* (RP) formulated by Checkland himself. A RP depicts the perceived problematic situation's relationships, viewpoints, structures and issues. By contrast. (mathematical) models – as simplification of reality - are essential components of HST to explore a system behaviour, capturing their variables and their interactions (Sposito 2021). According to Jackson (2011), once the model is built, it is possible to explore how the system behaves without taking any action that may negatively impact in the system itself - see Section 2.7 an example of Agent-based modelling.

2.3. Agroecosystems and Nutrient Contamination

System Thinking is particularly appropriate to apply in environmental and natural science. For instance, to tackle to agricultural problems where the relations between environment, economy and social systems are complex.

It is generally possible to specify a system with four elements: the inputs, the outputs, the states and a description as a model, or transformation, that relates inputs, outputs, and the system´s states over time (Sposito 2021).

The application of System Thinking to agriculture and livestock production enables the conceptualisation and description of an agroecosystem with two kinds of outputs (Hart, 1985). One type of output is related to *services and goods,* whilst the other type of output is related to *production processes*. According to Hart, the second output is associated with the environmental damage caused to the agroecosystem.

The inputs of the system are often considered as external *subsidies*. In production systems, efficiency is perceived as maximising products with the minimum possible use of external subsidies. According to Llanos et al. (2013), in pastoral dairy farms, the subsidies, interpreted as inputs, include, for instance, animal feed and fertilisers.

Moreover, to define a system is necessary to comprehend its *operation* (Meadows 2010). The system´s operation is given by the relation between components, as the processing of inputs, through internal flows of matter and energy, to produce outputs. The system definition must then consider monitoring the systems variables and a dynamic modelling of the problem.

In an agricultural production system, according to Dieguez et al. (2008), there is a linear relationship between the N inputs and the surplus losses to the environment. This indicates the limited capacity of retaining nutrients in products and that the excess is generally lost to the environment. In the same line, Veltman et al. (2017) state a complex connection between the efficient use of resources, environmental impact, and productivity increment. Likewise, when the production efficiency rises, the N and P surplus and carbon footprint tend to decline (Lizarralde and Astigarraga 2014).

Furthermore, Rockström et al. (2009) stated that the biogeochemical cycles of macronutrients are essential in agroecosystems. These nutrient cycles have been modified across history by humankind because of agricultural and industrial activities. In general terms, the N and P movement is accelerated through the agroecosystem by agriculture intensification and is associated with water flows. Water streams work as nutrient conductors, and because of runoff, water deposits function as a nutrient sink. This impact on the biogeochemical cycle of nutrients also contributes to climate change because of the increment of emission of greenhouse gases such as nitrous oxide. These are some of the anthropogenic pressures included by Rockström et al. (2009) in the Planetary Boundaries framework.

The planetary boundaries consist of nine biophysical processes that regulate the Earth system, as the following figure represents. Each of the processes has a threshold that if transgressed, it can be harmful or catastrophic due to the risk of destabilising the biosphere. These limits thus describe ´a safe operating space for humankind´ to survive and develop (Rockström et al. 2009, p.2).

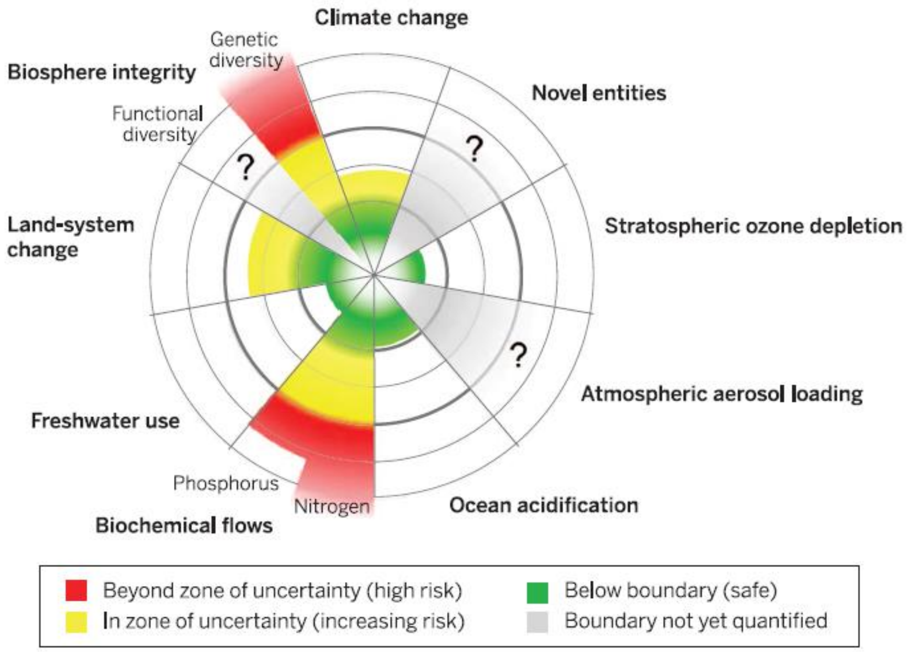


Figure 7. Planetary Boundaries.

Source: Steffen et al. (2015, p.1).

According to Smith (2003), the eutrophication of water systems is one of the principal environmental nutrient's impacts. Eutrophication is the over-enrichment of water by nutrients such as nitrogen and phosphorus (IPCC 2015). Although eutrophication is a natural process, human activity accelerates it.

The eutrophication in water systems provokes two main impacts - oxygen depletion and the explosive increment of damaging algal blooms (IPCC 2015). Another significant aspect of this phenomenon is the reduction of water quality and the change of freshwater ecological function and structure (Carpenter et al. 1998 cited in Dodds et al. 2009). Furthermore, the figure 8 depicts the key effects associated with nutrients' increment that impact on the value of freshwater ecosystem goods and services.

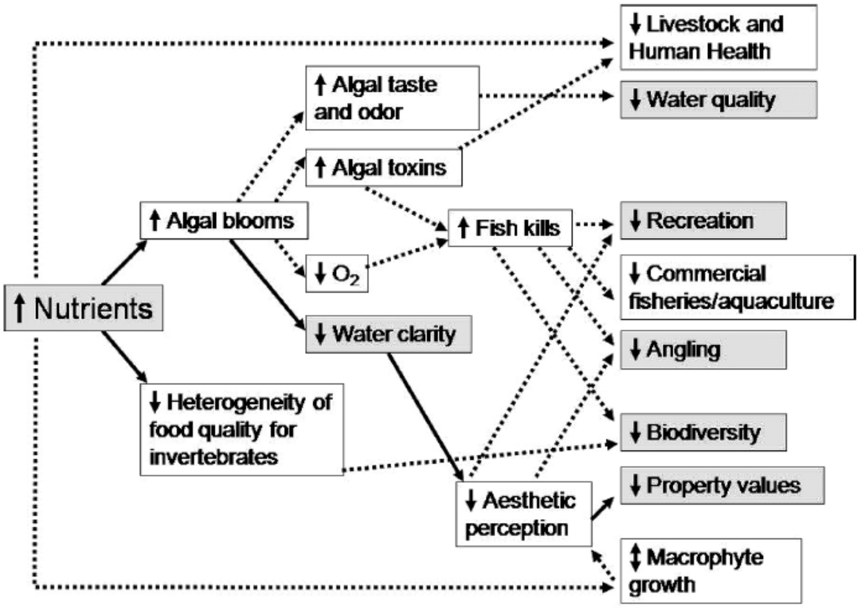


Figure 8. Eutrophication effects.

Source: Dodds et al. (2009, p. 12).

2.3.1 Dairy farm contamination

In many cases, the intensification of dairy production increases environmental impacts such as nutrient losses to streams and rivers and an increase in greenhouse gases (Baskaran et al. 2009). The contribution of dairy farms to nutrient losses to waterways can be categorized by *point and diffuse sources*. According to Tayyab & McLean (2015), the point sources are associated with grazing and water movement, and the diffuse or non-point sources involve fertilizer or manure applied in the paddock. Furthermore, a dairy farm's surface and groundwater contamination risk can be divided into geographical and property factors. These are influenced by the soil permeability, the slope and distance towards the watercourse, watercourse flow, water table depth and milking cows’ number (DINAMA et al. 2008).

According to the Minister of Environment (ME 2020), the major contributor to the greenhouse gases of Uruguay is the agricultural sector. In this sector, the gases that produce the most significant contribution are N_2O and CH_4, instead of having CO_2 as the principal GHG as other sectors. In dairy production, the primary carbon footprint is dominated by the agricultural phase (Lizarralde 2010). Furthermore, methane emissions come mainly from the food fermentation that occurs in the rumen. In reference to nitrous oxide, the main source of emissions is the excretion of N in the urine of animals and the N fertilizer applied (Lizarralde 2010).

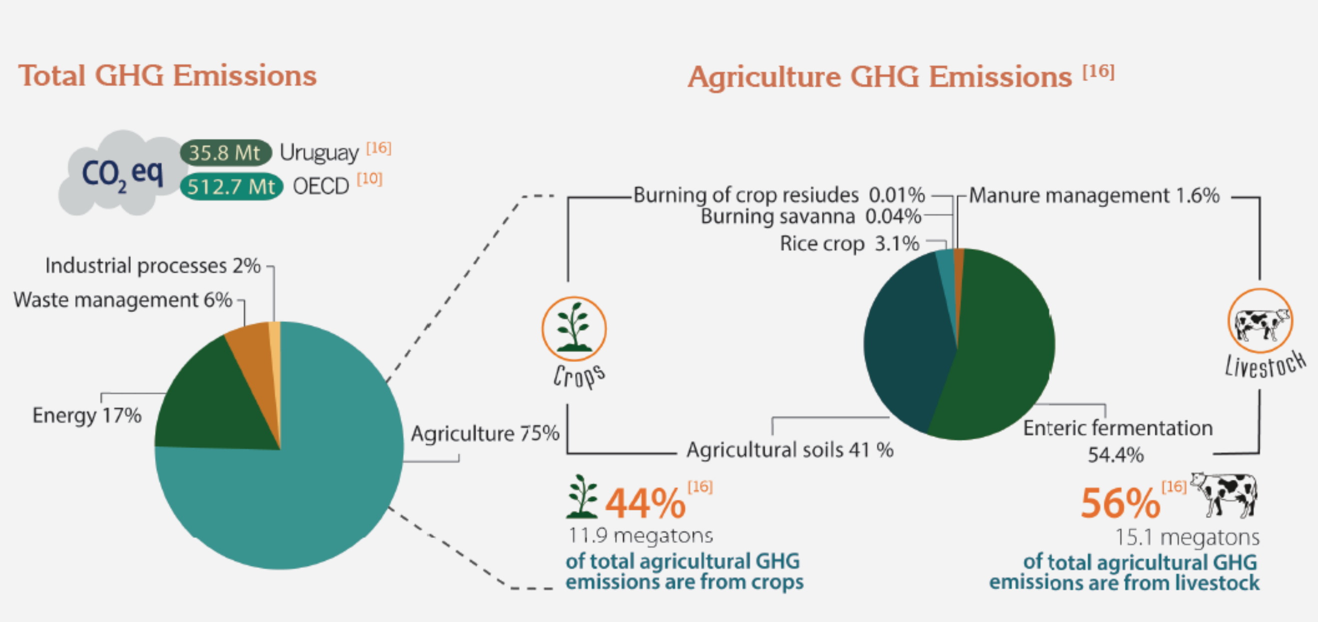


Figure 9. Uruguayan agriculture GHG emissions.

Source: World Bank and CIAT (2015, p.4).

An example of dairy farm impact occurs in the Santa Lucia Basin of Uruguay through the significant effects of eutrophication (Barreto et al. 2017; Olano 2017; Delbene 2018). This large basin is a predominant dairy farm region with cultivated and natural pastures and is essential to Uruguay because it is the primary drinking water resource (Aubriot et al. 2017). Uruguayan research found that the streams in basins with a higher proportion of dairy farms had lower quality than those with fewer dairy farms (Arocena et al. 2012). Similarly, Dodds et al. (2009) estimated that all the dairy farms ecoregions studied in North America had an excess of total N and P values for rivers and lakes.

2.4. Nutrient’s Dynamics in a Farm

According to FAO (2018a) and Cherry et al. (2008), to comprehend the effect of farms management practices, it is essential to understand the nutrients dynamics. Consequently, in this section, the N and P main dynamics are described.

2.4.1. Nitrogen dynamics

Nitrogen is an essential nutrient for life and represents the fourth element in the abundance of biomolecules (Irisarri 2014). The N cycle in farm systems has three inevitable principal loss pathways: nitrate (NO_3) leaching, nitrous oxide (N_2O) emissions, and ammonia (NH_3) volatilization (Whitehead 1995 cited in Ryan et al. 2011). According to Eurostat (2011), significant N losses to the atmosphere occur in N_2O, NH_3, nitric oxide (NO) and dinitrogen (N_2). While NH_3, N_2O and NO are pollutants, the N_2 emission no. Apart from that, N losses to aquatic systems in nitrate, ammonium, and dissolved organic N, leading to pollution and reducing soil fertility. The following figure represents the N losses and flows schematically in agricultural systems.

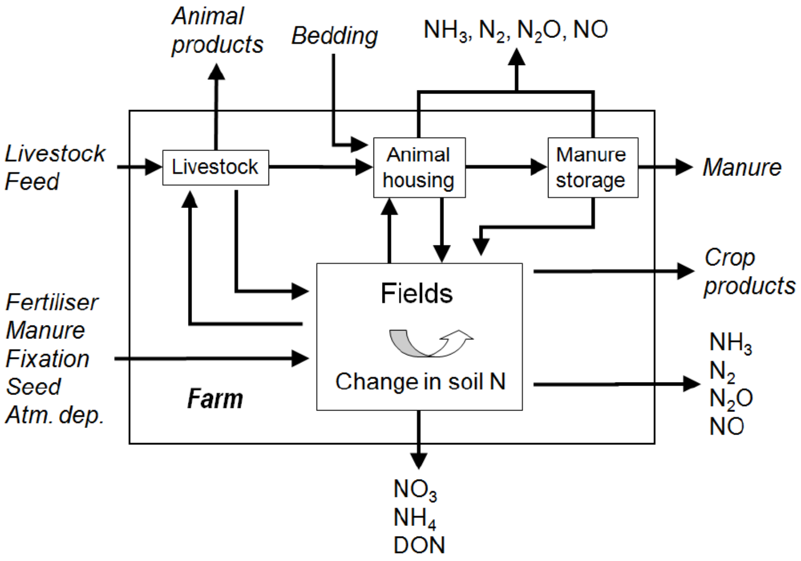


Figure 10. Main N flows and losses in agricultural systems.

Source: Eurostat (2011 p. 8).

Davidson et al. (2012) state that the agriculture, industry, and energy sources have been duplicated the amount of annual reactive N in the soil. Similarly, Schlesinger (2009) claim that the current agriculture is increasing the amount of N fertilizer used and is altering the N cycle, growing the nutrient losses to the environment.

According to IPCC (2019b), N_2O is a regular gaseous product of the nitrification-denitrification processes, and the soil availability of inorganic N is the main controlling factor in this reaction. In Uruguay, it is estimated that 99% of this gas emission derive from the agricultural sector, and 90% of these come from the excretions of grazing animals (MVOTMA, 2010).

Furthermore, agricultural soils are considered the primary source of N_2O, including the N from the ground, recent atmospheric deposition, fertilization, crop residues and the presence in underground aquifers (Irissari 2014). According to Rochette and Janzen (2005), biological nitrogen fixation

(BNF) is not considered a direct source of N_2O because there is no evidence of significant emissions from this process.

According to Mosier et al. (1996), the increment of N_2O emissions has been related to the increase in N fertiliser use and the mineralisation rise of organic N in agricultural ecosystems because of changes in management or land use. In crops after fertilisation, the emissions usually increase for a relatively short period and then return to the initial level (Mosier 1998). The report of IPCC (2019b) states to assume a factor of 1% of the N added to the soil to prepare national inventories of N_2O from agriculture. Furthermore, the basal emission level is more related to the level of organic matter in the ground and its mineralisation rate, rather than only depending on recent additions of N to the soil (Peterson et al., 2006). Uruguayan research (Perdomo et al. 2009) found that the use of fertiliser in the crops did not increment the emission of N_2O, probably due to the high use efficiency by the cultivation (Perdomo et al.2009).

While Perdomo et al. (2009) found no consistent differences between the emission of N_2O from direct sowing compared to conventional tillage, other authors reported much higher N_2O fluxes under direct sowing (Ball et al. 1999 and Passianoto et al. 2003, cited in Perdomo et al. 2009).

Perdomo et al. (2009) also observed that the N_20 emissions were higher in continuous agriculture than in natural fields or grasslands. Also, Mosier et al. (1998) suggest minimizing the fallow period to decrease the N_2O emission. In the same way, Perdomo et al. (2009) demonstrated that the event with the highest emission of N_2O occurred in the fallow period.

In reference to BNF, Canfield et al. (2010) state that it is the largest source of fixed N in the biosphere, and it is carried out by prokaryotes collectively called diazotrophs. Díaz Rossello (1992) demonstrated that the pastures rotation incorporated approximately 1 kilogram per hectare of total N by 25 kilograms of dry matter of aerial parts produced by legumes.

According to Cherry et al. (2008) and Davidson et al. (2015), improving nitrogen use efficiency (NUE) is the most effective form of increased productivity and decreased environmental impact. It is because, by restricting the N surplus, the process of leaching decrease considerably.

Furthermore, Ryan et al. (2011) state that if feeding N intake increases, N output in urine, feces, and milk increases, NH_3 emissions increase, N_2O emissions increase and NO_3^- leaching increases. In the same way, Rotz et al. 2005 state that when the N inputs increase, the N losses grow, as is represented in the following graph.

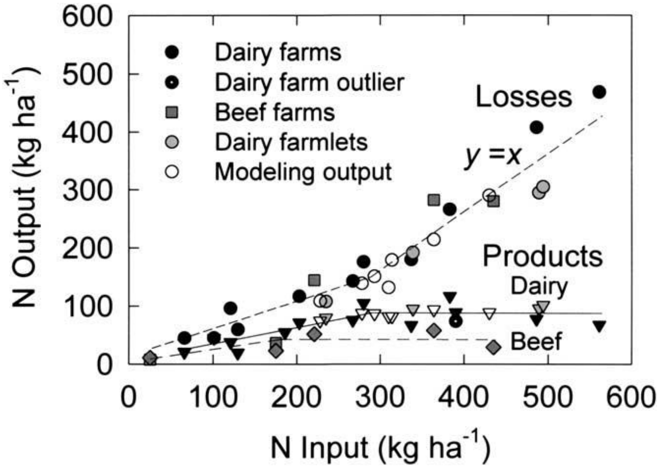


Figure 11. Relation between N input and N output.

Source: Rotz et al. (2005, p. 2142).

2.4.2. Phosphorous dynamics

Withers et al. (2014) stated that P is a primary macronutrient essential for the plant’s growth, and agriculture production has increased its use since the last century. The current dependency of inorganic P in conventional agriculture farms is limited because there are finite global reserves of rock phosphate (PO_4^{3-}). Besides, the reliance on inorganic fertilizers is increasingly inefficient and costly (Withers et al. 2014).

In contrast to N, soils' P buffer effect makes this nutrient need a more extended mitigation strategy. Also, the P soil affinity makes that to control its pollution is required to ´address susceptibility to particle dispersion, detachment, and transport along surface and subsurface pathways´ (Cherry et al. 2008, p. 4).

It has gone from deficit to excess situations of this nutrient in the soil (Withers et al. 2014). According to Fernández-Marcos (2011), phosphorus application in amounts greater than crop requirements lead to a progressive P concentration increment in the soil. Particularly in dairy farms, effluent and manure as organic fertilizer also contributed to this surplus.

The runoff and lixiviation are the main forms of P losses (Fernández-Marcos 2011). Furthermore, Withers et al. (2014) state that the P accumulation in soils and sediments leak into the surface waters and contribute to eutrophication. The P carried by runoff is in solid particles and dissolved phosphorus (Smith et al. 2017). These runoff losses are significant in sloping soils and soils with poor structure and a lack of vegetation cover that facilitate water erosion. Furthermore, the presence of dissolved phosphorus in the surface runoff water increases when the fertilizer is applied to the soil surface (Fernández-Marcos 2011).

According to De Lucca (2020), positive P balances are consequences of the constant inputs from the soil-surface fertilization and animal feed. Furthermore, the soil management of not tillage and the surface application of inorganic fertilizer or manure produces a P stratification of the soil

(Smith et al. 2017). The stratification is the major amount of P in the first soil centimetres and the consequent increment of the potential losses of P by runoff, principally soluble form. Perdomo et al. (2015) and Castagno (2020) report high phosphorus stratification in the first 2.5 cm of soil in Uruguayan dairy farms.

In that way, Perdomo (2015) states that to evaluate runoff, the soil analysis of the first 2.5 centimetres of soil is better than the first 15 centimetres. It is because the soil layer that interacts with the runoff water is between 0 to 2.5 centimetres. Furthermore, it is documented that increases in total and soluble phosphorus loss are associated with direct seeding and stratification (Perdomo et al. 2015).

According to Sharpley et al. 2013, the historic fertilization of PO_4^{3-} sources on the surface, the direct deposition of manure by livestock and soil management generated a legacy of P. Because of this legacy, current mitigation practices are causing a smaller and slower water quality response (Sharpley et al. 2013). The store of P in the land, principally in the first layer of soil is masking the reduction of P losses and inducing the lag time for system response. Similarly, the research of De Lucca (2020) observed a long-term and continuous loss of soluble P in the test treatment caused by the P background or legacy.

Figure 12 represents the P agroecosystem response and the lag time influence of the natural, soil, and best management practices processes.

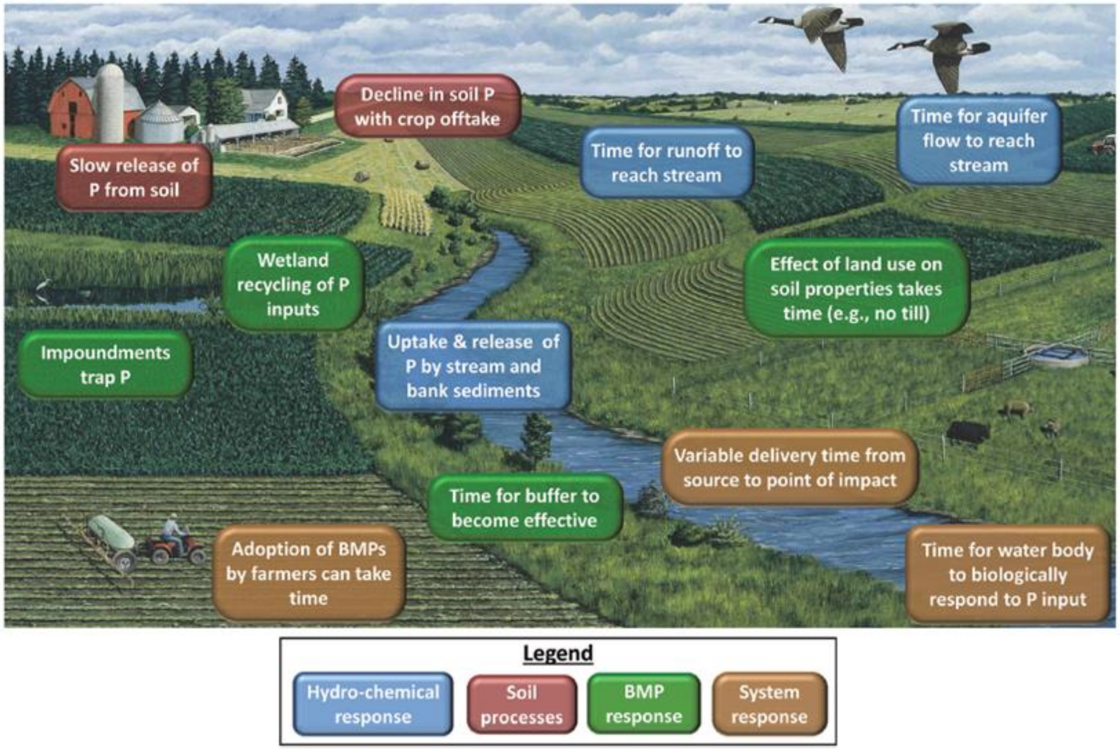


Figure 12. Representation of P agroecosystem response, processes, and lag time.

Source: Sharpley et al. (2013, p.1309).

De Lucca (2020) stated that management practices to reduce P losses to surface water bodies should contemplate the diminishment of soluble and particulate phosphorus. Furthermore, Kleinman et al. (2011) the losses of soluble phosphorus would not be affected by the introduction of management measures that reduce the rate of erosion but only by those that reduce the levels of labile phosphorus and the stratification of this nutrient in the upper layer of the soil. Several investigations (Kleinman et al. 2015 and De Lucca 2020) recommend periodic soil inversion to break P stratification and decrease available P levels on the surface layer. However, the soil inversion should be done in summer when the risk of erosion is low (Quincke et al., 2007; Smith et al., 2007 cited in De Lucca 2020). Also, it is necessary to carry out additional management practices after this tillage to reduce risk, for example, planting fast-growing annual summer pastures (De Lucca 2020).

According to Sharpley et al. (2013), the most significant transport factors are the location in the basin, the soil management practices, the rainfall and runoff. These factors differ across the soils, and it is needed to identify the risk areas of export of phosphorus to decrease the diffuse contamination by this nutrient (Fernández-Marcos 2011). Because of that, it is helpful the P index method to predict the risk of farming P contamination (Sharpley et al. 2001). Perdomo et al. (2015) state that this index can estimate the P losses from agricultural soils. Similarly, Tayyab and McLean (2015) state that quantifying potential P losses, such as the Danish P index, is a prerequisite to achieve an efficient mitigation strategy.

2.5. Management Strategies

It is expected that the increment in food demand would increase not only the agricultural land used but also the production intensity associated with more nutrient’s losses to the environment (Zhang et al. 2015). Numerous investigations have hence been focused on management practices and farm technologies to achieve efficient use of nutrients, reduce pollution and at the same time increment yields (Zhang et al. 2015; Charlón et al. 2014).

There are practicable opportunities to reduce the farm system environmental impact. For example, reducing the subsidies, incrementing the BNF, calculating proper doses and using effluents and manure to recycle nutrients (Charlón et al. 2014). The management strategies chosen to minimise nutrient losses to the environment depends on the farm condition and pollution risk (Fernández-Marcos 2011).

Farm nutrient management is complex, and many decision-making aspects are involved. In that sense, Pretty (2008) focused on the farmer's skills and knowledge, augmenting that the human capital increases the agroecosystem resilience and makes it more independent of costly external inputs.

The primary dairy farm management practices that impact N and P dynamics are expanded in the following subchapters.

2.5.1. Land use

Land use defines the proportion of land covered by crops, grass, legumes of the total farm area (IPCC, 2014). Also, its concept is associated with the land management of the farm. Both aspects can impact the nutrient’s dynamics through several processes that are explained below.

The presence of legumes in the pastures can significantly reduce the farm N inputs because of the biological fixation of the species (Garcia et al. 2021). This process increments the N availability for the grass of the pasture. It means that the mixture of legumes with grass increases nutrient cycling and ecosystem services (Garcia et al. 2021). In the same way, Charlón et al. (2014) stated that increment in the BNF contributes to a farm system being more autonomous to external nutrients inputs and reduce the environmental impact associated.

Regarding land management, some practices are correlated to reduce erosion and conserve the soil structure (Prieto and Osorio 2019). Overall, it is associated with maintaining vegetative cover, buffer zones, reducing tillage, cultivating along the level lines, and correct irrigation management. Similarly, Castagno (2020) demonstrated that higher percentages of soil covered were associated with lower nutrients in runoff water.

Aubriot et al. (2017) claim that to reduce the nutrient losses to waterways is necessary to create buffer zones. To be more precise, according to Lescano et al. 2017, the buffer zones are strip areas between water bodies and crops or livestock production systems that preserve the water quality and diminish nutrient exportation.

According to Lemaire et al. (2015), integrating grass and crops is suitable for improving diversity. In that way, the grassland-cropping rotation results in bigger carbon sequestration and reduction of N emissions, being grasslands essential to minimizing environmental impacts (Lemaire et al. 2015). Furthermore, it is reported an increment in soil organic matter and nutrient retention. Also, the increase of permanent grasslands contributes to reducing nutrient exports as well as maintaining ecosystem services. Similarly, Fariña and Chilibroste (2019) state that the use of permanent or long-term pastures instead of annual crops can decrease the biosphere integrity losses in areas where pastures dominated the original landscape.

2.5.2. Type of animal's diet

Darre et al. (2021) mention that the type of cow's diet is determinant in the dairy farm environmental impacts. This means that the diet proportion of pasture versus concentrates influence the farm nutrient losses.

According to Ryan et al. (2011), the more kilograms of concentrates in the diet, the higher N is available for leaching. In the same way, Tayyab and McLean (2015) state that precise feeding is a valuable strategy to reduce P losses.

Arriaga et al. (2009) conclude that matching nutrients ingestion and requirements is a convenient strategy to decrease N and P excretion in dairy farms. Also, it is possible to optimize supplying feed that contains highly assimilable phosphorus and decrease the P of the excreta (Fernández-Marcos 2011). Similarly, dietary manipulation through the accurate protein intake to animal requirements can reduce N excretion. The increment in NUE and phosphorous use efficiency (PUE) in milk can lead to reductions in N and P excretion (Arriaga et al. 2009).

2.5.3. Stocking rate

The stocking rate influences the farm system performance, not only for the production but also for the environment (Fariña and Chilibroste 2019).

The cow excretion on the paddock can be related to the nutrient losses to the environment. In that way, the lower stocking rate generates lower excreta, which could represent a reduction in environmental nutrient losses (Fernández-Marcos 2011; Arriaga et al. 2009). The excretions deposited in a particular farm area is correlated with the time spent there. Because of that, managing cows' spatial and time distribution is essential to avoid nutrient surpluses in areas where plants cannot use them or be collected for paddock distribution (Gutiérrez et al., 2009).

According to Chilibrostre and Fariña 2019, Uruguay has a lower stocking rate than other countries, implying a lower load of fertilisers and excreta per hectare. It means that the risk of nutrient exportation to waterways is lower. However, it is essential to efficiently distribute the excreted nutrients to avoid losses outside the farm (Klootwijk et al., 2016).

In Castagna (2020), this research's evaluation at the stocking rate levels does not affect diffuse contamination of surface waters since there were no differences in the concentration of nutrients observed in the water runoff.

2.5.4. Synthetic fertilizer and effluent management

Synthetic fertilizer - According to FAO (2018a), it is recommended to make a fertilization programme based on the chemical analysis of soils and the plant's nutritional requirements. Moreover, it is recommended to incorporate the fertilizer into the soil, avoiding the application on the surface to reduce the P stratification in the first ground layers (Fernández-Marcos 2011). Also is recommended the use of PO_4^{3-} fertilizers of slow or controlled release and control the excessive fertilization (Kleinman et al. 2015; De Lucca 2020). Besides, in regions where the rainfall has a specific period, it is possible to space a time between the precipitation and fertilizer application. In the case of Uruguay, where the precipitation occurs unpredictably throughout the year is not possible to plan precisely this time (De Lucca 2020).

In Uruguayan research, De Lucca (2020) demonstrated that while the non-fertilizer treatment had a lower losses level of total P, the fertilizer treatment exceeded the USA limit (5 kg total P ha-1 year-1). On the other hand, the soluble limit was exceeded in all treatments, including the non-application (1 kg soluble P ha-1 year-1). That high P exportation suggests that these farms are partly responsible for the eutrophication problems registered in the Santa Lucia River Basin (Barreto et al. 2017; De Lucca 2020).

Dairy farm effluents - It has been reported that the correct effluents and manure management is fundamental to utilize it as an organic fertilizer and avoid a risk of contamination of the soil, surface, and groundwater (Dairy NZ 2015; Tayyab & McLean 2015; INALE 2019).

INALE (2019) states the necessity of evaluating the effluent, volume, nutrient levels and characteristics. Also, it is needed to define a minimum area of application, considering the current levels of phosphorus and N in the soil, the requirements of the planned crops, the contribution by biological fixation, and contribution by inorganic fertilization and manure in the case of potential fields to be grazed (INALE 2019). Likewise, the application rate must not exceed the soil infiltration rate. This principle allows minimizing the risk of soil erosion due to drainage and surface runoff, both due to particle and nutrient carry-over (INALE 2019). In the same way, according to Senattore and Russo (2019), the average rainfall in the area and the soil capacity determine the possibility of irrigating and the dimension of the effluent pool needed.

According to INALE (2019), the criteria to select an area to apply effluents involve soil analysis Bray I phosphorus less than 31 ppm, the critical value established by MVOTMA (2013) as a maximum limit above which no there is a response to phosphorus fertilization. Besides, it is necessary to consider minimum distances watercourses, water extraction wells, bordering farms, and excluding prepartum cows and categories under one year.

There is needed adequate waterproofing of the lagoon to avoid the effluent infiltration to groundwater. Also, it is required to design the lagoon dimension in concordance to the farm effluent generation and the possibilities to apply the effluent to soil (INALE 2018).

Besides, it is recommended to incorporate manure or effluent in the soil instead of applying it to the surface. Also, using the waste at the right moment is suggested to avoid a runoff, such as when the soil humidity is adequate or when the probability of rain is low (Fernández-Marcos 2011).

Exist different effluents management systems depend on the particularities of the dairy farm (Senattore & Russo 2019). There are diverse ways of solid separation, accumulation, and distribution of the effluent. These different systems contribute to the diversity of effluents between dairy farms. In general terms, the main characteristics of the dairy farm effluents are high content of organic matter and high concentrations of nutrients such as N and P (INALE 2019).

In Uruguay, there has been a change in conception in the management of dairy effluents. While in the past century was a promotion of biological treatment and disposal to a watercourse, nowadays it is promoted to storage in a lagoon and applied to the land as organic fertilizer (Senattore & Russo 2019). There is proved that the biological treatment is not sufficient to lower the organic matter and nutrients that provoke water pollution (Senattore & Russo 2019). In the same way, Aubriot et al. (2017) state that to improve the efficiency in the use of nutrients is required the use of dairy effluents as organic fertilizer. Because of that, the new tendency can be named nutrients circular economy or nutrients circularity. The following figure represents the nutrient´s circularity process.

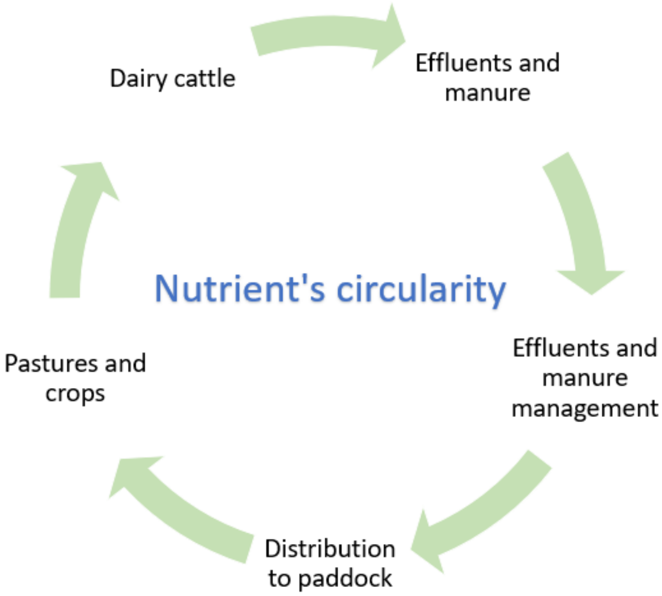


Figure 13. Nutrient´s circularity.

Source: elaborated by the author.

2.6. Nutrient Budgeting Approach

Turning now to the research evidence on evaluating the farm nutrient efficiency, Gourley et al. (2007, p. 1065) define the nutrient budget ´as an accounting approach for nutrient inputs, stores and outputs´. In the same way, Cherry et al. (2008) describe the nutrient budgeting as a valuable and straightforward tool to data generation, analysis and evaluation of farm inputs and outputs. According to Eurostat (2011), the N and P budgets offer holistic indicators of the environmental pressure of agriculture. It is essential however to distinguish between nutrient balances and nutrient budgets. While the balance only calculates the difference between the input and output of a nutrient, the budget partitioned the balance between loss pathways (Eurostat 2011).

Surprisingly, there are differences between Gourley et al. (2007) and Cherry et al. (2008) about the tool´s suitability. While the first one states that nutrient budgets are equally helpful in estimating N and P environmental losses, the second research argues that it is more beneficial to N due to the nutrient´s soil dynamics.

According to Cherry et al. (2008) these evaluations do not consider mitigation's timing and transport characteristics and assume a direct causal relationship between potential and actual nutrient loss. This issue is associated with the data required and the uncertainties and assumptions.

Gourley et al. (2007) distinguish three levels of approaches to nutrients budgets depending on ´the intended purpose of the study, which should also define the scale, the required accuracy, the data required, and the data collection strategy´. These kinds of budgets are described in the following figure, farm-gate, field, and farm-system level.

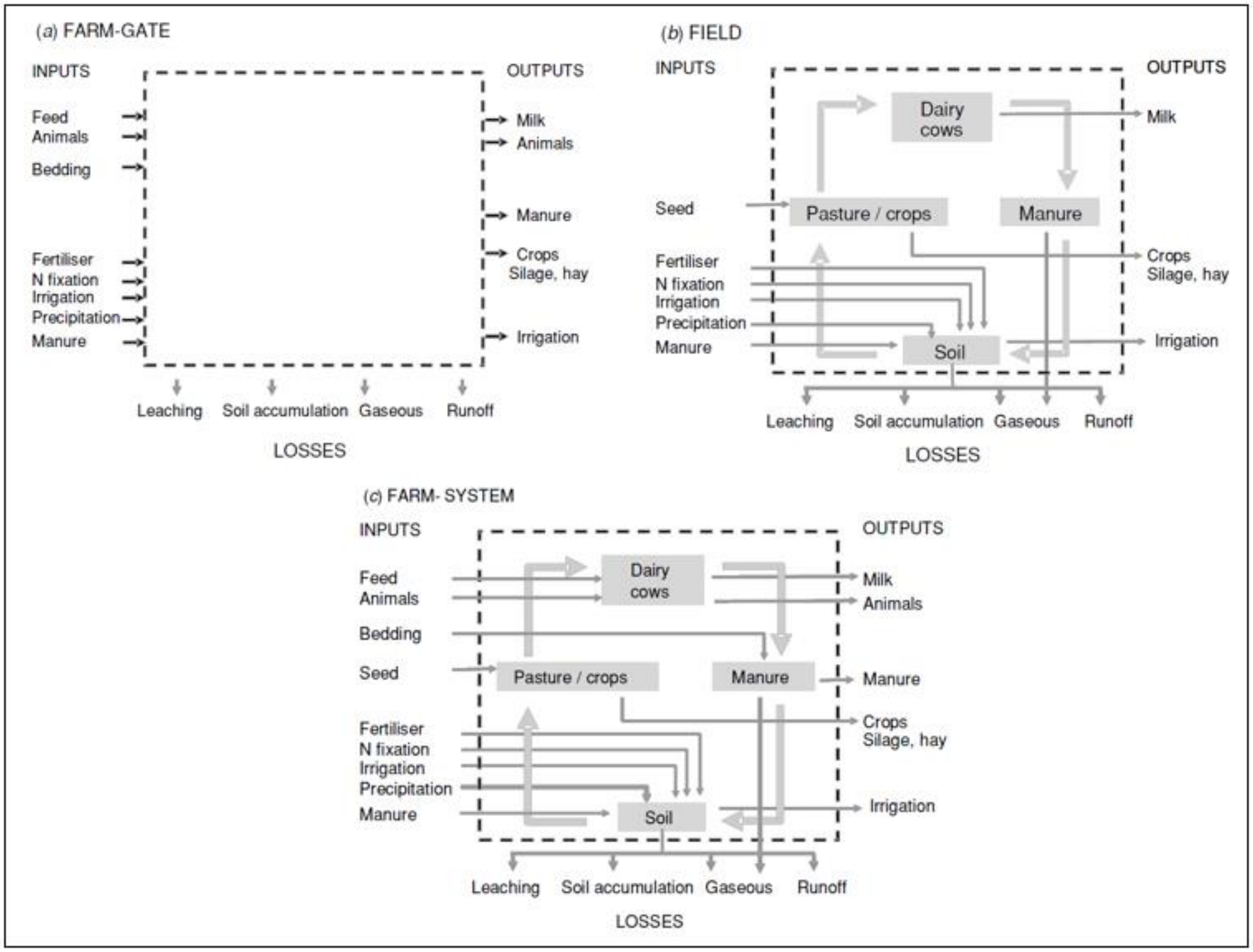


Figure 14. Dairy farm nutrient budgets: farm-gate (a), field (b) and farm-system (c).

Source: Gourley et al. (2007 p. 1066).

According to Gourley et al. (2007), the farm-gate budgets are the most common because they are easier to calculate from available farmer data and accurate sources. Although the farm gate nutrient budget can identify a nutrient surplus or a deficit, it does not include the nutrients circulation across the farm and internal transformations ´which may be contributing to nutrient use inefficiency and adverse environmental outcomes´ (Gourley et al. 2007, p. 1068). Another option, field budgets, are used to estimate the soil's net loading with nutrients and assist in comprehending the nutrient distribution patterns within the farm. In contrast, the farm system budget level analyses the internal transformations and nutrients dynamics to evaluate the whole system's efficiency, as represented in the figure 14.

Several investigations, such as Carbó (2011) and Gourley et al. (2012), said that this tool is beneficial to adjust the agriculture management practices reducing nutrient losses to the environment and improving the economic margins. Apart from supporting nutrient management decisions, the budgets can be helpful to research and as a regulatory tool (Gourley et al. 2007).

The following figure describes the primary N and P inputs and outputs in the agroecosystems.

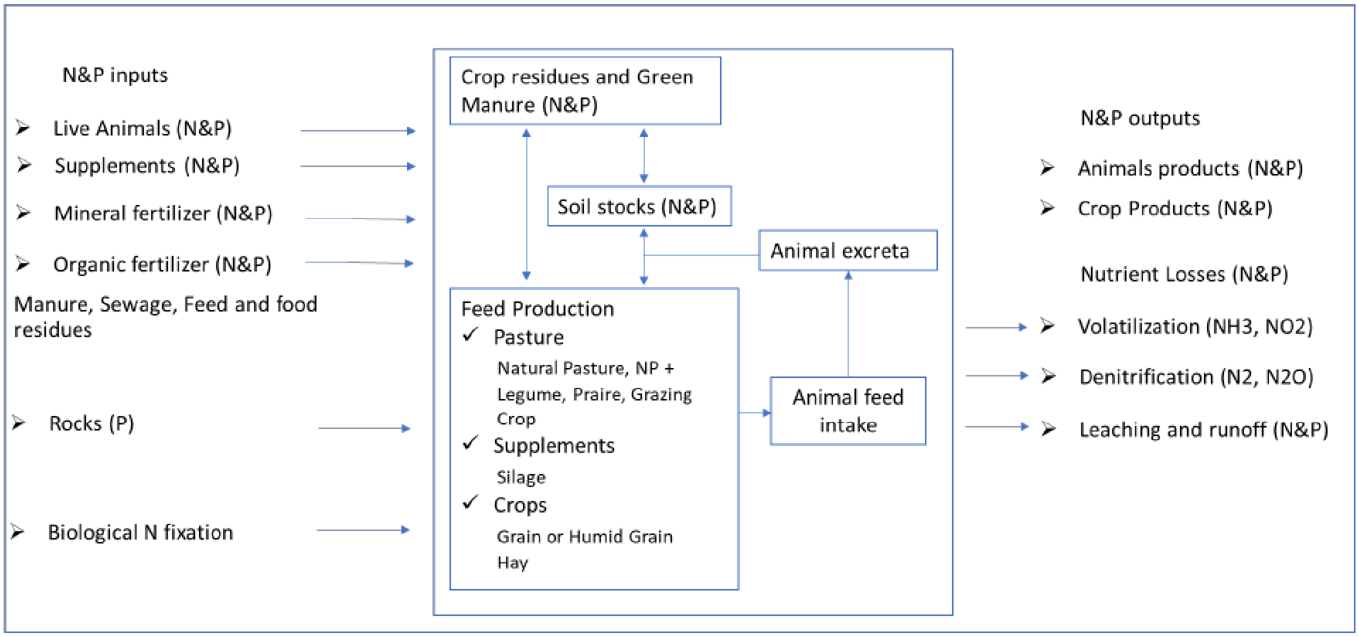


Figure 15 . Diagram of N and P inputs and outputs in agroecosystems.

Source: Becoña et al. (2020, p.8).

In the case of N, the main entrance of this nutrient to the agroecosystem is N mineral fertiliser, fixation of atmospheric N by legumes and soil bacteria, deposition from the atmosphere and livestock feed. Apart from that, there are minor inputs such as animal bedding and seeds (Eurostat 2011).

N is detained in animal products, milk and meat, crop products, and exported manure (Eurostat 2011). Furthermore, the N outputs are the losses to the environment by volatilisation, denitrification, and lixiviation. According to Eurostat (2011), gaseous losses occur from effluent and manure management and paddock management. Furthermore, the ground and surface water losses occur via leaching or runoff and ´on poorly managed farms, nitrogen can also be lost in runoff from animal housing, animal holding areas and manure storage´ (Eurostat 2011, p. 32).

In reference to P, the central system inputs are the mineral fertiliser and the livestock feed. Like N, the P outputs can be divided into animal products, crop products and environmental losses (Eurostat 2011). The nutrient losses to the environment can be separated into punctual and diffuse losses. While punctual refers to the loss from the effluent management system, diffuse refers to the paddock losses (Perdomo et al. 2015).

Numerous worldly investigations developed nutrient budgets in dairy farms (Gourley et al. 2007). A recent Uruguayan experience in effluent management evaluation incorporates the nutrient budget approach for five institutional dairy farms, including universities and research institutions (Biovalor 2018; Rodriguez 2021). This thesis complements the previous research, evaluating the farm-system nutrient budget in a familiar case study farm.

2.7. Modelling Approach

Suitable models can describe agroecosystems, answer questions, and solve problems (Railsback and Grimm 2019). Moreover, agricultural modelling permits the characterisation and quantification of nutrient transformation, transport, and retention (Cherry et al. 2008).

According to Muller (2017), with modelling is possible to analyse how a system change. For example, how the reduction of nutrient loss impacts the rest of the system. Furthermore, Jackson (2011), as mentioned, considers that once the model is built, it is possible to explore how the system behaves without taking any action that may negatively impact the system itself.

According to Railsback and Grimm 2019, *Agent-Based Modelling (ABM)* is a convenient tool to find solutions to issues related to the environment. As is described by these authors, ABM is appropriate to be used ´in systems composed of autonomous ´agents´ that interact with each other and their environment, differ from each other over space and time´ (Railsback and Grimm 2019, p.4). This modelling approach allows the evaluation of the complex agroecosystem possibilities and their heterogeneity between individuals. Moreover, ABM enables the modelling of different management practices spatially in space and time. The ABM system´s approach is convenient for modelling agriculture nutrient pollution because it is a complex issue involving many agents.

While traditional models describe and represent the whole system, ABM represents the system´s agents. This difference allows ABM to tackle issues that other models cannot (Railsback and Grimm 2019). Similarly, Grimm et al. (2010) state that ABM is opportune to explain system performance because it embraces agents' interactions and adaptative behaviour.

Another advantage of ABM is that it permits rapid evaluations of diverse possibilities to gain decision making time (Cherry et al. 2008). In contrast to that benefit, Railsback and Grimm (2019) state that this multilevel model required advanced management skills.

In the Uruguayan context, there is only an example of ABM development. The so-called ´Sequia Basalto´ model is an ABM of livestock producers facing drought conditions (Bartaburu et al. 2011). The development of this ABM involved stakeholders in co-designing it, including the farmers and technicians. This approach contributed to the understanding and communicating the drought situation and improving the adaptive capacity of Basalt Uruguayan cattle farmers (Bommel et al. 2014).

There exist many programmable platforms for developing agent-based models, and one of the most used is NetLogo. It was written by Uri Wilensky in 1999 and has been in constant development ever since at the Center for Connected Learning and Computer-Based Modelling (NorthWestern 2021). NetLogo is a programmable modelling environment for simulating natural and social phenomena. It is hence especially suitable for modelling complex systems that develop over space and time. The modellers can instruct hundreds or thousands of ´agents´ operating independently. NetLogo allows exploring the connection between the micro-level individual behaviour and the macro-level patterns that occur from their interaction (NorthWestern 2021).

2.7.1. ODD protocol

According to Grimm et al. 2010, the ‘ODD’ (Overview, Design concepts, and Details) protocol aims to standardize the descriptions of agent-based models.

ODD permits reading and writing ABM descriptions quickly and enable no technicians to model replication (Grimm et al. 2020). This protocol of descriptions is based on written text and can involve equations and brief algorithms.

The ODD protocol is structured in seven elements that must be used as given with the numbering. These elements are alienated into three categories as a protocol order, but the categories are not used in the model descriptions. The categories ´Overview´, ´Design concepts´, and ´Details´ (acronym ODD) explain the ODD structure. Each of them has a different purpose, ´giving an overview, explaining how design concepts important for ABMs were used, and explaining all the details of the ´machinery´ of the model` (Grimm et al. 2020 p. 2). Also, the protocol includes eleven design concepts that can be added for the description if necessary. The ODD protocol structure is represented in the following figure.

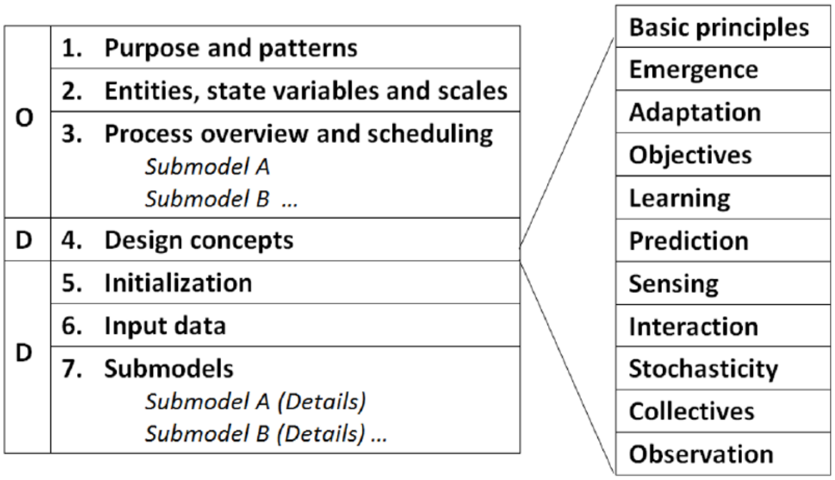


Figure 16. Structure of model descriptions using the ODD protocol.

Source: Grimm et al. (2020, p.2).

In section 3.4. it is presented a summary ODD protocol of the ABM developed for the thesis' research.

CHAPTER 3: METHODOLOGY

Chapter 3 focuses on the description of the methodology and the key methods used in this thesis. Firstly, the research methodology that guides the thesis is outlined. This is followed by an explanation of the case study and, finally, by the explanation of how the nutrient's budgets and the agent-based model (NPM) are developed.

3.1. Research Methodology

The research methodology is a multimethodological approach, which means using a combination of methodologies and methods together in the same systemic intervention – see Section 2.2 (Sposito 2021). This multimethodology was created following the basis of the ´Rational Holistic Planning and Decision-Making Model´ formulated by Sposito (2020a) and incorporating some steps of the ´Framework for exploring futures through collective learning´ formulated by Wedderburn et al. (2013).

The research methodology provides a framework that involves several suitable methods to understand the influence of dairy farm management practices in the N and P dynamics and their influence on the environment.

The multimethodology proposed comprises the six stages of Sposito's model: (1) Problem formulation, (2) Situation and diagnosis, (3) Solution, (4) Decision-taking, (5) Implementation, and (6) Monitoring. In addition, the multimethodology incorporates the substages (2A) System representation and behaviour, (3B) Evaluation of system performance, and (3C) Evaluation of strategies-scenarios and decisions of Wedderburn et al. (2013) framework. The research methodology is depicted in Figure 17.

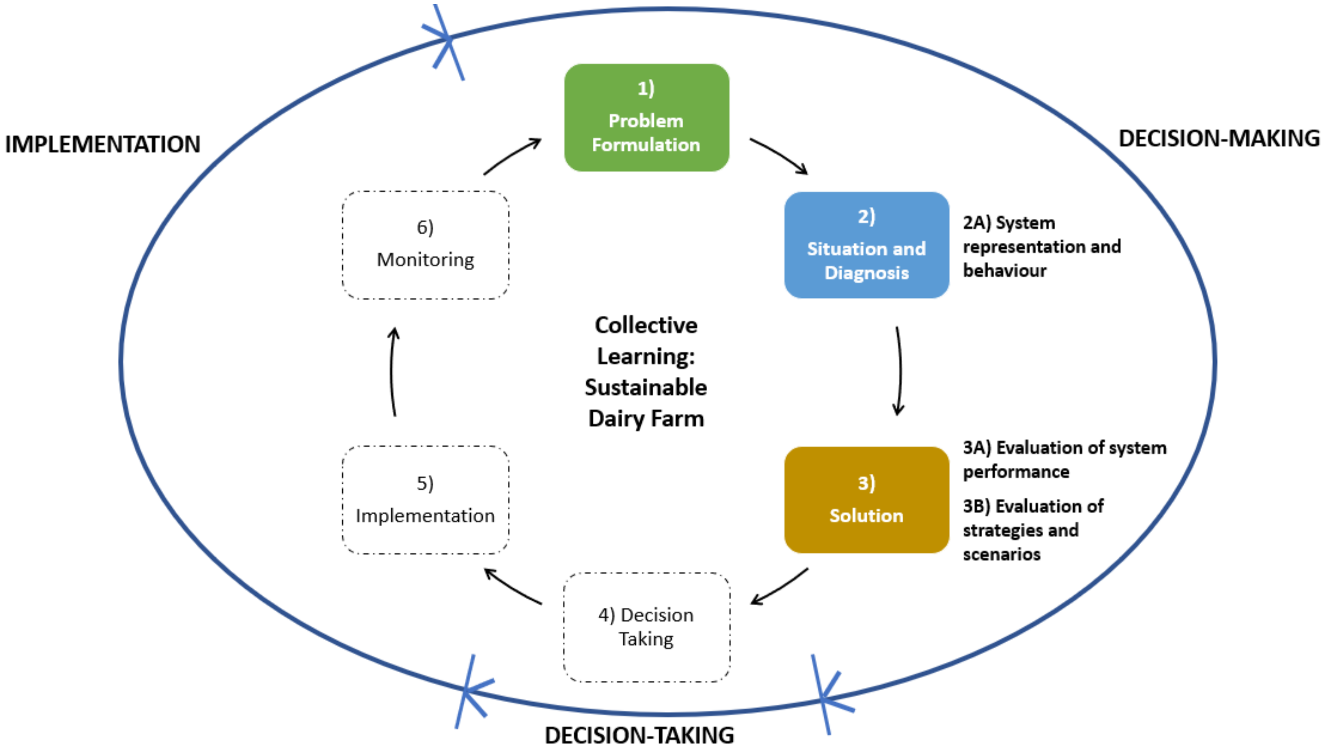


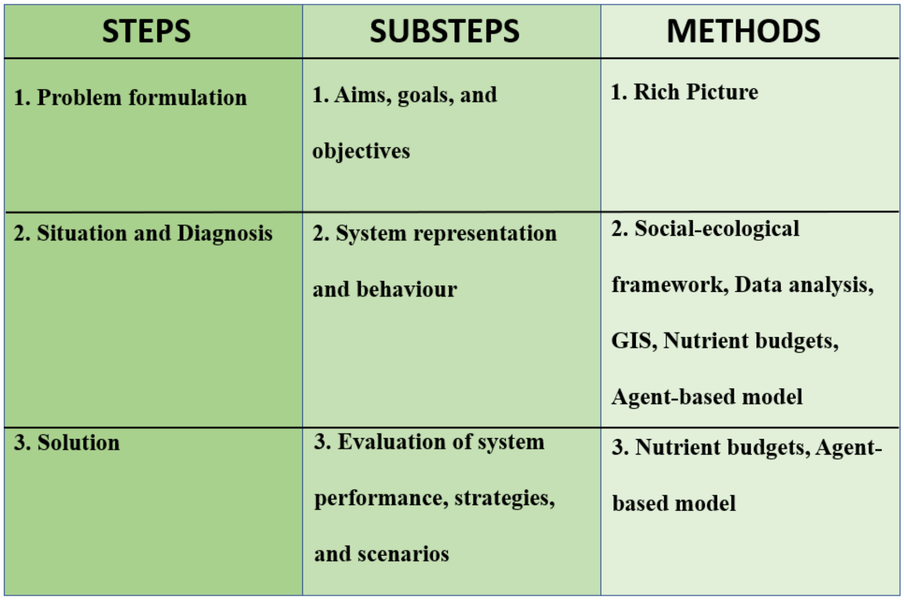
Figure 17. Research multimethodology.

Source: elaborated by the author. Adapted from Sposito (2020a) and Wedderburn et al. (2013).

The process is cyclical, interactive, and tiered. Furthermore, the process is divided into three distinctive parts, decision-making, decision-taking, and implementation, as represented in the figure 17. ***It is essential to state that this thesis encompasses only the decision-making part due to the scope of the research. This means that the research includes only Stages 1, 2 and 3***.

In the present research, the methodology is applied to the farm level of analysis but it can be used at a regional level. The model represents the farmer responsibility in the decision-making process, as they role in the farm management decision. The farmer inclusion depicted as a component inside the system of concern is named in the planning field as ‘collaborative or participatory planning’ (Healey 2006 cited in Sposito 2020a). Similarly, the concept of *collective learning* proposed in Wedderburn et al. (2013) is included in the methodology. This collective learning process can modify the farmer´s decisions on management and contribute to sustainable production. In this research, collective learning consists of communication with the farm case study and the farmer's group (see section 3.2.). Two communication forms were carried out with the farmer (see Appendix A.3.). The learning communication with the group of farmers consisted of one virtual meeting and a meeting in the field to show the thesis results (see appendix A.3.).

The multi-methodological approach is appropriate for dealing with complex, uncertain and risk problems because it is based on the ´combinations of methodologies (possibly from different paradigms) and methods together in a single intervention´ (Jackson 2019). In that way, the research methodology includes several methods in the different stages, as is represented in figure 18.



STEPS	SUBSTEPS	METHODS
1. Problem formulation	1. Aims, goals, and objectives	1. Rich Picture
2. Situation and Diagnosis	2. System representation and behaviour	2. Social-ecological framework, Data analysis, GIS, Nutrient budgets, Agent-based model
3. Solution	3. Evaluation of system performance, strategies, and scenarios	3. Nutrient budgets, Agent-based model

Figure 18. Research Stages and Methods.

Source: elaborated by the author, adapted from Sposito (2020a).

The focus of the research, as was explained, is in the decision-making stages. In the first stage of the multimethodological approach, the *´problem formulation´*, the method selected is a rich picture. It is a soft system method representing the system of concern, including the different components, actors, relations, and issues (Checkland and Poulter 2006, see section 2.2.). That system representation has an emphasis on dairy farm nutrient problems and management strategies.

Regarding the second stage, *´situation and diagnosis´*, a social-ecological dairy farm framework and data collection analysis is required to understand the farm system´s situation. The data collection is based on the productive registers provided by the farmer of the case study. Also, that stage includes developing nutrient budgets (see section 2.6) and modelling through an agent-based model (see section 2.7). Also, the method Geographic Information System (GIS) is necessary to include the geographic features of the farm in the modelling. The system representation allows the evaluation of the system performance.

Apart from that, the third stage, *´solution´*, involves the nutrient budget and the agent-based model to evaluate strategies and scenarios to improve the system performance.

3.2. Case Study

3.2.1. Uruguayan dairy farm context

This section describes the Uruguayan dairy farm sector to understand the case study.

Uruguay is located in South America between Argentina and Brazil, and their extension is 176.000 km2, where approximately 160.000 km2 are potential agricultural soils (INE 2011). Because of that, the Uruguayan economy is based on agriculture, and dairy production is one of the most critical activities because of the income generated and the labour involved (INALE 2021).

Figure 19. Map of Uruguay in South America.

Source: elaborated by the author, adapted from Google Maps (2021).

According to INALE (2021), the Uruguayan dairy sector involves 3,300 dairy farmers and produces 2,200 million litres of milk annually; 73% of the farms remit milk to the processing industry, and 23% are cheese producers. While 30% of industrialized dairy is for the internal market, 70% is destined for export, being Uruguay the seventh-largest milk exporter in the world (INALE 2021).

As shown in the following figure, the dairy farms are concentrated in the south and southwest of Uruguay, particularly in the Santa Lucia River Basin.

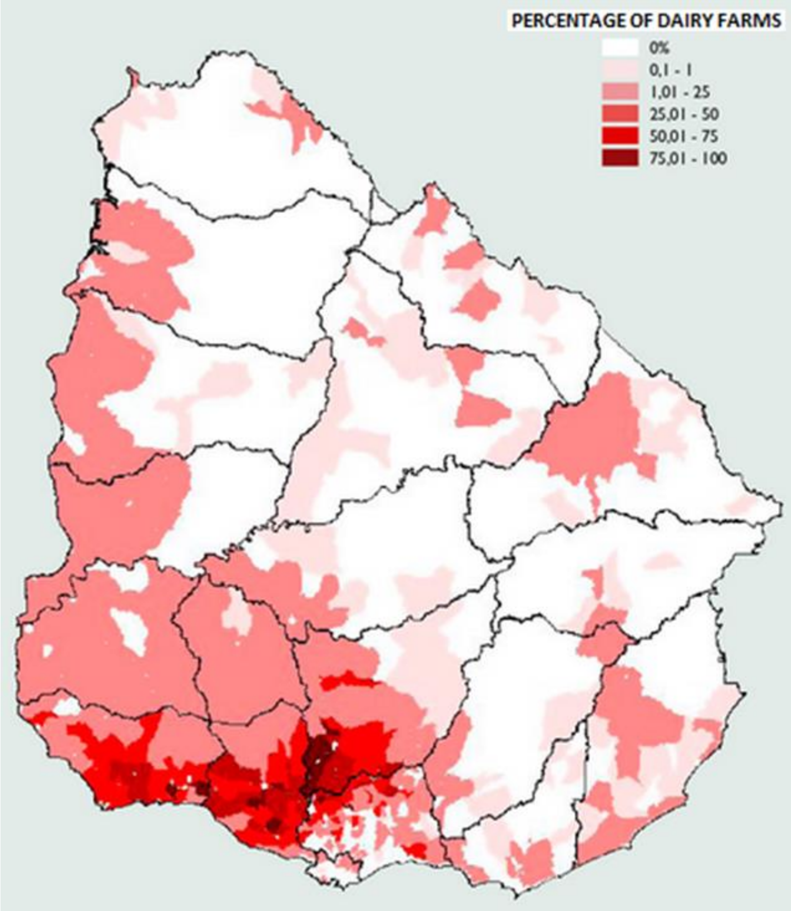


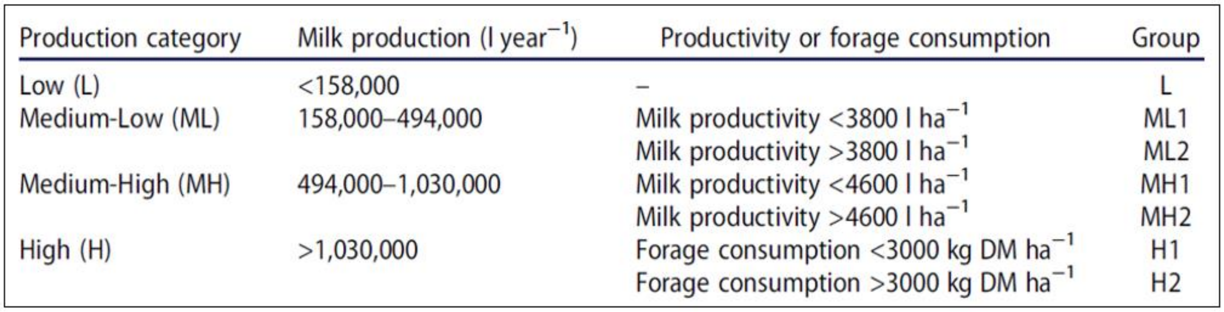
Figure 20. Percentage of dairy farm per area of evaluation.

Source: adapted from MGAP 2015.

The Uruguayan dairy system is characterized by a pastoral-based diet, with grass and legume pastures as the main component of the diet (Darré et al. 2021). Furthermore, according to Fariña and Chilibroste (2019), the average Uruguayan diet of the dairy cows is 9.5, 3.1, and 4.2 DM/cow/day of pasture grazed, silage, and concentrate. Although dairy production is chiefly based on pastures, the average dairy system has a medium level of supplementation in silage and grains because of the seasonality of grasslands (Fariña and Chilibroste 2019).

The Uruguayan National Dairy Institute (INALE) has conducted a national survey on dairy farms. The survey was designed to sample a stratified subset of the Uruguayan dairy farms, and the results are summarized in a typology of dairy farms. The dairy farm's typology criteria are based on milk production and milk productivity/forage consumption. The typology is divided into seven groups, as is represented in the following figure.

Table 2. Uruguayan Dairy farms typology INALE.



Production category	Milk production (l year^{-1})	Productivity or forage consumption	Group
Low (L)	<158,000	–	L
Medium-Low (ML)	158,000–494,000	Milk productivity <3800 l ha^{-1}	ML1
		Milk productivity >3800 l ha^{-1}	ML2
Medium-High (MH)	494,000–1,030,000	Milk productivity <4600 l ha^{-1}	MH1
		Milk productivity >4600 l ha^{-1}	MH2
High (H)	>1,030,000	Forage consumption <3000 kg DM ha^{-1}	H1
		Forage consumption >3000 kg DM ha^{-1}	H2

Source: adapted from Darré et al. (2021).

According to MGAP (2013), milk production has incremented by more than 250% since 1980. This production intensification is associated with greater use of external subsidies to the system, such as concentrates and chemical fertilisers, which increased the tension with the environment (Darré et al. 2021). Because of that tension, the Uruguayan government made public strategies to promote management practices to reduce the environmental impacts (MVOTMA, 2013; MVOTMA 2018). One of these strategies is associated with improving farm infrastructure to effluents management (MGAP 2020).

Because of the importance of dairy production in Uruguay, it is essential to evaluate the farm performance and analyse their management practices to improve nutrient efficiency and decrease the environmental impacts.

3.2.2. Main of Characteristics of the Case Study Farm

The focus of the case study is a real Uruguayan dairy farm. The selected farm has registers of management and productivity that enabled to undertake a sound analysis. The database analysis was complemented with interviews and farm's visits to gather further required information. The study of both the database registers and the information gathering was finally carried out.

The farm is located in the southern limit of the department of Soriano, Uruguay. As explained above, the southwest of Uruguay is a historic dairy farm region (see Figure 20). This means that the focus farm is situated in a Uruguayan representative dairy region. The farm location is shown in the following figure.

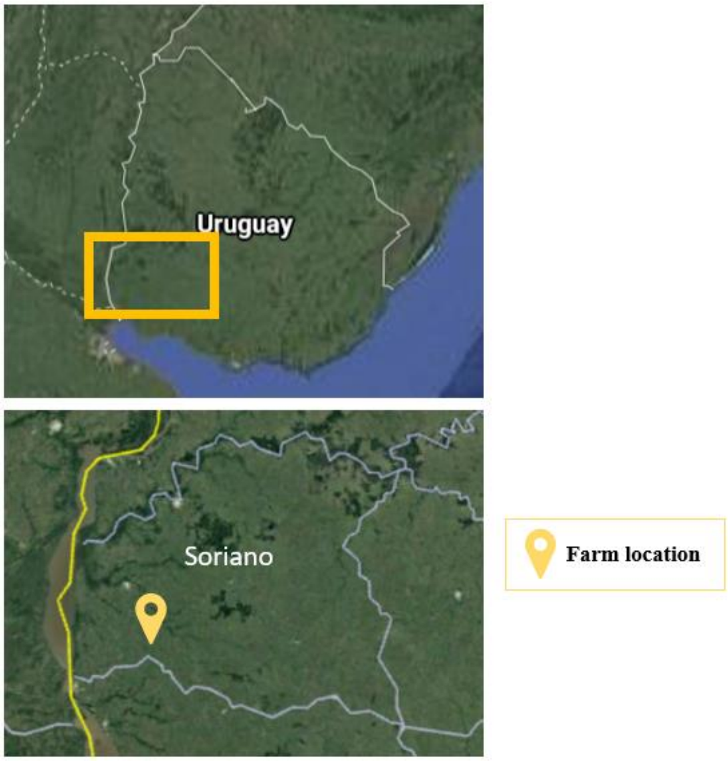


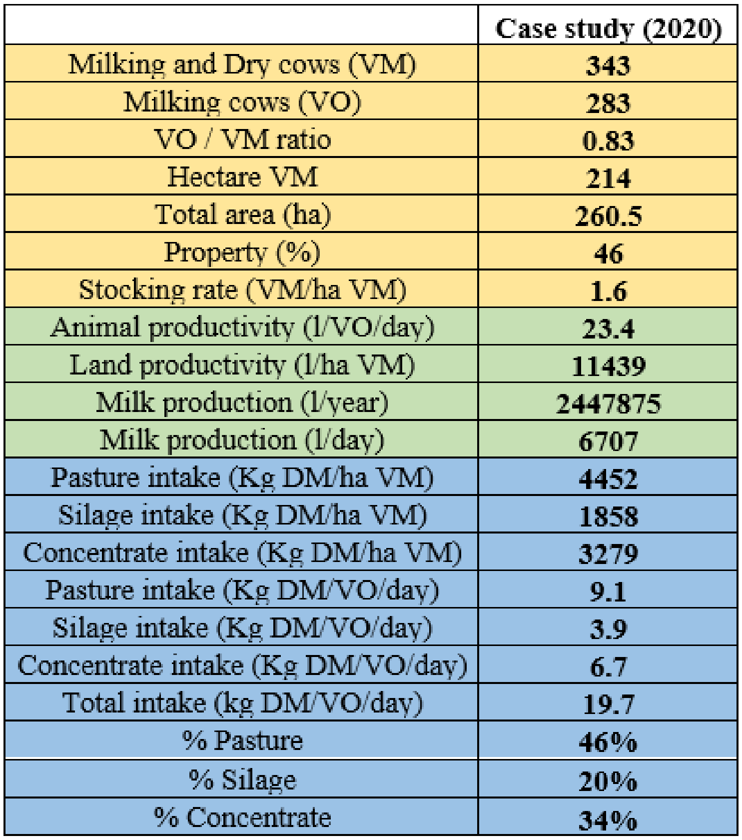
Figure 21. Farm location.

Source: elaborated by the author, adapted from Google maps (2021).

This dairy farm has produced artisan cheese since 1973 during several family generations. Since commencement, they have increased the area, the number of cows and the volume of production. The family comprises five members who all participate in farm and cheese production. In addition to the family's workers, there are 13 workers involved in dairy farm and cheese production.

The 2020 case study summary is represented in the following table.

Table 3. Case study summary.



	Case study (2020)
Milking and Dry cows (VM)	**343**
Milking cows (VO)	**283**
VO / VM ratio	**0.83**
Hectare VM	**214**
Total area (ha)	**260.5**
Property (%)	**46**
Stocking rate (VM/ha VM)	**1.6**
Animal productivity (l/VO/day)	**23.4**
Land productivity (l/ha VM)	**11439**
Milk production (l/year)	**2447875**
Milk production (l/day)	**6707**
Pasture intake (Kg DM/ha VM)	**4452**
Silage intake (Kg DM/ha VM)	**1858**
Concentrate intake (Kg DM/ha VM)	**3279**
Pasture intake (Kg DM/VO/day)	**9.1**
Silage intake (Kg DM/VO/day)	**3.9**
Concentrate intake (Kg DM/VO/day)	**6.7**
Total intake (kg DM/VO/day)	**19.7**
% Pasture	**46%**
% Silage	**20%**
% Concentrate	**34%**

Source: elaborated by the author.

The farm under study can be considered a typical Uruguayan dairy farm because it is characterized by a pastoral-based diet, with grass and legume pastures as the main component of the diet (Darré et al. 2021).

It is situated in the Uruguayan typology groups with higher milk productivity and is on a medium scale referring to the area (see the previous subsection). It also has a high stocking rate compared with the national average (see Appendix A.6.)

The farm has an extension of 260.5 hectares divided into two distinct areas that are in turn subdivided into paddocks. The area used by the dairy cows is named ´Tambo´ and has 126 hectares. The other area is composed of four sectors used by the rest of the animals and has 134.5 hectares (called ´rest of the area´). It is worth mentioning that parts of the feed reserves (meadow bales) and concentrate (wet corn grain silo) are produced in the ´rest of the area´. Because of that, those feed reserves are considered inputs to the studied and modelled system. The ´Tambo´ area and their paddocks are represented in the following figure.

Figure 22. ´ Tambo´ area and their paddocks.

Source: elaborated by the author, adapted from Google earth (2021).

The total farm paddocks are described in the figure 23. It includes the ´Tambo´ paddocks and the ´rest of the area´ paddocks (named ´Guigou, Manera, El Rancho and La Conquista´).

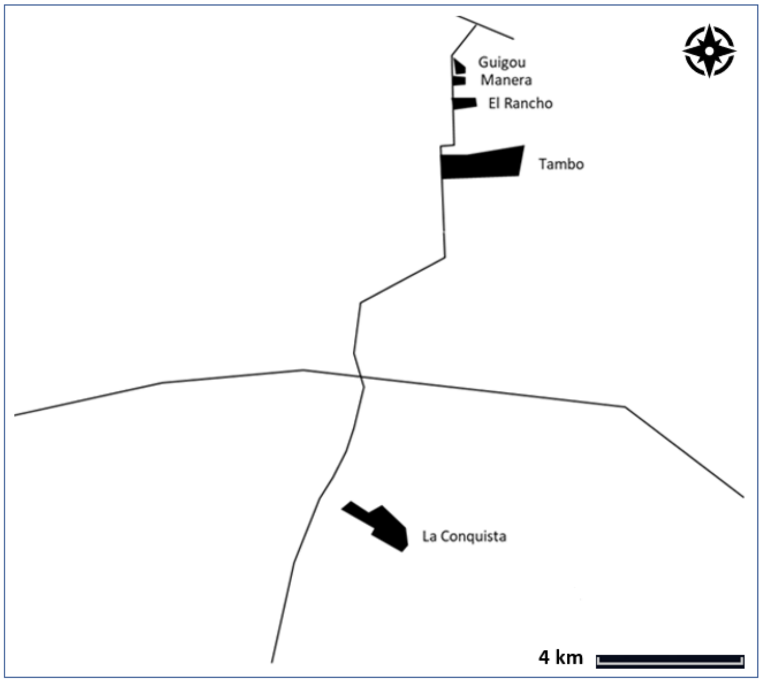


Figure 23. Total farm paddocks, ´Tambo´ and ´rest of the area´ paddocks.

Source: elaborated by the author, adapted from farm registers.

The focus farm under study is part of a local group of 30 dairy farms located in the Departments of Colonia and Soriano, where the dairy industry is central. The 30 farms are primarily artisan cheese producers, and the group is coordinated by an agronomist, a veterinarian, and a sociologist. This point is essential because this thesis's development includes communication with the farmer group to support peer learning (see Section 3.1.).

The information resulted from the analysis was used to develop the nitrogen and phosphorus budgets and the ´NPM´ Agent-based model presented in Chapter 4. As mentioned, the nutrients budgets are a decision support instrument for evaluating farm management practices and their impact on the environment. The ´NPM´ agent-based model development supports the analysis and evaluation of possible management scenarios.

3.3. Nutrients Budgets

This section describes the *Nutrient Budget Method* developed in this research. Its application includes two nutrients' budgets, one destined to ´Tambo´ paddocks and the other to the whole farm. In both areas, budgets of nitrogen (N) and phosphorous (P) are also developed.

As was defined in the literature review, the nutrient budget is a tool that permits adjusting agriculture management practices to reduce nutrients losses to the environment and improve farm nutrient efficiency (see Section 2.6). The nutrient budget diagram representing the inputs and outputs of the dairy farm of the research is illustrated in the following figure.

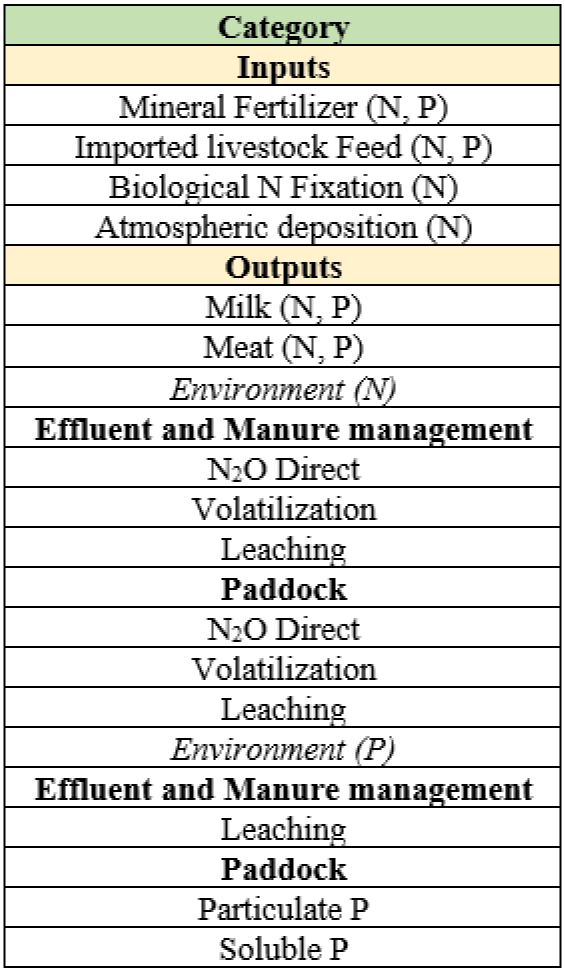
Figure 24. Nutrient budget dairy farm.

Source: elaborated by the author.

According to Eurostat (2011), there is no international legal framework for N and P budgets compared to greenhouse gas emissions that IPCC has promoted. As a result, there is no established international standard terminology or methodology for nutrient budget development. Because of that, many authors refer to the same terms differently.

The main inputs, outputs and terms used on the nutrient budget developed in the present research are summarized in the table below.

Table 4. Summary of farm inputs and outputs.



Category
Inputs
Mineral Fertilizer (N, P)
Imported livestock Feed (N, P)
Biological N Fixation (N)
Atmospheric deposition (N)
Outputs
Milk (N, P)
Meat (N, P)
Environment (N)
Effluent and Manure management
N_2O Direct
Volatilization
Leaching
Paddock
N_2O Direct
Volatilization
Leaching
Environment (P)
Effluent and Manure management
Leaching
Paddock
Particulate P
Soluble P

Source: elaborated by the author.

As a difference to the ´Tambo´ budget, the whole farm budget considers all the animal categories and the values of the entire farm variables. It means that the whole farm nutrients budget evaluates all the components of the entire system (to understand the differences between both kinds of budgets, see Appendix A.4.).

The nutrients budgets for the year 2020 are generated using the farm's records and bibliographic review. From other research works, assumptions are made to estimate the data needed to calculate the budget variables. The data, assumptions and terminology used in the study are presented in appendices (see Appendix A.4.).

The nutrient budget emphasises understanding the nutrients environmental outputs and partitioning the different losses pathways (see section 2.6.).

3.4. NPM Agent-based Model

This section describes the Nitrogen Phosphorus Management (NPM) multi-agent model jointly developed with Professor Francisco Dieguez (UDELAR Veterinary Faculty). This model evaluates the management practices and spatialization of nutrients in dairy farms. The summary description of the model is guided by the ODD protocol, explained in Section 2.7 of the Literature

The agent-based model simulation model was developed on the NetLogo platform version 6.2 (NorthWestern 2021). NetLogo is a multi-agent programmable modelling environment suitable for modelling complex systems (see Section 2.7.).

The development of the model was based on the register's records provided by the case study dairy farmer and from a literature review. Model development includes the farmer' registers and monitoring for 2020, which included (on a monthly scale): the number of animals, composition and milk production, diet profile (pastures, reserves, and concentrates) and land use. As was mentioned previously, some parts of the feed reserves (meadow bales) and concentrate (wet corn grain silo) are produced in the same farm, but in another fraction of the establishment, so they are considered inputs to the studied and modelled system. The central dynamics in the ABM has carried out a daily step (see Appendix A.4. and A.5.).

The dynamic assigning the animals to the pasture (set of patches) with the highest biomass, keeping them in that pasture until a remanent of 1500 kg DM/ha. The animals consume the DM of each diet component according to the monthly diet profile provided by the farmer. This diet has its corresponding protein and P proportion and excretes N and P at each step (considering a similar ratio to the time spent in the dairy parlour and on the paddock, 4/24 hours, and 20/24 hours, respectively). The ABM model calculates the N and P budget for each patch. Also, the different pastures have an individual growth rate and protein and P values (see Appendix A.4.). The farmer provided the soil P content by soil analysis information. The following figure summarizes the NPM model process.

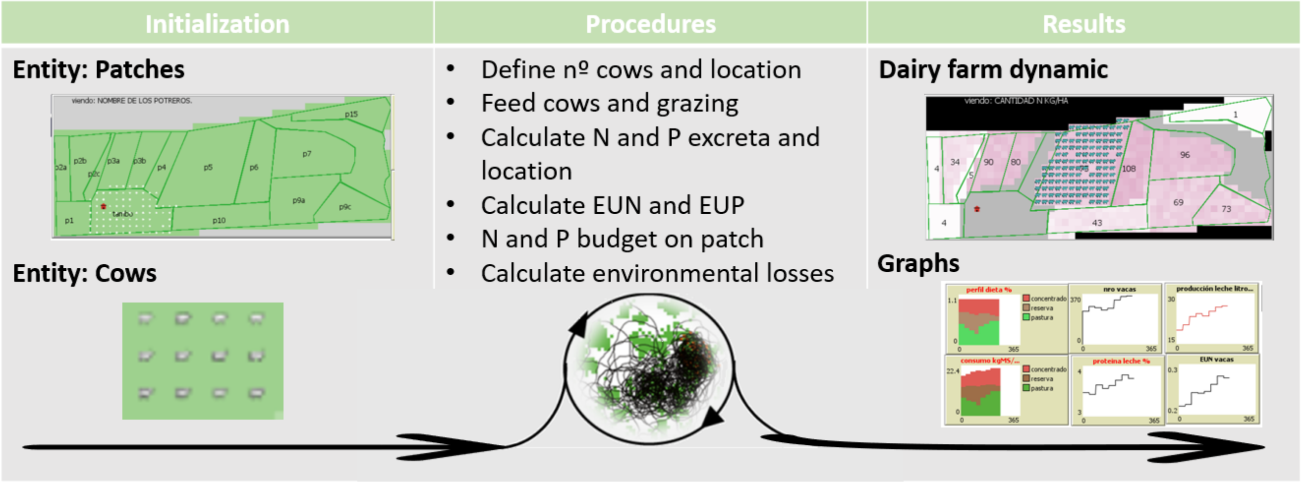


Figure 25. NPM Model process.

Source: elaborated by the author, adapted from Grimm et al. (2020).

3.4.1. Purpose

The overall *purpose* of the NPM model is to evaluate dairy farm management practices that influence N and P dynamics. NPM model simulates how the farmer management decisions affect the whole farm system nutrients dynamics. Specifically, the model addresses the following questions:

- According to farming practices in the case study: which is the spatial and temporal pattern of nutrients at the modelled system?
- Which is the contribution of each nutrient budget component (excreta, paddock environmental losses, effluent environmental losses, and biological N fixation) to whole system results?

3.4.2. Entities and states variables

The model includes the following *entities*: Patch, Cow, Effluent Management System. The *Entities* and *States Variables* of NPM are described in appendixes (see Section A.5.). The *spatial* and *temporal* resolution and extent: a time step in the model represents one day, and the simulation can be for the year of evaluation. NPM model is spatially explicit and represents the area of the dairy farm case study.

Simulations are based on 13 paddocks with different extents each, representing a total area of 126 hectares. The landscape or world is a grid of 50 x 20 patches with 2600 m2 each, but only 846 patches represent the ´Tambo´ area, according to GIS information provided by the farmer.

3.4.3. Process overview and scheduling

The core *process* of the NPM model is the nutrient budget in each patch. This process is repeated every time step and is based on these other processes: pastures growth, nutrients dynamics and presence and permanence of cow in the patch. It is important to highlight that the NPM model represents the scale of colours according to the variable value of each patch. Also, the interface represents the patches average variable value of the same paddock.

Scheduling is very significant in the NPM model because it represents the farmer management. The scheduling refers to number of dairy cows, milk production and composition, dairy cows' diet, fertilizer application and pasture growth rate.

3.4.4. Design concepts

The most important *design concepts* of the model are:

- Objective: the design model objective is to represent the farm case study, using GIS and land use information.
- Observation: The number of cows, the animal diets levels, the cow's production, and the total amount of biomass in each paddock are recorded daily.
- Communication: The main communication variables are represented in the model interface. Its interface includes the use of ´on/off switch´ from each nutrient budget component, the NUE and PUE graphs, and the dynamics of the N and P separately in paddock and effluent management system. The interface represents in a colour scale the values of the main variables of N and P dynamics. These specific design aspects are to facilitate collective learning and communication between farmers, researchers, and other actors.

- Interaction: there exist three kinds of interactions; cow-patch and cow-system management effluent.
- Stochasticity: by default, there is nothing Stochasticity. When initializing, there are variables generated with random values like initial DM availability of paddocks.
- Adaptation: Cows react to decreasing pasture biomass levels in paddocks by being less attracted to them, and after a limit level, they move to another paddock with more biomass.

3.4.5. Initialization

The NPM model is initialised with the information provided by the farm, like the land use and the number of dairy cows (see appendix A.4.). Also, it is essential to highlight that the GIS is included in the initialisation. Furthermore, the simulations were set to start on 1st of March.

3.4.6. Input data

Model dynamics are driven by *input data* representing data from different sources, including extensive literature review and data from the farm case study. The data from the model development is described in appendices (see Appendix A.4.).

3.5. Farm Management Scenarios

The research formulated four farm management scenarios to evaluate possible solutions to the problem situation with the nutrient budget method. These scenarios intent to answer the following questions:

- Which is the impact of the different dairy farm management practices on the nutrient dynamics?
- Which are the dairy farm management practices that reduce nutrient losses to the environment?

The management scenarios evaluated in the research are specified in the following table. Each scenario is compared with the current situation of the dairy farm case study.

Table 5. Scenarios evaluated

Management	Scenario	Note
1)Land use: BNF	BNF drops 20% compared to the current situation	17 hectares of Leguminosae area is replaced by Festuca, and the Festuca is fertilized with the farmer criteria
2)Dairy cows feed	Pasture: 56% Silage: 20% Concentrate: 24%	10% increment on pasture intake Same silage intake 10% decrease in concentrate intake
3)Stocking rate	Number of dairy cows drops 20%	Assumption: Reduces to 80% the milk production and total dairy cows feed compared to the current situation
4)Effluent	Organic fertilization	The effluent is used as fertilizer in the rest of the area, not in the ´Tambo´ paddocks.

Source: elaborated by the author

For understanding internal changes in the nutrient budget for each scenario, refer to Appendix A.4.

CHAPTER 4: RESULTS

Chapter 4 presents the results of the research through the application of the methods included in the methodology. Stage 1 of the methodology, *problem formulation* is carried our using a *Rich Picture* method. Results of the Stage 2, *situation and diagnosis* are described through a social-ecological dairy farm framework, the nutrients budgets, and the agent-based model. Finally, the analysis of management scenarios is presented as a guide to possible *solutions* (Stage 3) to the formulated problem. The results presented in this chapter are discussed in the subsequent chapter, *Discussion*.

4.1. Stage 1 - Problem Formulation

The problem formulation is conducted via the *Rich Picture* (RP) method (see Section 2.2.). According to Checkland and Poulter (2006), the 'RP method is most appropriate to capture the components and complex relationships of the system of interest. The RP in the following figure is thus very useful for comprehending and analysing the dairy farm process, its relationship with the N and P cycles and their negative impacts on the environment. The RP represents the components of the dairy farm system, their interactions, farmers, and the negative externalities to the environment as one of the significant system issues.

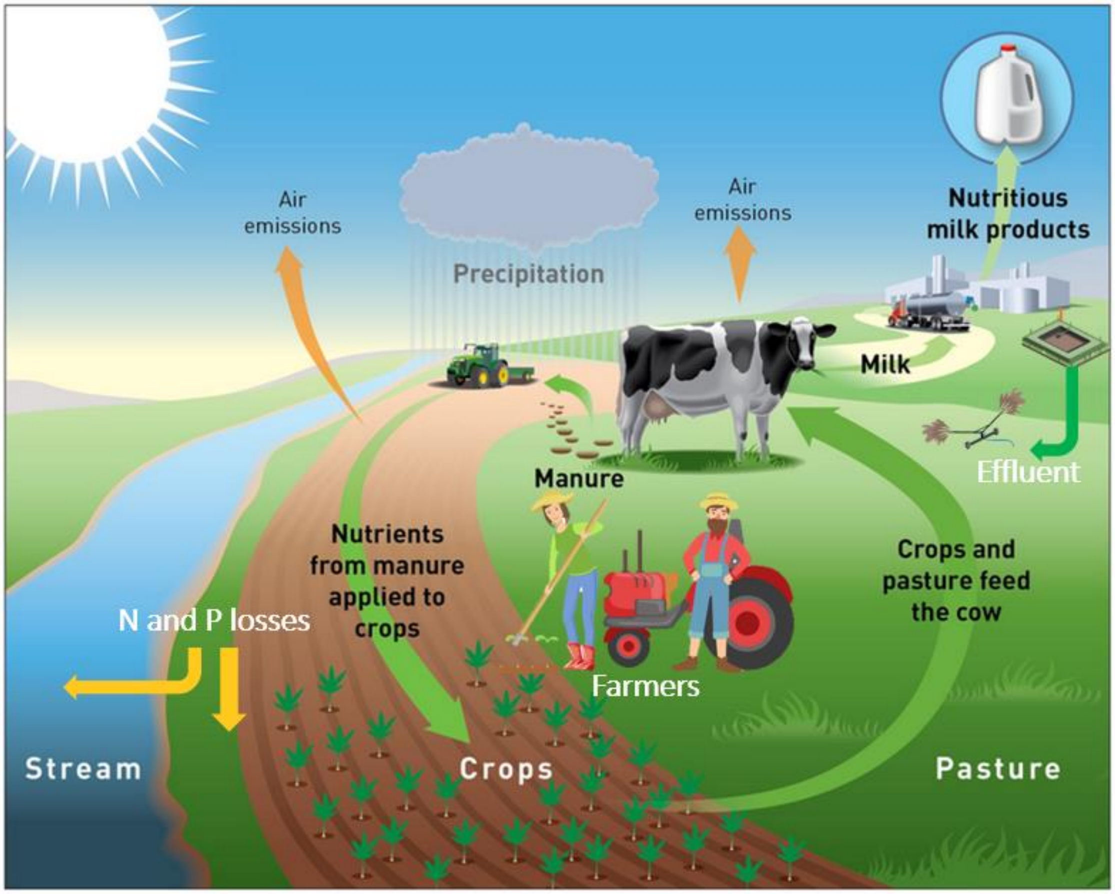


Figure 26. Rich Picture of a Dairy Farm.

Source: elaborated by author, adapted from The Dairy Alliance (2021).

It is essential to highlight that the farmers are represented as the main actors of the dairy farm because of their role in the overall system management. The environmental impacts are divided into air emissions and the nutrients losses to soil and water. The water pollution is not only to the stream but also to the aquifer under the surface. The management practices are included in the rich picture; for example, the rich picture represents the utilization of manure and effluent to fertilize the crops or the importance of pasture in cows' diet apart from concentrates or silage.

4.2. Stage 2 - Situation and Diagnosis

The results related to the situation and diagnosis are described through a social-ecological dairy farm framework, nutrient budgets, and an agent-based model. It is important to mention that the results of the nutrient budgets and the agent-based model are related to the area grassed by the dairy cows (´Tambo´ paddocks). As was explained in Section 3.2., the significant nutrient losses occur in ´Tambo´ paddocks because of the higher intensive use. Nevertheless, the results also include the nutrient budgets for the total dairy farm area in order to understand the whole farm system.

4.2.1. Social-ecological dairy farm framework

It is essential to define the scale to be evaluated since dairy farm systems have significant heterogeneity in size, land tenure, social, productive, and economic reality (see section 3.2.). Likewise, the analysis must be functional at this scale. As mentioned, the present research is focused on a Uruguayan medium scale dairy system.

Dairy farms are complex socio-ecological systems due to the interactions between social, biophysical, climatic, edaphic and management components (Stirling et al. 2021). Similarly, Wedderburn et al. (2013) argue that pastoral-based dairy and livestock systems depend on the feedback between producer’s behaviour, natural resources, and biological cycles to generate a series of services necessary for human well-being as well as maintain the integrity of the ecosystem.

The diagnosis of the system (human, productive and natural capital) is an essential starting point to preserve the desired responses and ascertain the proposed transformations. Furthermore, for the dairy farm analysis, it is necessary to consider all the elements that influence the behaviour and decision-making of the producers. The following figure outlines the dynamics of the system, which will be described in the following sub-sections.

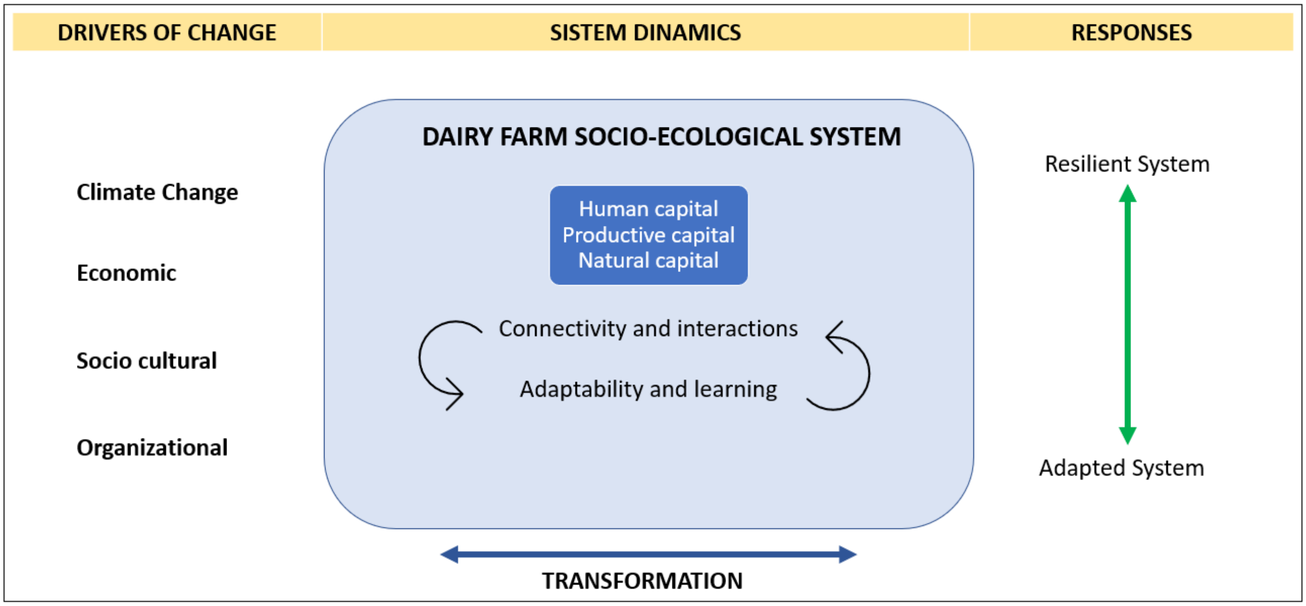


Figure 27. System Dynamic.

Source: elaborated by the author, adapted from Chapin et al. (2009).

According to Mazzeo et al. (2017a), *resilient thinking* intends to understand the mechanisms that ensure the system's resilience in facing external pressures and internal dynamics changes. Furthermore, resilience comprises three characteristics: the amount of change that a system can assimilate to maintain its function and structure, its capacity for self-organisation, and learning and adaptation. In that sense, ´resilience is the property of the system and persistence or probability of extinction is the result´ (Holling 1973/2010R cited by Sposito 2020b).

Internal factors to maintain - The system with the current configuration presents certain internal factors that are considered significant strengths to be maintained and enhanced. These factors, or aspects, can be classified into *human capital, productive capital, and natural capital and ecosystem services*.

Firstly, referring to *human capital*, the system under study is based on family production (see Section 3.2.). This means that part of the workforce comes from the family nucleus of the farm. The farm family's human capital is essential because the dairy system's experiences and knowledge are transmitted from generation to generation over the years, such as the care of the soil and productive and cultural practices. One example of this transmission of experience is the production of Colonia's cheese (denomination of origin). This type of cheese is original from Uruguay and was produced since the late nineteenth century, maintaining and enhancing the local and artisan cheese (Canaparo et al. 2019). Another internal factor to preserve is the organisation of producers; for example, in the form of cooperatives, groups or societies of milk producers. This type of organisations is clearly a strength in the sense of enabling continuous learning and adaptation to external factors and shocks (for example, changes in the costs of inputs). In addition, it is essential to maintain young people in the sector due to is a critical social aspect associated with the future generation of farmers.

Secondly, maintaining factors associated with *productive capital* refer to the specific characteristics of dairy cattle, their genetics developed over the years and their adaptation to the environment. Other aspects to maintain, the management experience on livestock and pastures, responding to the production of food such as milk and meat.

Finally, the *natural capital* internal factor identifies the general Uruguayan dairy as a pastoral-based production. This is considered an advantage in terms of sustainability and animal welfare over other forms of grain-based dairy production where cows tend to remain locked up throughout the day. This internal factor is a window of opportunity that grants diversity and redundancy to the dairy system, betting on a quality dairy product that stands out in international markets. Another factor in maintaining and promoting is the caring for the biodiversity of the fauna and flora of the natural fields and meadows. It is also essential to maintain these internal factors that promote regulatory ecosystem services, such as water purification and carbon sequestration.

External factors - drivers of change - Farmers are also conditioned by external factors, which can be considered as pressures for the socio-ecological dairy farm system. The following figure represents the direct and indirect external factors that can impact dairy farmers.

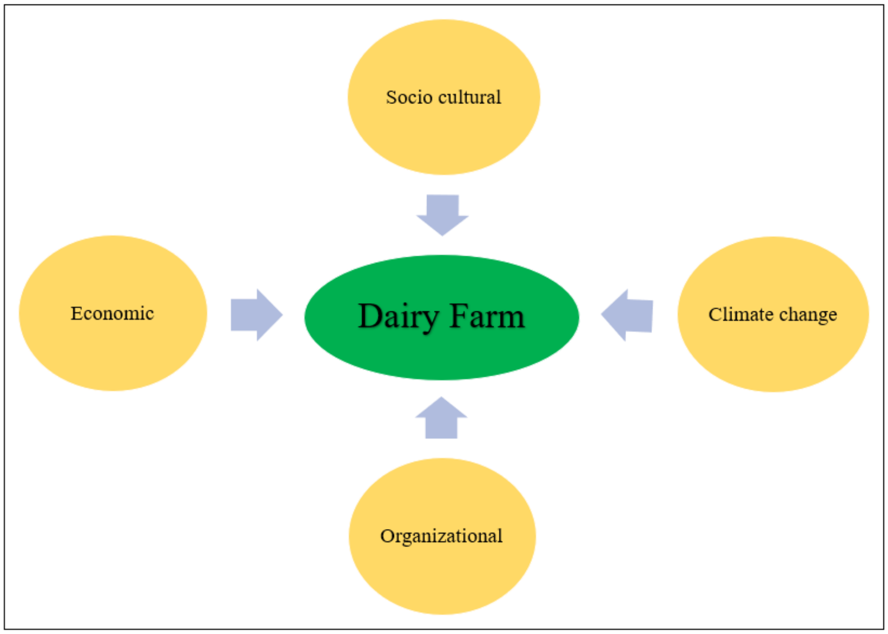


Figure 28. Dairy farm and drivers of change.

Source: elaborated by the author.

Firstly, the economic space is represented by the pressures and demands generated by the production chain and the market. This chain of production on a local and global scale is associated with the global and regional markets that set prices, cost of inputs and value of the productive land. On the other hand, there are socio-cultural pressures such as consumer perception and migration of the rural population to urban centres. This socio-ecosystem is also affected by political factors such as environmental regulations and the rate of change (Wedderburn et al. 2013).

A highly relevant driver of change in agroecosystems is climate change. This factor affects the system's key attributes, such as vulnerability, adaptation, and resilience (IPCC et al. 2015; Mazzeo et al. 2017b). For example, the variability in rainfall and increases in temperature affect forage production, water availability and animal stress, among other productive factors. According to Errazola (2021), climate change would affect the suitability of the land to produce Lucerne in the northeast and northwest of Uruguay by 2050. This means that climate change is likely to negatively impact one of the main feed dairy pastures in the future.

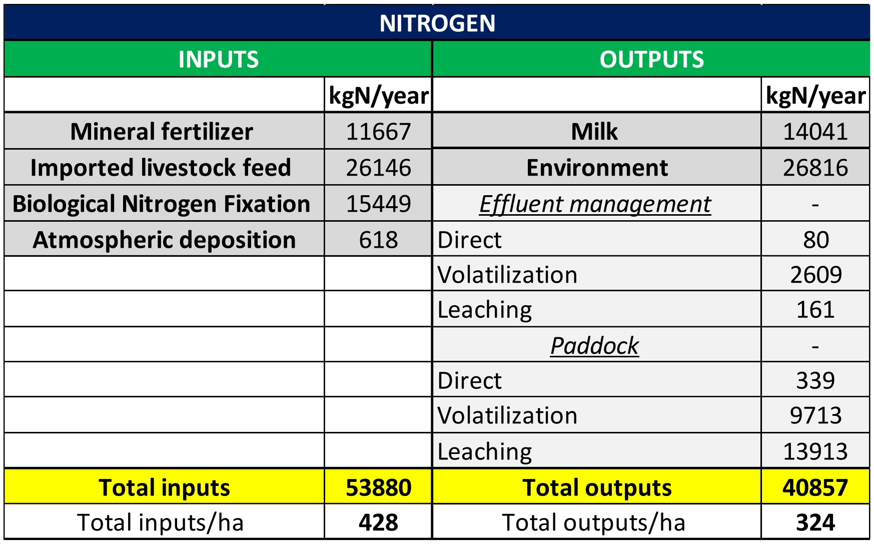
Drivers of change do not work independently but rather interact, increasing the system's complexity and condition the dairy system's dynamics and response. On the other hand, it is essential to incorporate uncertainty as a property of the system and develop the anticipatory capacity to manage the uncertainty given mainly by external factors, such as climate and its impact on milk production. Furthermore, dealing with complex, uncertain and risk issues sometimes involves learning to live with a high degree of uncertainty and ambiguity (Sposito 2021).

4.2.2. Nutrient budgets

This section describes the results of the nutrient budgets following the methodology described (see Section 3.3.) Firstly, the nitrogen and phosphorous budgets are applied to the ´Tambo´ paddocks. Secondly, the nutrient budgets are developed for the whole farm area. To interpret the numbers of the circle charts, refer to the corresponding nutrient budget table.

´Tambo´ Nutrient budgets- The table 6 summarizes the nitrogen budget for ´Tambo´ paddocks (see section 2.6. and 3.3. to understand the terminology used).

Table 6. Nitrogen budget of ´Tambo´.



NITROGEN			
INPUTS		OUTPUTS	
	kgN/year		**kgN/year**
Mineral fertilizer	11667	**Milk**	14041
Imported livestock feed	26146	**Environment**	26816
Biological Nitrogen Fixation	15449	*Effluent management*	-
Atmospheric deposition	618	Direct	80
		Volatilization	2609
		Leaching	161
		Paddock	-
		Direct	339
		Volatilization	9713
		Leaching	13913
Total inputs	**53880**	**Total outputs**	**40857**
Total inputs/ha	**428**	Total outputs/ha	**324**

Source: elaborated by the author.

As shown in table 6, the N inputs are divided into mineral fertilizer, imported livestock feed, BNF, and atmospheric deposition. The proportion of these N inputs is illustrated in the following figure, where the main N inputs are the imported livestock feed, the second most important is the Biological Nitrogen Fixation (BNF), thirdly the mineral fertilizer, and the contribution of atmospheric deposition is minor.

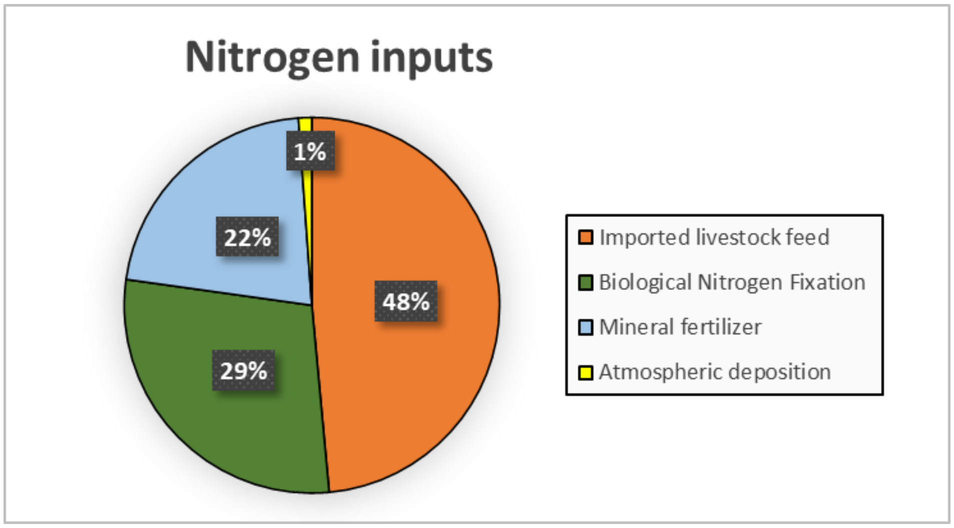


Figure 29. N inputs ´Tambo´ paddocks.

Source: elaborated by the author.

The N outputs evaluated in the ´Tambo´ nutrient budget are represented in figure 30. It includes that the 66% of the N outputs of the nutrient budget ´Tambo´ are in milk, and 34% are environmental outputs.

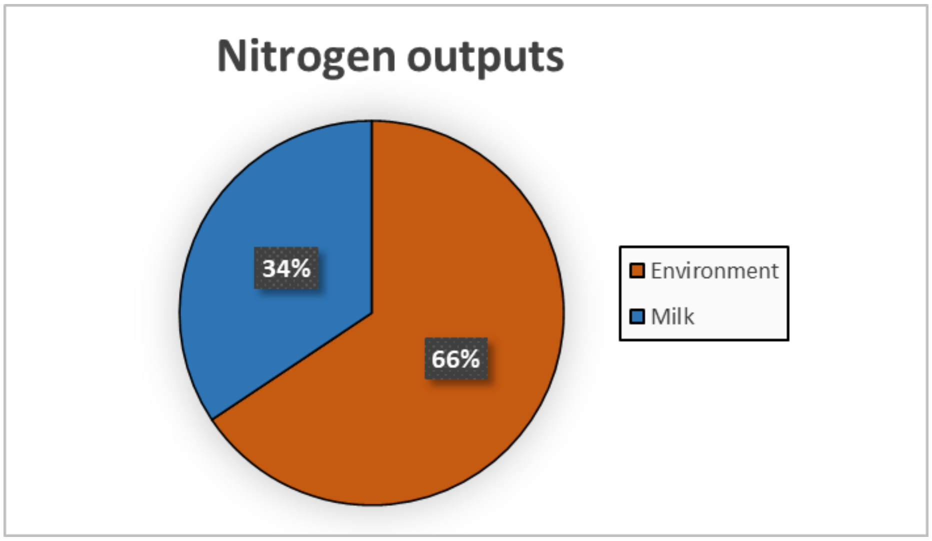


Figure 30. N outputs ´Tambo´ paddocks.

Source: elaborated by the author.

Furthermore, the ´Tambo´ paddocks' environmental N outputs can be considered losses divided into paddock and effluent management losses. For the paddock and effluent, the nutrient budget evaluated the direct N_2O, volatilization and lixiviation losses depicted below.

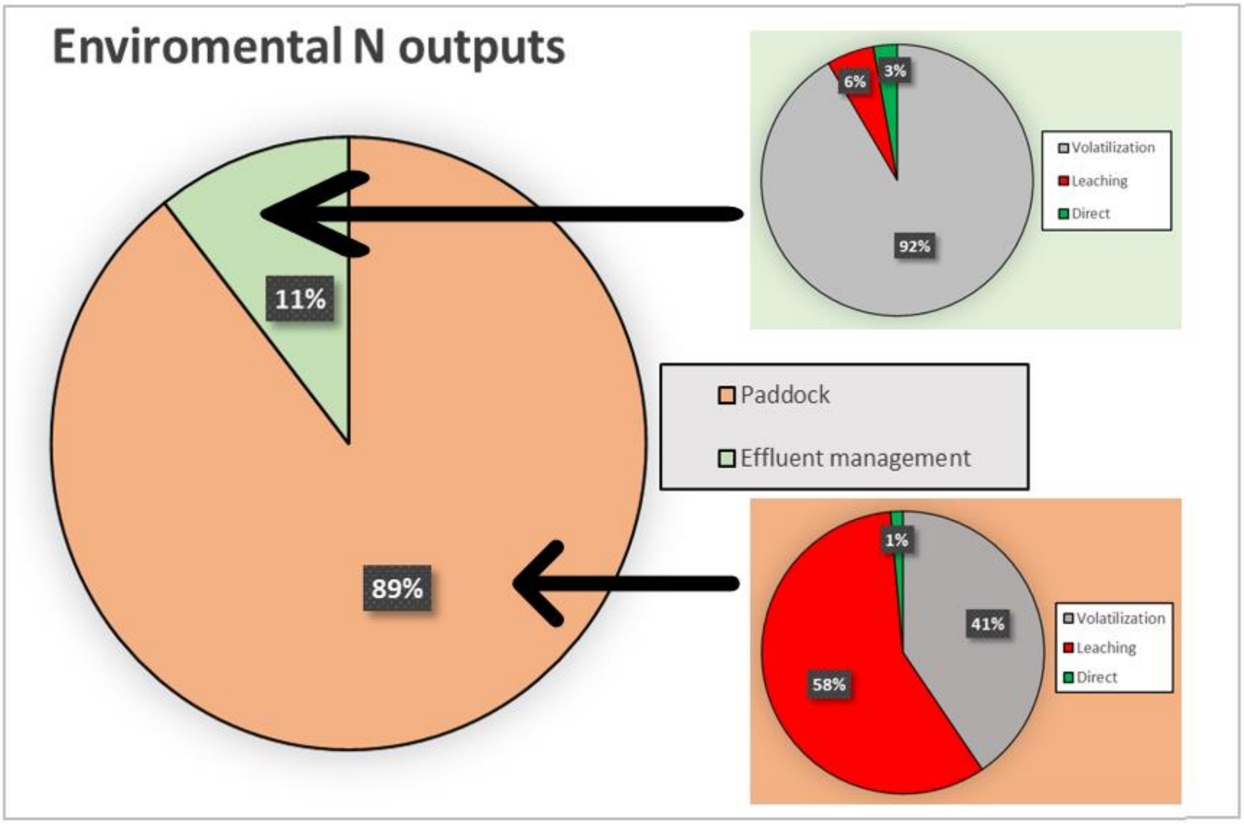


Figure 31. Environmental N outputs ´Tambo´ paddocks.

Source: elaborated by the author.

Turning now to the P nutrient budget from the ´Tambo´ paddocks, the following figure summarizes the results (see section 2.6. and 3.3. to understand the terminology used).

Table 7. Phosphorous budget of ´Tambo´.

PHOSPHOROUS			
INPUTS		**OUTPUTS**	
	kgP/year		**kgP/year**
Mineral fertilizer	0	**Milk**	2448
Imported livestock feed	4437	**Environment**	1205
		Effluent management	-
		Leaching	162
		Paddock	-
		Particulate P	395
		Soluble P	648
Total inputs	**4437**	**Total outputs**	**3653**
Total inputs/ha	**35**	Total outputs/ha	**29**

Source: elaborated by the author.

Interestingly, the P inputs only represent the imported livestock feed, as is illustrated in the figure 32. As a difference to N, other forms of inputs did not appear. This critical point is explained in the following chapter discussion.

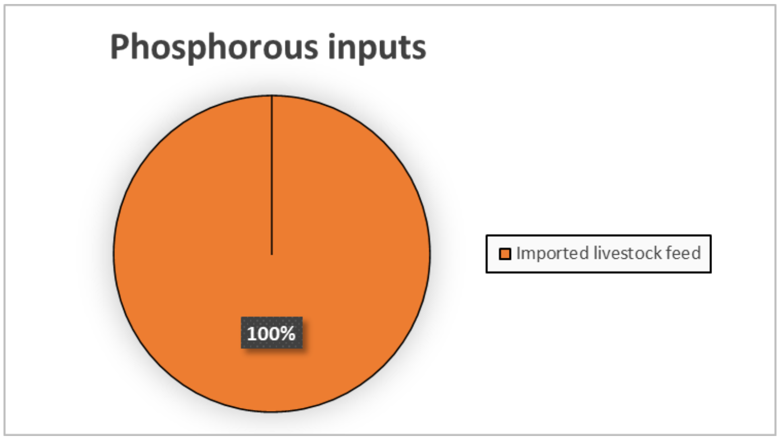


Figure 32. P inputs ´Tambo´ paddocks.

Source: elaborated by the author.

Approximately two-thirds of P outputs are in milk, and the balance one-third are environmental outputs, as the following diagram depicts.

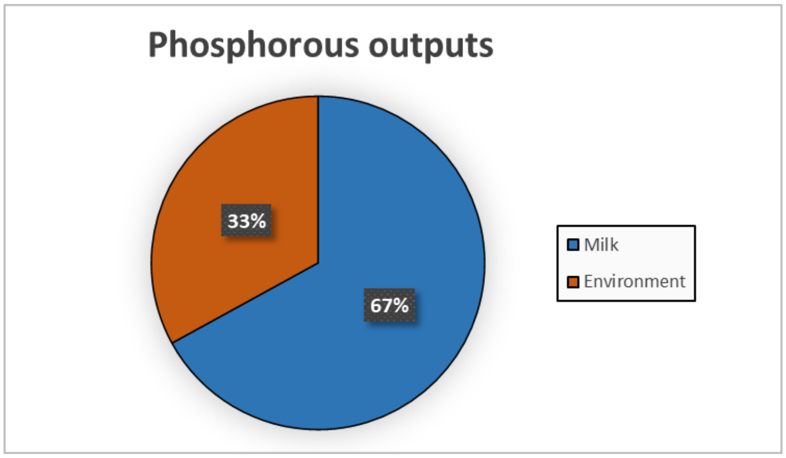


Figure 33. P outputs ´Tambo´ paddocks.

Source: elaborated by the author.

As indicated previously, the environmental losses can be classified into those from the paddock and those from the effluent management system. Around 90% of the P losses are from the paddock, subdivided into particulate P and soluble P.

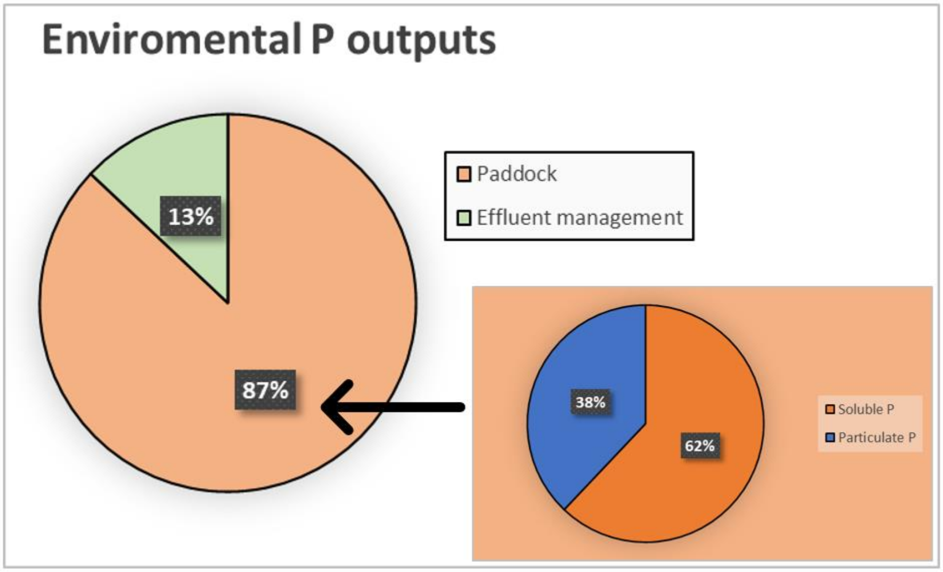
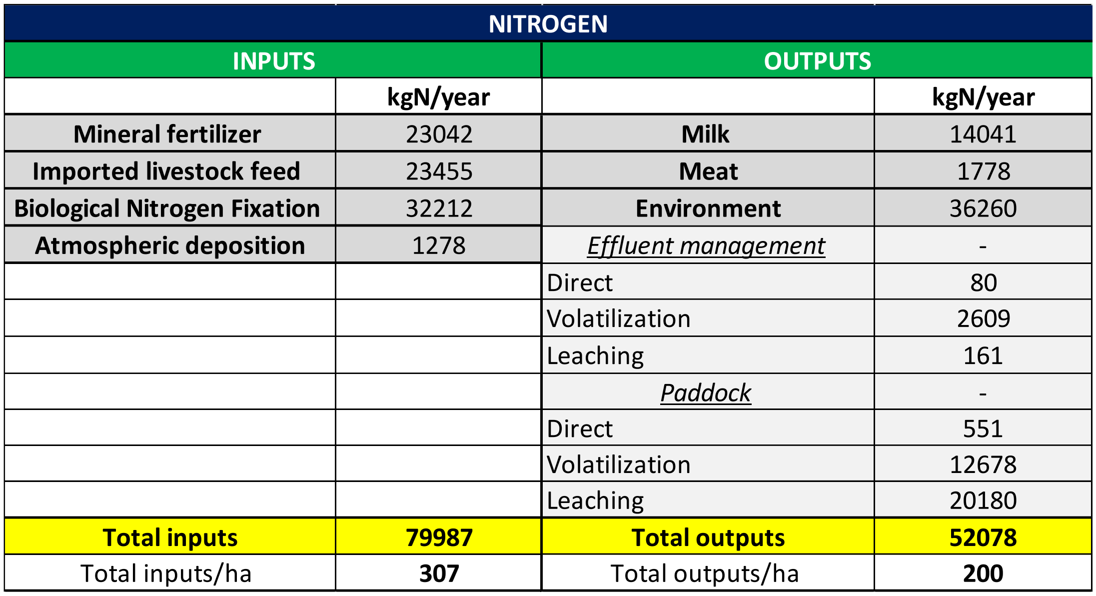


Figure 34. Environmental P outputs ´Tambo´ paddocks.

Source: elaborated by the author.

Whole farm Nutrient budgets - As was explained in the methodology (see Section 3.3.), the whole farm nutrient budgets represent the analysis of the total area of the case study farm. The summary for the N whole-farm nutrient budget is shown in the subsequent figure. It is essential to highlight here that the whole farm analysis involves the meat sold as new output compared to the N budget for the ´Tambo´ (see appendix A.4.).

Table 8. Nitrogen budget of the whole farm



NITROGEN			
INPUTS		**OUTPUTS**	
	kgN/year		**kgN/year**
Mineral fertilizer	23042	**Milk**	14041
Imported livestock feed	23455	**Meat**	1778
Biological Nitrogen Fixation	32212	**Environment**	36260
Atmospheric deposition	1278	*Effluent management*	-
		Direct	80
		Volatilization	2609
		Leaching	161
		Paddock	-
		Direct	551
		Volatilization	12678
		Leaching	20180
Total inputs	**79987**	**Total outputs**	**52078**
Total inputs/ha	**307**	Total outputs/ha	**200**

Source: elaborated by the author

The proportions of the N inputs and outputs for the whole farm are shown in figure 35. The principal N inputs are from the Biological Nitrogen Fixation (BNF), and the main outputs are environmental losses.

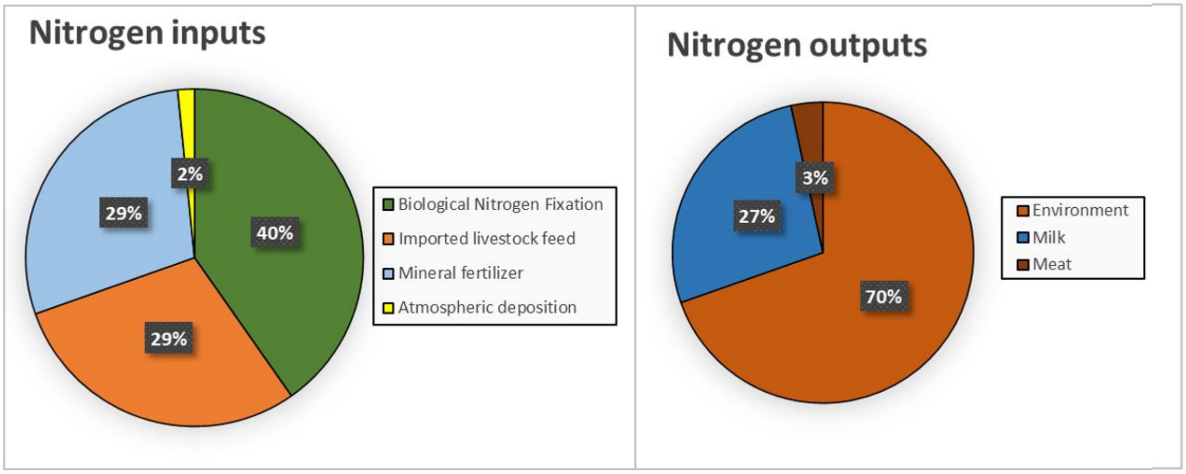


Figure 35. N inputs and outputs whole farm.

Source: elaborated by the author.

In addition, it is essential to present the results of the P nutrient budget for the whole farm.

Table 9. Phosphorous budget of the whole farm.

PHOSPHOROUS			
INPUTS		**OUTPUTS**	
	kgP/year		**kgP/year**
Mineral fertilizer	2084	**Milk**	2448
Imported livestock feed	3552	**Meat**	529
		Environment	2113
		Effluent management	-
		Leaching	162
		Paddock	
		Particulate P	1013
		Soluble P	938
Total inputs	**5636**	**Total outputs**	**5089**
Total inputs/ha	**22**	Total outputs/ha	**20**

Source: elaborated by the author.

As the figure 36 shows, the whole budget includes P inputs from mineral fertilizer. Moreover, compared to the ´Tambo´ budget, in this analysis the P outputs proportion change, with milk the greater, followed by environmental losses and meat sold.

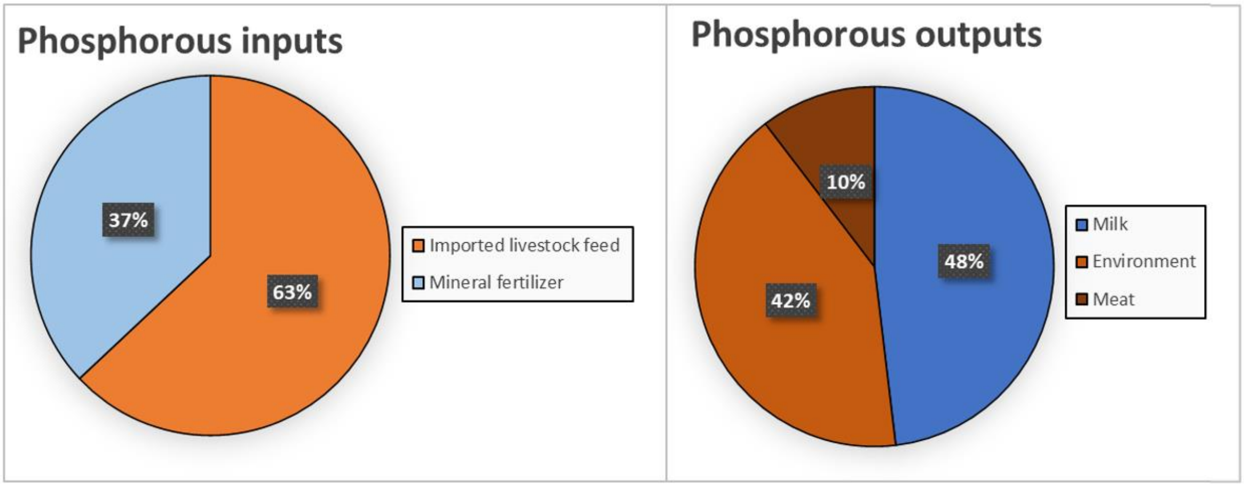


Figure 36. P inputs and outputs whole farm.

Source: elaborated by the author.

4.2.3. Agent based model NPM

This section presents the agent-based model developed named NPM (see Section 3.4.). The results show the ABM simulates the nutrient dynamics and the problem formulated in a spatial and temporal pattern. The primary nutrient dynamic results are presented. The contribution of animal excreta is compared to the complete nutrient budget modelling to understand how ABM can analyse the nutrient dynamics.

Before examining the different model nutrient dynamic results, it is fundamental to understand how the NPM model represents the dairy farm case study. The following figure thus shows that the NetLogo interface displays the dairy farm paddocks with their name using the GIS information provided by the farmer. The milking parlour is situated in its actual place and the cows are in the paddock.

In addition, the figure includes the graphs with the records provided by the farmer, cow number, milk production and protein and cow intake over the year. The graphs represent the value of the variable across the year simulated.

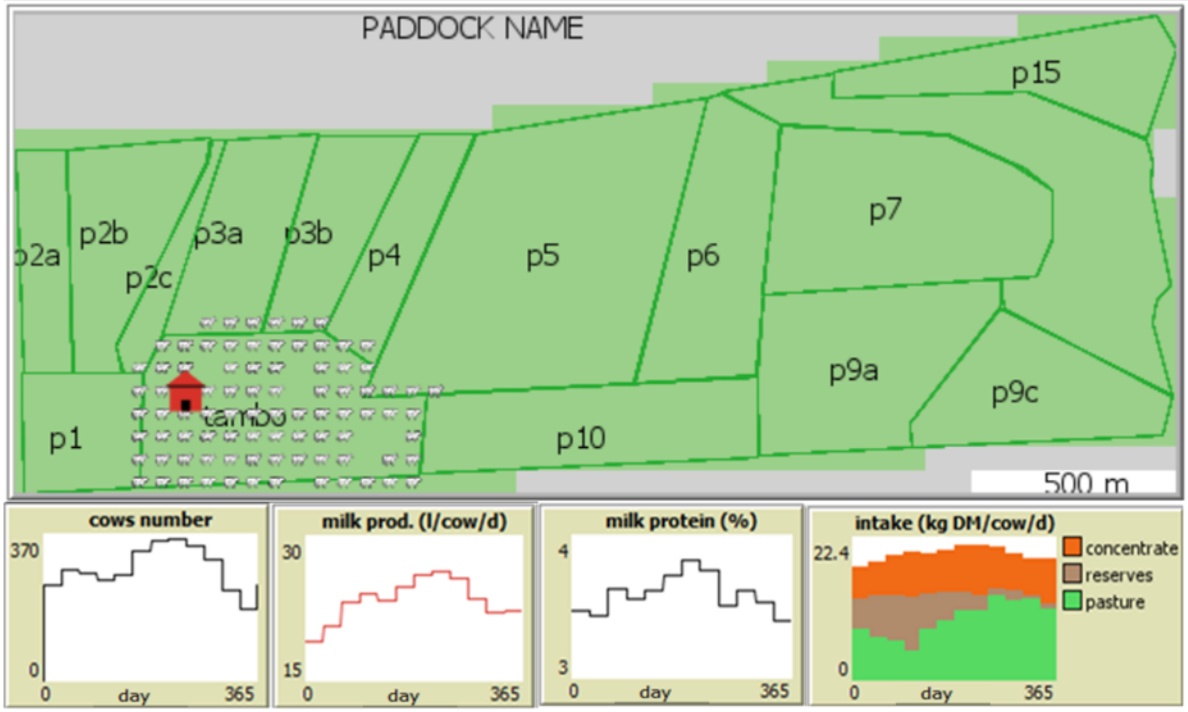


Figure 37. NPM model.

Source: elaborated by the author (NetLogo 6.2.).

Turning now to the cow nutrient use efficiency provided by the model simulation, the graph shows that there has been variation in the NUE and PUE across the year 2020 simulation. Both curves had a gradual increment in the first trimester and then a diminution of the efficiency in the last months of the year simulated. The month variation is explained because of the different monthly diets and different milk production.

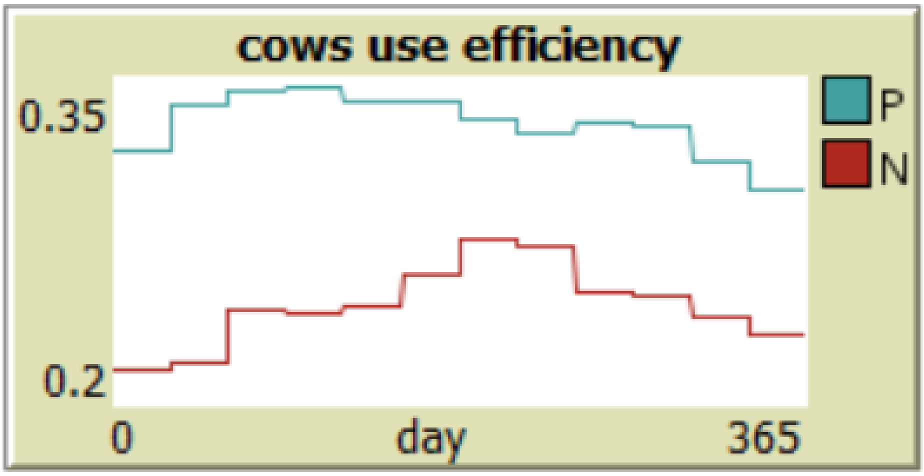


Figure 38. Cows use efficiency.

Source: elaborated by the author (NetLogo 6.2.).

The 2020 simulation of the case study dairy farm is summarized in figure 39. It includes eight graphs that represent the variation of different variables across the year simulated:

- Graph I shows N variation on the paddock in the different land uses across the year simulation.
- Graph II describes the variation of N total, N mobile, and N immobile.
- Graphs IV and VIII represent the N and P in the effluent management system across the year.
- Graphs III and VII show the N and P environmental losses.
- Graphs V and VI represent the average P on soil and the difference between land uses.

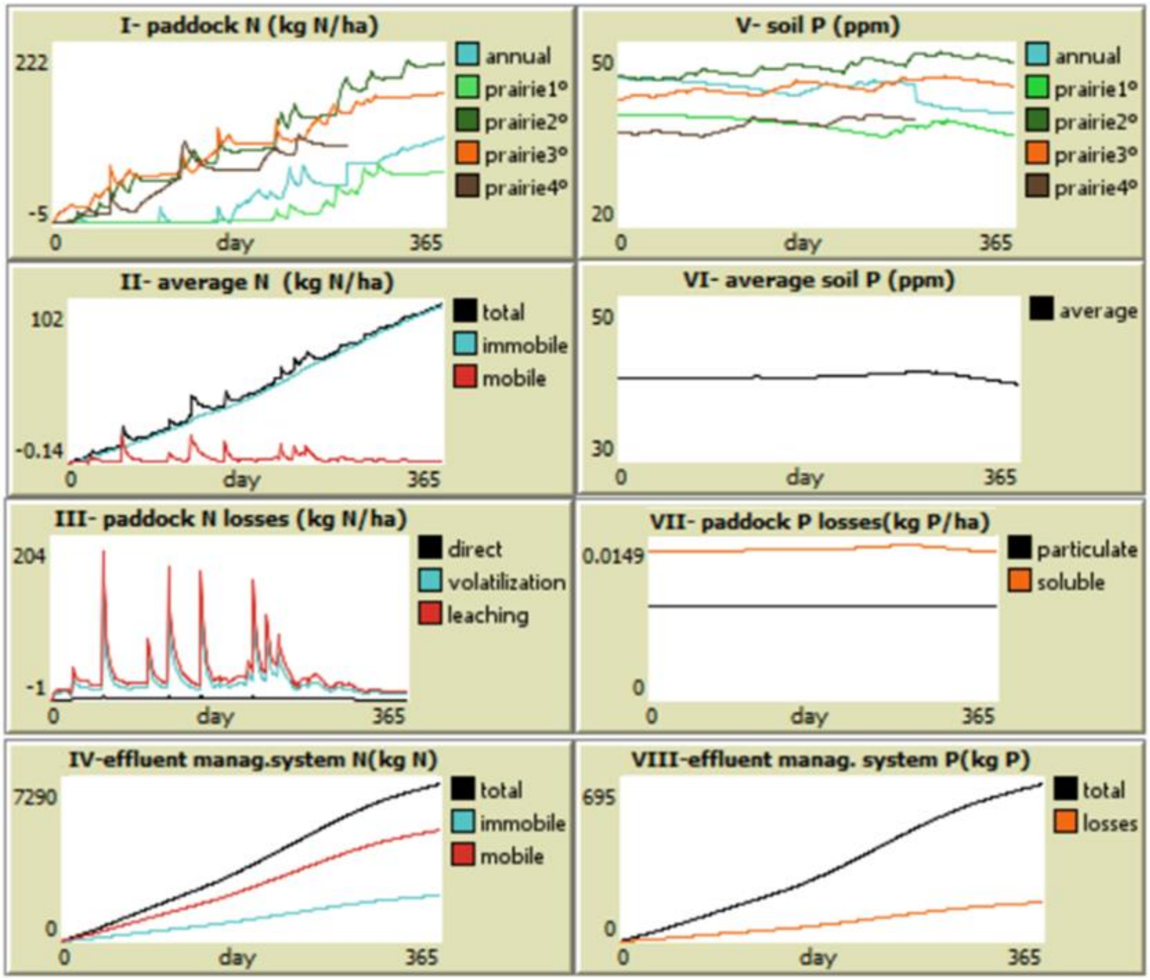


Figure 39. Results of 2020 simulation.

Source: elaborated by the author (NetLogo 6.2.).

As was pointed out in Section 2.7, ABM allows the spatialization of complex system dynamics. Figure 40 illustrates the soil P dynamic, including the initial soil P situation, the soil P after one-year simulation only counting cow's excretion, and finally the soil P in the complete simulation. The simulation was made with only excretion as the factor is important to comprehend how much P returns to the paddock by excretion.

The model interface represents the P soil change by colour, and the graphs allow to understand the average situation in the ground. The charts show the initial P soil analysis of 41 ppm and the variation across the year simulated. While considering only cows' excretion, the P-value increases across the year, and in the entire nutrient dynamic situation, the line is stable across the simulation.

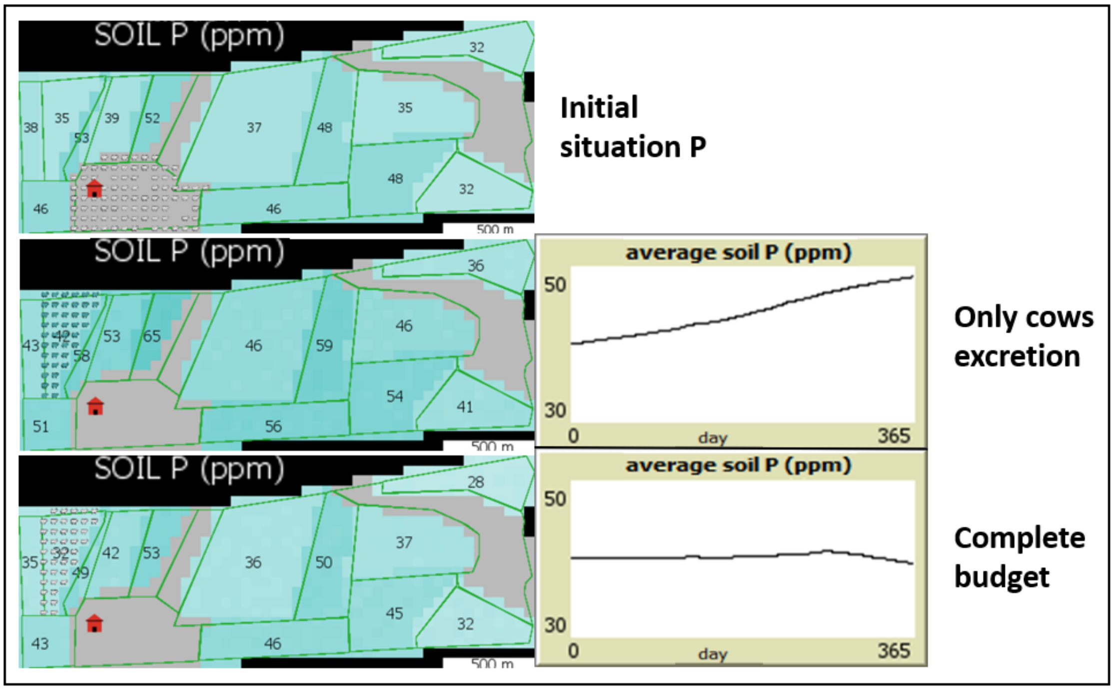


Figure 40. Soil P dynamic.

Source: elaborated by the author (NetLogo 6.2.).

The NPM model also allows the comprehension of the soil N dynamic. The figure 41 illustrates how much N returns to the paddock by excretion. Also, it is possible to understand how much N stays in the soil after one year of complete simulation. The paddock colours show the value of N on soil - the redder, the higher level of N. Besides, the graphs explain the kilograms of N depending on land use. It is essential to highlight here that as a difference from the P analysis, the initial N on soil assumed in this simulation is 0. This is represented in both graphs that at the beginning of the model simulation, where the kg N/ha is 0.

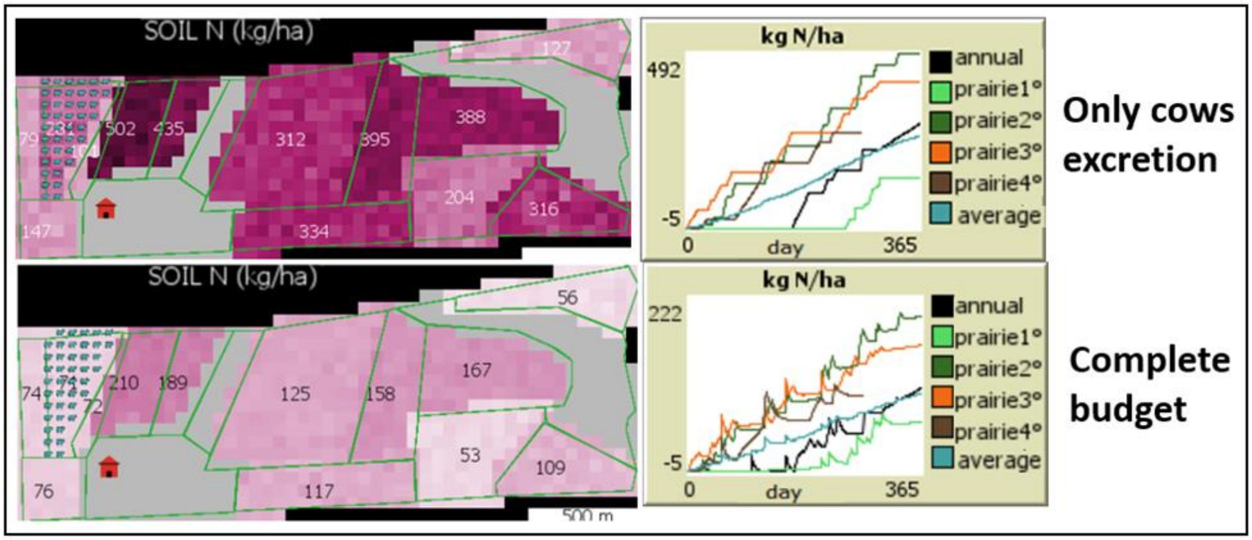


Figure 41. Soil N dynamics.

Source: elaborated by the author (NetLogo 6.2.).

4.3. Stage 3 - Scenarios as Possible Solutions

This section presents the results of different, and possible, farm management scenarios (see Section 3.5.) and their impacts on nitrogen and phosphorous dynamics. The scenarios are evaluated via the nutrient budgets. The impacts are mainly reflected in the nutrient use efficiency, inputs, and environmental losses.

The following table summarises how the farm management scenarios assessed impact nutrient inputs, outputs, and cow's nutrient efficiency. The 4th Scenario is not included in this table because it was analysed to the whole farm and not only to the ´Tambo´ paddocks.

Table 10. Farm management practices scenarios.

	Study case Current situation	Scenario 1 Land Use	Scenario 2 Diet	Scenario 3 Stocking rate
NITROGEN				
Total inputs/ha	428	415	377	386
Total outputs/ha	324	329	326	269
Milking cows NUE	24%	24%	24%	21%
PHOSPHOROUS				
Total inputs/ha	35	-	26	28
Total outputs/ha	29	-	29	25
Milking cows PUE	33%	-	36%	30%

Source: elaborated by the author.

The results of each management scenario are described in the following subsections.

4.3.1. Land use

Scenario 1 represents the change in land use (see Section 3.5.). This modification of land use does not change the NUE but changes the dairy system's N inputs and outputs. The proportion of inputs vary, as is shown in the figure 42. This chart reveals that the proportion of mineral fertilizer increased because of the reduction of N fixed by the Leguminosae. In addition, the environmental N outputs increment 560 kg N/year (see scenario 1 N budget in Appendix A.7., table 14).

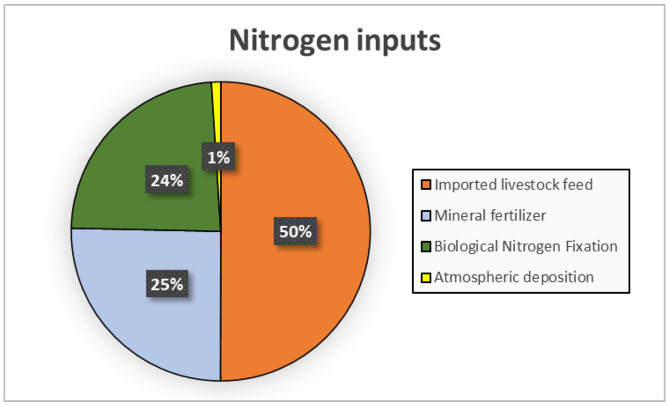


Figure 42. N inputs for scenario 1.

Source: elaborated by the author.

4.3.2. Type of diet

Scenario 2 refers to the cow's diet proportion (see Section 3.5.). As shown in table 10, while the NUE maintains the current situation value, the PUE increases 3% compared to the current PUE. Furthermore, in this management scenario, the N input drops by 50 kg N/ha and N output increases by 2 kg N/ha. Also, the proportion of N inputs changes because the imported livestock feed decreases significantly compared with the current farm situation, as is represented in the following figure.

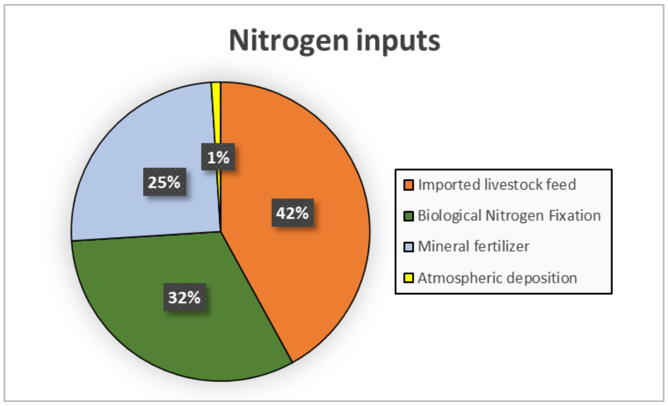


Figure 43. N inputs for scenario 2.

Source: elaborated by the author.

The P input drops by 9 kg P/ha, and the P outputs maintain the same value per hectare. However, the farm P environmental outputs (kg/year) change in the value of the punctual losses of the effluent management (see scenario 2 P budget in Appendix A.7., table 17).

4.3.3. Stocking rate

Scenario 3 refers to a decrease of stocking rate, showing that the total N output is lower because not only the N on milk decreased, but also did the environmental N losses. Still, the P outputs decreased due to the lower milk production. Table 10 indicates the lower NUE and PUE in that situation compared to the actual case study. Moreover, this scenario covers a lower effluent generation due to the stocking rate reduction (see Appendix A.7., table 18 and 19).

4.3.4. Effluent management

In *Scenario 4*, the effluent is used as organic fertilizer in the paddock of the rest of the area. Because of this, the mineral fertilizer used in the whole farm has decreased. This is expressed through the proportion of N and P inputs of the whole farm nutrient budget (see Appendix A.7., Tables 20 and 21). In the following figure, it is also possible to appreciate that the proportion of mineral fertilizer decreased compared to the current dairy farm situation.

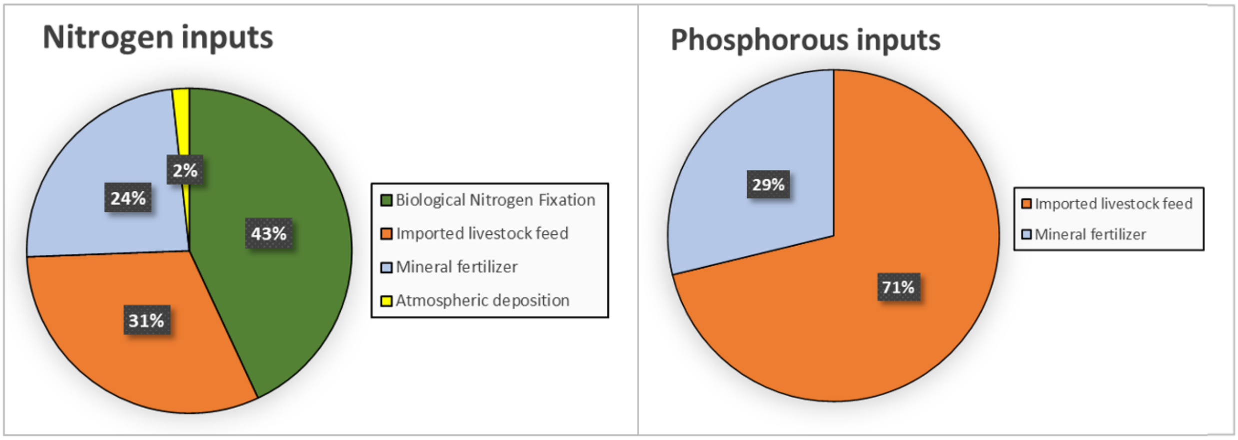


Figure 44. N and P inputs scenario 4 Whole Farm.

Source: elaborated by the author.

Regarding the outputs, Scenario 4 shows an increment in paddock volatilization by 518 kg N/ year (see Appendix A.7., Table 20).

CHAPTER 5: DISCUSSION

Chapter 5 discusses the main findings in the first three methodological stages - *problem formulation, situation and diagnosis, and solutions*, and compare them with other relevant studies. The analysis and discussion are particularly focus on the problem formulated, the nutrient dynamic results, and the collective learning and sustainable dairy farming. The applications of nutrient budget and agent-based model in a farm-scale are also analysed.

5.1. Problem Formulated and Nutrient Dynamics

As explained in the previous chapters, the nutrient budget and the modelling are very suitable methods for understanding the problem formulated and the farm nutrient dynamic. According to Cherry et al. (2008), the nutrient budget is a valuable and straightforward tool to analyse farm data and evaluate the nutrients inputs and outputs. However, the nutrient budget method has some limitations and can be appropriately complemented with suitable modelling. In this way, models allow the quantification of nutrients dynamic to describe and analyse the environmental performance of a farm. Furthermore, the ABM modelling enables the analysis of the model agents in space and time (Railsback and Grimm 2019).

The present thesis applies both methods to analyse the N and P dynamics deeper. Firstly, the application of the nutrient budget allows to understand nutrient inputs, outputs, efficiency, and environmental impacts. Secondly, in a complementary way, the NPM model analysis in this thesis enables to understand the nutrient flows in the dairy farm’s year simulation, or for different components separately, for example, simulating only with the cow's excreta. As was mentioned before, the modelling permits exploring how the system behaves without taking any action that may negatively impact the system itself (Jackson 2011, cited by Sposito 2021).

5.1.1. Nutrients budgets and NPM model

The results of the analyses of the farm in Uruguay across the nutrient budgets produced similar values to regional and European investigations. This is exemplified, for instance, in research undertaken by Carbó (2011), who showed nutrient budget values related to N and P per hectare (value = inputs - outputs) of 121.5 kg N/ha/ year and 18.3 kg P/ha/year – results very similar to those presented in Chapter 4 of the present thesis. Similarly, other research by Van Leeuwen et al. (2019) reported five pasture-based dairy farms with similar inputs and outputs values to those obtained in the Uruguayan dairy farm studied. This suggests that the methodology used in the thesis produces common dairy farm values. However it is essential when comparing results with similar research to consider the farm's productive reality and the country's production conditions.

Furthermore, Lizarralde (2013)'s research for Uruguay, produced similar values of nitrous oxide emissions from the effluent management system and N excreted per cow per year. According to a summary of studies from New Zealand, France, the United Kingdom, and Denmark (Ledgard 2009), the leaching found in that summary is similar to the value for the N input level of the case study farm. The previous sentences allow considering the thesis calculation methodology and sources consulted for the environmental nutrient losses as suitable.

As indicated previously, the soluble P losses from the paddock were more significant than the particulate losses. It is in accordance with the Uruguayan research (Perdomo 2015) about the P index -the sum of soluble and particulate P. This index helps to evaluate the management area level and identify the area with the highest contribution of P. Interestingly, the approach in this thesis of assessing the ´Tambo´ paddocks separately from the whole farm paddocks showed the higher P index in the ´Tambo´ area, thus reflecting the more significant P inputs in the ´Tambo´ area. While the P index can be conceived as a static value for the current situation, the P budget can be analysed as a measure of direction because it involves more variables.

Focusing on the consideration of the whole farm nutrients budget, it showed expected results due to the reality of the case study farm. By having less intensive production in the rest of the farming area compared to the ´Tambo´ area, the values for the whole farm inputs and outputs per hectare were lower than those reported in the ´Tambo´ nutrient budget. This is partly explained by the stocking rate and excreta of dairy cows in ´Tambo´ paddocks compared to the low stocking rate of other cow categories in the rest of the area.

Regarding NPM model application, according to Wedderburn et al. (2013), the ABM allows the exploration of farm systems’ behaviour. The NPM model developed and applied in this thesis allowed visualising the farm heterogeneity between the different paddocks. It was also possible to evaluate the nutrient dynamics depending on land use and time of cow grazing. The specialisation of the NPM model is beneficial to analyse the different management decisions. Similarly, Veltman et al. (2018), using a process-based model for a dairy farm, proved that reducing the N and P environmental losses across beneficial management practices is possible.

According to the NPM model, for the case study farm, even if there is not fertiliser used, the P level in the soil may be maintained due to the contribution of cow excretions, as is shown in the simulating only cow's excreta simulation (see Figure 40). In the same way, De Lucca (2020) demonstrated that the soluble losses of P exceed desirable limits in the non-application treatment.

The high P exportation suggests that it is necessary to introduce other management alternatives apart from not fertilising. Because of that, to reduce the level of P on soil in the medium term, it is required to apply different management practices depending on the specific soil phosphorus level and the soil stratification. For example, it is possible to incorporate extractive plant species in terms of nutrients and export them in forage or grain. Moreover, if the stratification level is high, periodic soil inversion is recommended to break P stratification (Kleinman et al. 2015 and De Lucca 2020).

Animal nutrient use efficiencies based on dietary nutrients and nutrients in milk are beneficial to compare the potential for environmental impact. According to an extensive literature review (Rotz et al. 2005, Cherry et al. 2008, Arriaga et al. 2009, Ryan et al. 2011 and Davidson et al. 2015), improving cows NUE and PUE is the most effective form of increasing productivity and decreasing environmental impact. According to a study by Aarons et al. (2020), the case study farm with a NUE of 24%, is in the range of commercial dairy farms. Furthermore, Powell et al. (2010) found a NUE of 24% for a similar stocking rate, whilst Aarons (2021) reported an average of 21% NUE. Furthermore, the present thesis found a PUE of 33% for the current farm situation, which according to Aarons (2020) is in the expected range. Related to the NUE, it is necessary to adjust the cow's diet to the protein required. This means changing the N intake in the diet because the higher the N content, the higher the N losses the environment.

5.1.2. Farm management scenarios

According to Darré et al. 2021, the management factors related to the grazing system, land use, type of diet and the number of inputs can be more relevant in determining the environmental impacts of dairy systems than productivity per se. These management factors are equivalent to the scenarios evaluated in this thesis (see Section 3.5.).

Another research (Lemaire et al. 2015) analysed management situations to minimise trade-offs between farm production and the environment. They stated that an overly uniform land-use system and the excessive N–P loads in intensive animal areas lead to unacceptable environmental impacts. The present thesis results similarly showed that the current situation of the dairy farm's high stocking rate can be partly responsible for high N and P losses to the environment (see Section 4.2.2, Results – Nutrient Budgets.

Moving on to the scenarios evaluated, *Scenario 3* tried to understand how a lower stocking rate impacts the results – it showed lower environmental outputs. Predominantly, they are expressed in paddock and effluent N losses. In the case of P, the reduction is only in the effluent losses, probably because it is not possible to see an influence on paddock losses due to the limitations of the nutrient budget approach. The reduction in environmental losses is mainly due to the lower generation of excreta due to fewer cows, as was stated in the bibliography (Fernández-Marcos 2011; Arriaga et al. 2009). Additionally, the NPM model is beneficial for evaluating and understanding the excreta impact on the paddock (see Figures 40 and 41).

In *Scenario 1* of land use, because of the reduction of Leguminosae, the proportion of the inputs changed, reducing the BNF and increasing the inputs that affect the environment and cost money to purchase like mineral fertilizer. In a similar study, Garcia et al. (2021) concluded that Leguminosae in the pastures can significantly reduce the farm N inputs, increment the N availability for the grass, nutrient cycling and ecosystem services. Rochette and Janzen (cited by IPCC 2019a) also claimed that BNF is not considered a direct source of N_2O emissions. Furthermore, this scenario showed that the BNF does not generate environmental losses and reduces mineral fertilizer use. Although the total input of N into the system decreases 1535 kg N, this input reduction is in BNF, and the farm loses autonomy to external nutrient inputs (Charlón et al. 2014).

Turning now to the cow's diet, some research suggests the diet strongly influences environmental losses (Ryan et al. 2011, Tayyab and McLean 2015, Darre et al. 2021). What is more, Aarons et al. (2020) stated that imported animal feed is a more significant source of nutrients than fertilizer inputs. This means that the proportion in the cow’s diet of pasture versus concentrated feeding defines the possible farm nutrient losses (Darre et al. 2021). Furthermore, according to Ryan et al. (2011), the more kilograms of concentrates in the diet, the higher N is available for leaching. In *Scenario 2* in my research, the reduction of concentrates on the cow’s diet reduces the P outputs in the punctual losses of the effluent management. This reduction is because the animal produces a lower P on excreta with the new diet. Furthermore, it is not possible to evaluate the change of P diffuse losses of the paddock because the nutrient budget approach is not sensitive to that change.

According to the results of *Scenario 4*, the dairy farm effluent can be used as organic fertilizer in the paddocks of the rest of the area, decreasing the mineral fertilizer use and changing the proportion of N and P inputs. It is important to highlight here that the effluent cannot be used in the ´Tambo´ paddocks because of the excessive P on the soil. Currently, the farmer does not apply any P fertilizer on the ´Tambo´ area because the farm has a P accumulation on the ground. This is shown in the soil analysis by high P bray values (41 ppm P bray average, see Appendix A.4.). This situation is caused by P surplus that manifests in soil accumulation and as losses to watercourses by erosion or runoff (Perdomo 2015).

The scenarios evaluated in the thesis show the same NUE value described previously, except in *Scenario 3*, which reduces 3% because a probable limitation in the calculation methodology. In the case of PUE, when the cow's diet was less concentrated (Scenario 2), it transformed to 36%, being the dairy cows more efficient in converting the P feed into milk. Besides, in the fewer stocking rate *Scenario 3*, the PUE was 30%. It is essential to highlight that the scenarios applicability to the NUE and PUE analysis is limited because of the scenario's methodology used and their impact on the nutrient budget.

5.2. Collective Learning and Sustainable Dairy Farm

Any research that successfully attempts to address sustainability challenges needs the close collaboration between researchers (academics) and not-academics; i.e.; *people in the problematic situation* (Checkland and Poulter, 2006; Norström et al. 2020). Therefore, the collective learning pursued in this thesis intended to address the communication between the researcher and the farmers. The thesis process thus included strong interaction with the farmers to promote collective learning (see Appendix A.3.). This approach is considered extremely beneficial for analysing the formulated problem and designing pathways and implementation actions to achieve a more sustainable dairy farm production. Furthermore, farm nutrient management is a complex problem, and many decision-making aspects are involved. It is therefore essential to incorporate the farmer's skills and knowledge to attain a more resilient agroecosystem (Pretty 2008).

Turning now to specific interaction with the case study farmer and his close collaborators, the communication with them was based on describing the nutrient budget results and the agent-based model. This included a framework and demonstration of the tool's applicability. In addition, in another opportunity, the main findings of the thesis were transmitted to the farmers' group (see Appendix A.3.). Remarkably, the farmer of the case study was very interested in the model and nutrient budget because of the sense of belonging in seeing the reality of his farm. In the interactions, the farmer suggested possible future utilisation of the model. Furthermore, the case study farmer said that it could be interesting to explore the nutrient dynamics in the long term, not only for a one-year simulation.

In the discussion, the farmer also said that the P analysis of the thesis was interesting and should be considered by the farmers in the group that currently have a lower P accumulation on the soil. This suggests that the NPM model transmits the reality of the P accumulation on the ground and the environmental losses efficiently. In that sense, the farmer made an interesting reflection on the historical P fertilization in the farm that, according to him, was excessive and higher than the pasture's requirements. Moreover, the farmer said that he is worried about reducing the level of P on the soil. In a comparable situation, Cherry et al. (2008) found that the particular soil's P buffer effect clearly needs a comprehensive mitigation strategy. Similarly to the case study farm situation, Sharpley et al. (2013) reported that the historic fertilization of P sources on the surface, the direct deposition of manure by livestock, and the soil management generated a legacy of P.

Apart from soil analysis for monitoring P, it can be an excellent strategy to evaluate Milk Urea Nitrogen (MUN) as an indicator of the N situation in the farm system. Due to N mobility in the soil, MUN can be an appropriate indicator of N in the excreta and in the whole system (Marshall et al. 2020). In the same way, the MUN allows monitoring the protein status of cows and avoiding the addition of excessive degradable nitrogen to the diet. During the interaction with the farmers the incorporation of MUN analysis into farm management was discussed. The MUN analysis is monitored regularly in dairy farms that remit milk to the industry. On the contrary, artisan cheesemaker dairy farms are not expected to analyse MUN; thus, as the group of farmers are cheesemakers, they considered this as a useful idea to incorporate.

Furthermore, according to Wedderburn et al. (2013), the collective learning approach can also enable policy planners to engage and learn about the impact of the individual decisions and strategies to improve the problematic situations.

In the same way, this research aimed to contribute to the strategic planning of the national Government of Uruguay to achieve a more sustainable dairy farm production. In this context, I believe that the thesis research and outcomes provide useful instruments and information in developing farm-scale policies to achieve this fundamental goal for the country. The dairy farm sector is vital for Uruguay, and it is included in the national plans to reduce the nutrient contamination to waterways and the greenhouse gas reduction goal (MGAP 2019; MVOTMA 2019). Furthermore, the research in the thesis contributes to local management, associated with the measures of the Santa Lucia River Action Plans. Mainly, it contributes to dairy farm sustainable development in measures 3 and 5 (MVOTMA 2013) and the axis 2 of reduction of nutrients contamination from point and diffuse sources (MVOTMA 2018).

CHAPTER 6: CONCLUSION

In this final chapter, the *main findings* of the research are firstly summarised. Secondly, the contribution to knowledge is described by reference to the answering of the *Research Questions* posed at the beginning of the study (in Chapter 1). Thirdly, some research limitations and methodological considerations are mentioned. Further research on the topic and specific directions for improvement are then discussed. The chapter concludes with a personal reflection.

6.1. Fundamental Findings

The key findings of this research can be summarised as follows.

- Application of the *Nutrient Budget Method* provides a good understanding of nutrient inputs and outputs in farm systems. The nutrient *inputs* are highly related to external livestock feed (including concentrates) and N fixed by Leguminosae. Furthermore, the environmental *outputs* are significantly associated with the characteristics of farm management.
- The nutrient inputs related to the livestock feed are partly responsible for the nutrient losses to the environment and resulting damage. As a consequence, based on the case study of a typical Uruguayan dairy farm, a reduction of the external livestock feed and an increment of pastoral cow’s diet would reduce the environmental impacts.
- In this approach, it is necessary to adjust the cow's diet to the protein required. The Milk Urea Nitrogen (MUN) analysis can monitor the protein status, avoiding excessive degradable nitrogen in the diet. This means that it is crucial to adjust the N intake in the diet, because the higher the N content, the higher the N losses to the environment.

- The excessive P accumulation on soil in the typical Uruguayan dairy farm needs a novel management strategy to reduce the continuous P losses to water systems. According to the agent-based *Nitrogen Phosphorous Management* (NPM) model, the non-use of P fertilization would not be sufficient to decrease the P levels on the soil for the case study farm.
- It is important to maximize the time animals spend in the pasture fields and minimize the time in the milking parlour and roads due to the role of cow's excreta as a fertilizer. Moreover, it is critical to reduce the generation of dairy effluent or losses outside the pasture fields.
- The NPM model is very useful as a communication with, and informing tool to, farmers. It permits *collective learning* between the researchers and the farmers – i.e.; ´the people in the problematic situation´.
- Agricultural research is firmly based and generally accepted by farmers when the problematic situation is formulated and the research is conducted in interaction with them. At the same time, this interaction allows farmers to better comprehend environmental issues and inform their management decisions from a sustainable perspective.

6.2. Contribution to Knowledge – Answer to the Research Questions

Implementing new management practices generally implies an initial increment in farmers´ costs, which can be progressively recouped as the farm becomes more sustainable and efficient. Consequently, it is vital to support farmers with the appropriate decision-making instruments. The *Nutrient Budget Method* and the *Nitrogen Phosphorous Management* (NPM) model are appropriate decision support tools for dairy farmers to evaluate nutrient efficiency and farm performance. At the same time, the approach to *collective learning* adopted in this thesis supports the construction of shared visions for the future and designing and implementing common actions among diverse actors for achieving the desirable future. Collective learning requires a constructive dialogue and capacity to analyse the present and the future, understanding shared spaces, strategic and operational objectives, and the different assumptions and possible solutions to the perceived problematic situations.

In what follows, the answer to Research Questions posed at the beginning of this thesis (in Chapter 1) are briefly discussed.

Research Question 1 (RQ 1) - *How can the current Uruguayan dairy farm configuration be transformed to be more sustainable?*

The Agroecosystem sustainability approach adopted in this thesis proved to be an appropriate one to address sustainable dairy farm issues. It is especially useful in addressing the complexity of the farm management practices interacting with the economic, ecologic, organisational, and socio-cultural fields. Furthermore, it is essential to understand the structural and functional relations between different components of the production systems.

Research Question 2 (RQ 2) - *Which are the dairy farm management practices that reduce nutrient pollution?*

As demonstrated in the thesis, increasing the area of Leguminosae pastures to augment biological nitrogen fixation (BNF) is an effective sustainable practice to reduce nutrient losses. Promoting the proper farm feed is also essential, leading to a more pastoral animals' diet. Besides, it is essential to regularly make soil nutrients analysis in order to fertilise only, and in what quantities, when the crops require it.

Research Question 3 (RQ 3) - *Which management scenarios (i.e.; actions) maximize nutrient efficiency and, at the same time, minimize the nutrient losses to the environment?*

As shown in the case study of a typical Uruguayan dairy farm, reducing the cows' stocking rate is an appropriate management decision to reduce nutrient loss to the environment. Another effective management practice is to promote the biological nitrogen fixation (BNF) and the pastoral diet. Moreover, the scenario of nutrient circularity using the effluent as fertiliser is another fam management action that maximises the nutrient efficiency and, at the same time, minimises the nutrient losses and damage to the environment.

Research Question 4 (RQ 4) - *Can Agent-based Modelling (ABM) spatialize the nutrient dynamics of a dairy farm?*

An agent-based model is an excellent tool for spatialising the nutrient dynamics in a farm system and utilising it for farmers' collective learning. Furthermore, the model can be used to represent and explore the behaviour of complex agroecosystems to find solutions related to environmental problems as well as enhancing the information required for successful strategic planning from national to regional/local and farm geographic levels.

6.3. Methodological Considerations and Research Limitations

The multimethodological research approach applied in the present thesis has an excellent capability to answer the research questions formulated. The methods selected to implement the methodology focused on dairy production systems are also clearly appropriate to each of the three methodological stages covered in this thesis: *problem formulation*, *situation and diagnosis. and solution* (see Figure 17). It is however important to mention here that the approach and methods used in this thesis are based on multiple accepted bibliography sources. Furthermore, the development of the Nutrient Budget Method and the NPM model uses many variables, which are thoroughly explained in this document and that can be conveniently applied in similar, and further, research. Because of this, it has been crucial to reference each variable and the data sources used. Notably, the evaluation of environmental N losses was more accessible than the P losses. This may be due to the fact that the Intergovernmental Panel on Climate Change (IPCC 2019) has a deeper analysis of greenhouse gas emissions equations associated with N.

Furthermore, the methods and the data used are not sensitive to the change of P diffuse losses in the paddocks. Due to this, the evaluation related to management practices and P paddock losses is limited. The applicability of the management scenarios to the Nitrogen Use Efficiency (NUE) and Phosphorous Use Efficiency (PUE) analysis is also limited because of the scenario’s methodology and their low impact on the nutrient budget. Also, the nutrient budget approach has not evaluated the variation in the accumulation of P and N in the soil because of the complexity of the processes involved. Likewise, this variation in the accumulation may explain the difference found between inputs and outputs on the nutrient’s budgets.

Finally, the time available for the thesis’ development (around 10 months in Uruguay) did not allow more interactions with farmers to promote further collective learning and implementation.

6.4. Further Research

Further research would be interesting to complement the present investigation to encompass the final steps of the multimethodology: *decision-taking, monitoring, and implementation* as depicted in Figure 17.

In addition, further research can be beneficial to evaluate the NPM model in the whole farm area of the case study, not only in the ´Tambo´ paddocks. This would enable the comprehension of the heterogeneity between the different intensity of pastures and animals' density in all the farm's areas. It can also be interesting to test the management scenarios evaluated on the NPM model. Besides, as suggested by the case study farmer, the model simulation would be improved by a long-term simulation. This would allow a deeper agroecosystem comprehension as well as enhance the farmers' decision making.

Although this research was based on a case study in Uruguay, the multimethodology applied and the methods developed within its framework can be clearly extended to other regions since comprehensive information has been provided in the thesis.

6.5. A Journey of Exploration

It is appropriate to conclude my journey of exploration in Australia and Uruguay with a quote from David Attenborough (2020, p. 220), one of the world's leading naturalists. It expresses my feelings of hope for a better world and my conviction that a sustainable future is possible.

> **´Homo sapiens, the wise human being, must now learn from its mistakes and live up to its name. We who are alive today have the formidable task of making sure that our species does so. We must not give up hope. We have all the tools we need, the thoughts and ideas of billions of remarkable minds and the immensurable energies of nature to help us in our work. And we have one more thing - an ability, unique perhaps among the living creatures on the planet - to imagine a future and work towards achieving it . . . All we require is the will´.**

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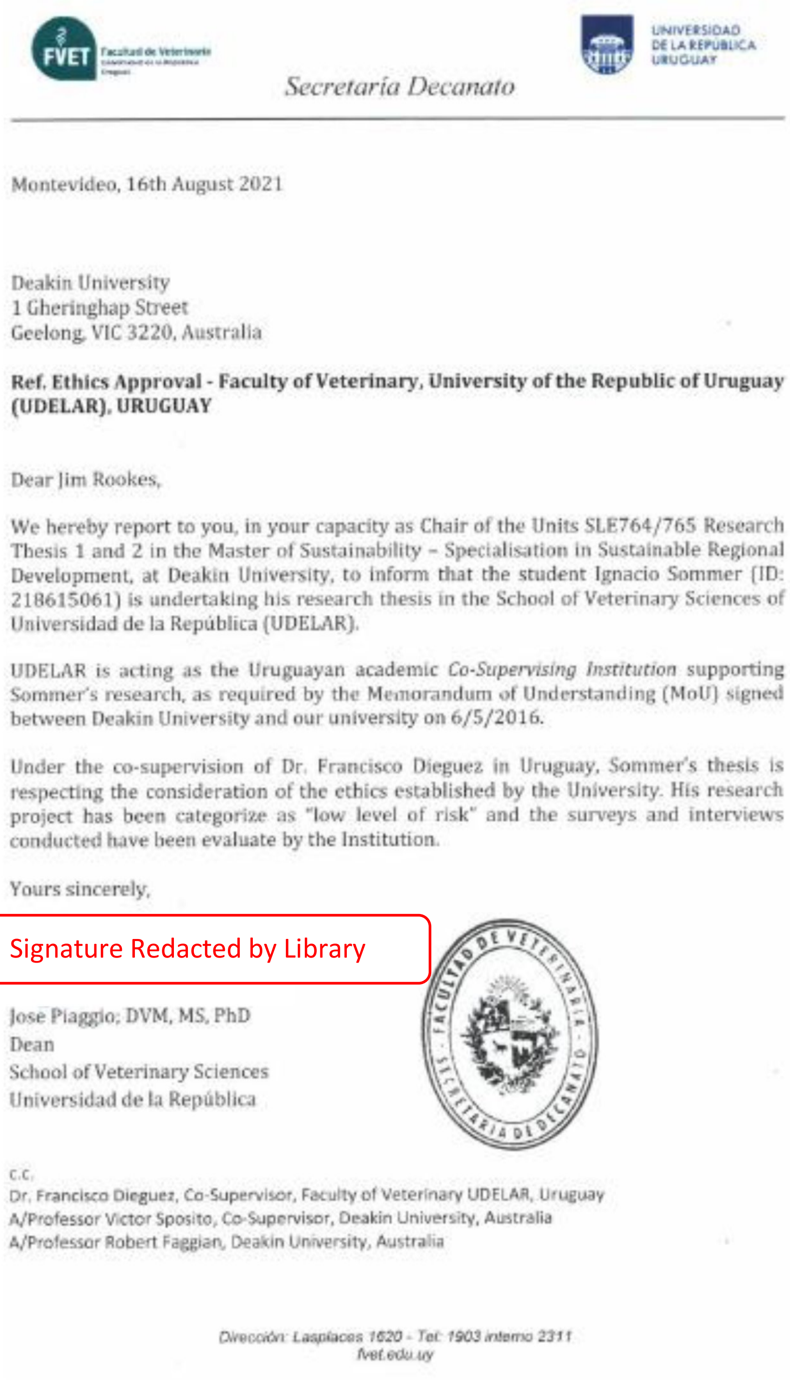
APPENDICES

A.1. Ethics approval from FVET UDELAR Uruguay as Co-Supervising Institution



FVET Facultad de Veterinaria
Universidad de la República Uruguay
Secretaría Decanato

Montevideo, 16th August 2021

Deakin University
1 Gheringhap Street
Geelong, VIC 3220, Australia

Ref. Ethics Approval - Faculty of Veterinary, University of the Republic of Uruguay (UDELAR), URUGUAY

Dear Jim Rookes,

We hereby report to you, in your capacity as Chair of the Units SLE764/765 Research Thesis 1 and 2 in the Master of Sustainability – Specialisation in Sustainable Regional Development, at Deakin University, to inform that the student Ignacio Sommer (ID: 218615061) is undertaking his research thesis in the School of Veterinary Sciences of Universidad de la República (UDELAR).

UDELAR is acting as the Uruguayan academic *Co-Supervising Institution* supporting Sommer's research, as required by the Memorandum of Understanding (MoU) signed between Deakin University and our university on 6/5/2016.

Under the co-supervision of Dr. Francisco Dieguez in Uruguay, Sommer's thesis is respecting the consideration of the ethics established by the University. His research project has been categorize as "low level of risk" and the surveys and interviews conducted have been evaluate by the Institution.

Yours sincerely,

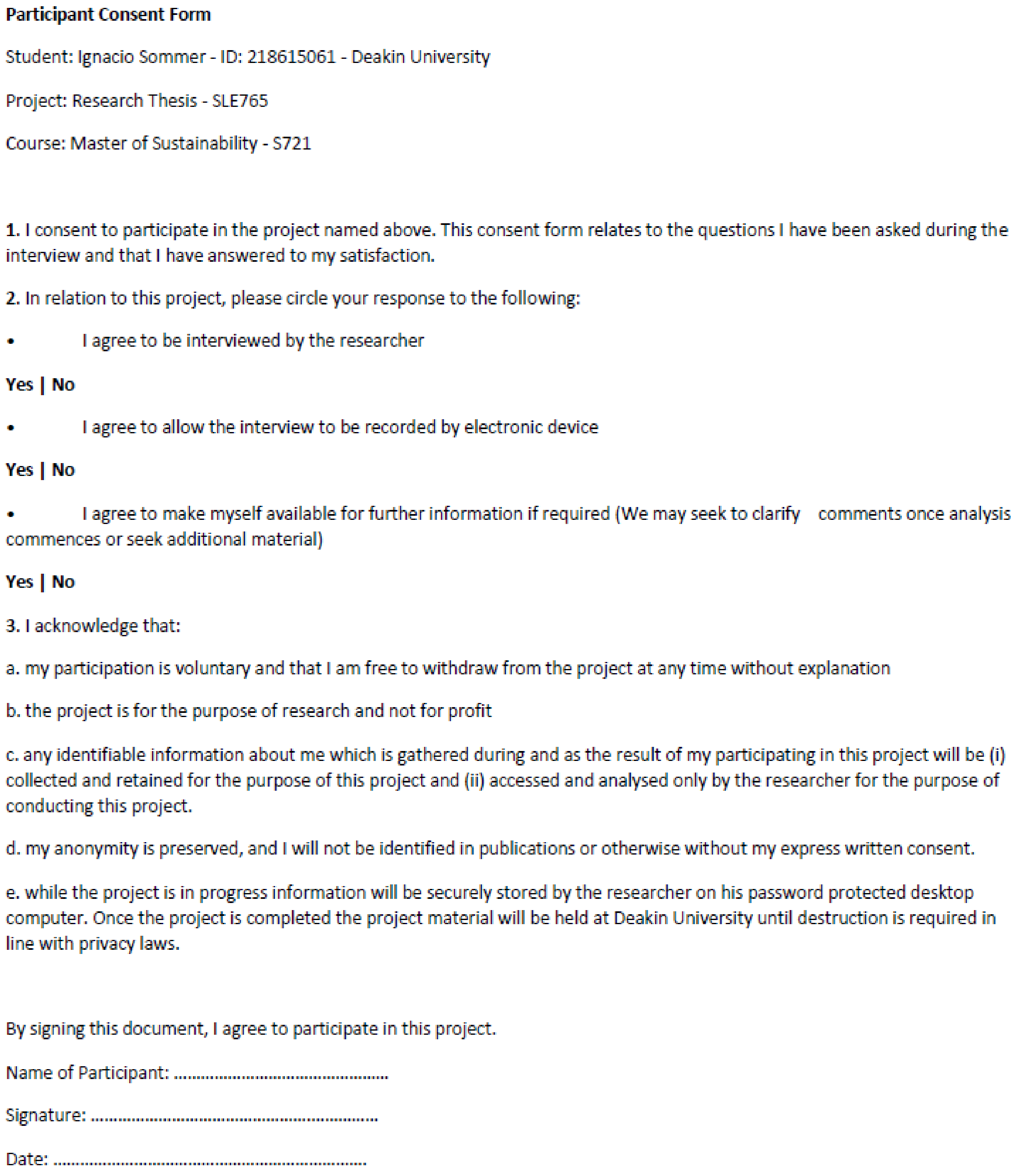
Signature Redacted by Library

Jose Piaggio, DVM, MS, PhD
Dean
School of Veterinary Sciences
Universidad de la República

C.C.
Dr. Francisco Dieguez, Co-Supervisor, Faculty of Veterinary UDELAR, Uruguay
A/Professor Victor Sposito, Co-Supervisor, Deakin University, Australia
A/Professor Robert Faggian, Deakin University, Australia

Dirección: Lasplaces 1620 - Tel: 1903 interno 2311
fvet.edu.uy

A.2. Participant Consent Form



Participant Consent Form

Student: Ignacio Sommer - ID: 218615061 - Deakin University

Project: Research Thesis - SLE765

Course: Master of Sustainability - S721

1. I consent to participate in the project named above. This consent form relates to the questions I have been asked during the interview and that I have answered to my satisfaction.

2. In relation to this project, please circle your response to the following:

- I agree to be interviewed by the researcher

Yes | No

- I agree to allow the interview to be recorded by electronic device

Yes | No

- I agree to make myself available for further information if required (We may seek to clarify comments once analysis commences or seek additional material)

Yes | No

3. I acknowledge that:

a. my participation is voluntary and that I am free to withdraw from the project at any time without explanation

b. the project is for the purpose of research and not for profit

c. any identifiable information about me which is gathered during and as the result of my participating in this project will be (i) collected and retained for the purpose of this project and (ii) accessed and analysed only by the researcher for the purpose of conducting this project.

d. my anonymity is preserved, and I will not be identified in publications or otherwise without my express written consent.

e. while the project is in progress information will be securely stored by the researcher on his password protected desktop computer. Once the project is completed the project material will be held at Deakin University until destruction is required in line with privacy laws.

By signing this document, I agree to participate in this project.

Name of Participant: ....

Signature: ....

Date: ....

A.3. Collective Learning

1) Farmer group communication: Via ZOOM

Date: 5/7/2021

Participants: 11farmers’ group and technicians’ group

Summary: *This first communication aimed to present the research objectives and invite the farmers to involve through the collective learning approach.*

2) Case study Farmer communication: Via ZOOM

Date: 28.7.2021

Participants: Farmer and farmer´s daughter

Summary: *The communication had the aim of asking doubts about the records provided by the case study farm. The meeting allowed the understanding of the farm functionality to continue developing the thesis and learn about the farm performance. The question refers to the following topics: livestock management, livestock weight, land use, cows’ diet, mineral fertilization and effluent management.*

3) Case study Dairy farm: visit to the farm

Date: 2.10.2021

Participants: Farmer and farmer´s daughter

Summary: *The farm visit had the aim to present the nutrient budget and agent-based model to the case study farmer. It was previous to show it to the whole farmer' group. Also, it aimed to receive farmer feedback to improve the nutrient budget analysis and the model in the last months of the thesis process. Finally, that instance allowed the collective learning between the thesis author and the farmer and family involved.*

4) Farmer group communication: face-to-face meeting

Date: 27.10.2021 Participants: Case study farmer, 13 group' farmers and 2 group' technicians.

Summary: *Firstly, the main findings of the thesis were transmitted to the farmers. Secondly, the farmers discussed the thesis results and shared the farmers' vision about the nutrient budget and agent-based model. One farmer suggests a solution for the paddocks that have excessive P on the soil. It was to use crops that extract more phosphorus from the ground, such as crops with higher nutritional requirements or crops for grain. Another point that emerged from the farmer case study is that the present research analysis is helpful for the less intensive farmers of the group with less P accumulation in the soil. It means seeing the opportunity of this collective learning and not making excessive phosphorus fertilization since perhaps using soil analysis is possible to verify that more phosphorus is not required. Also, some farmers are worried about the excessive P on soil that can represent losses to the rivers and can be regulated by the government. Furthermore,* a point of discussion was *to evaluate Milk Urea Nitrogen (MUN) as an indicator of the N situation in the farm system and as a possible strategy to implement. Also, in that meeting, the farmers talk about using pesticides and mineral fertilizer as issues that impact the whole system, especially the soil structure, soil biota, and organic matter decomposition. Furthermore, the farmer's group technician expressed the preoccupation with nitrate problems in water.*

A.4. Data for nutrient budget, ABM, and scenarios

Table 11. Data for nutrient budget, ABM, and scenarios.

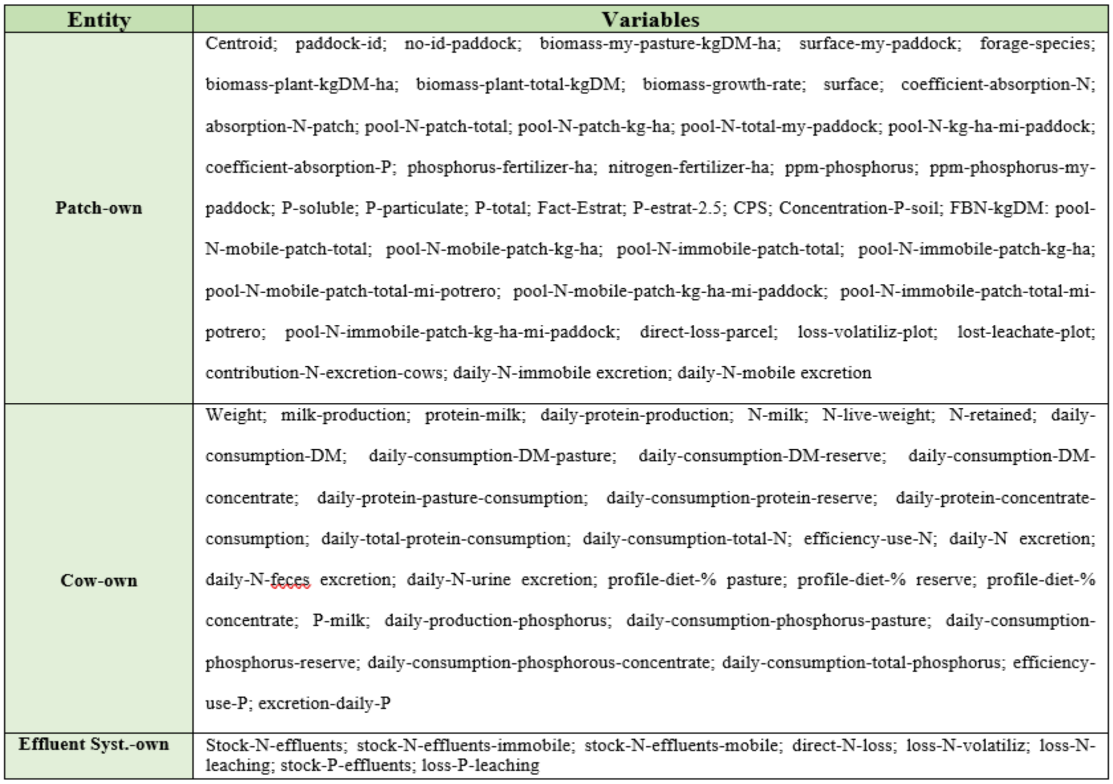
Data	Unit	Source	Note
Land use	Hectares	Farmer record	Type and area for each crop. Crop and pasture rotation.
Mineral fertilization	Kg N/ha/year Kg P/ha/year	Farmer record	Average ´Tambo´: 93 kg N/ha/year and 0 kg P/ha/year. Average ´rest of the area´: 85 kg N/ha/year and 16 kg P/ha/year (used to whole farm nutrient budgets)
Imported livestock feed	Kg/year	Farmer record	For the ´´Tambo´´ budget, it is assumed that imported feed is from outside the system, and some proportion is from the rest of the farm area (according to farmer records). Also, it is assumed that bale is completely used in the year. For the whole farm budget, it is assumed that the imported feed is from outside the system.
Fixation rate of N	Kg N/ha/year	INIA 1994	To calculate BNF. 30 kg N / ton DM of pasture
Atmospheric deposition	Kg N/ha/year	Paerl et al. 2002	-
Milk production	Kg milk/year Kg milk/cow/day	Farmer record	-
Meat sold	kg meat/year	Farmer record	It represent the meat sold. Only considered for the whole farm nutrient budget.
Number of animals	Annual average per category	Farmer record	-
Cow DM intake	Kg DM/day	Farmer record	Cow diet per month
N and P on livestock feed: pasture, silage and concentrate	Kg N/kg DM Kg P/kg DM	INIA 2004	-
N and P on milk	Kg N/kg milk Kg P/kg milk	Farmer record NRC 2001	N on milk=Protein milk/ 6.38 P on milk=0.1%
N and P on meat	Kg N/kg milk Kg P/kg milk	NRC 2003 NRC 2001	N cow live weight= 2.42% P on meat=0.72%
N on animal excreta	Kg N/cow/day	IPCC 2019b	Tier 2, equation 10.31. N is available in 25% of manure and 100% of urine
P on animal excreta	Kg P/cow/day	P excreta: P diet – P milk	
Proportion of time in paddock and in milking parlour	Hours per day	Farmer	Dairy cows spend 4 hours per day in milking parlour and 20 in paddock. To calculate manure proportion and effluent generation
Conversion factor protein to nitrogen	-	INIA 2004	-
NUE and PUE	%	Aarons et al.2020	Animal nutrient use eefficiency (%) = Milk nutrient / Nutrient Intake * 100
GIS	-	ArcMap 10.7.1	Only for ABM. Farmer register implemented on ArcMap
Pasture's growth rate	KgDM/day	Otero and Castro 2019	Only for ABM
Absorption of N and P by the plants	Kg N-P/ton DM	IPNI	Only for ABM
N total, N mobile, and N immobile	Kg N/year	Prado et al. 2016	Only for ABM. N mobile: 100% urine + ¾ of feces + fertilizer. N immobile: ¼ of feces + BNF
N OUTPUTS: Effluent and Manure management			
N_2O Direct	Kg N/year	IPCC 2019b	Tier 3, equation 10.25
Volatilization	Kg N/year	IPCC 2019b	Tier 1, equation 10.26
Leaching	Kg N/year	IPCC 2019b	Tier 1, equation 10.27
N OUTPUTS: Paddock			
N_2O Direct	Kg N/year	IPCC 2019a	Tier 1, equation 11.1

Volatilization	Kg N/year	IPCC 2019a	Tier 1, equation 11.9
Leaching	Kg N/year	IPCC 2019a	Tier 1, equation 11.10
P OUTPUTS: Effluent and Manure management			
Leaching	Kg P/year	Assumption	Assumption: 20% of the P into the effluent management system is leached in the year due to the condition
P OUTPUTS: Paddock			
Particulate P	Kg P/ha//year	Perdomo et al. 2015	Calculated using the P index. Enrichment Index: 1.5; total phosphorus: 450 mg/kg soil; erosion: 4.7 and 6.3 Mg soil/ha/year
Soluble P	Kg P/ha//year	Perdomo et al. 2015	Calculated using the P index. Runoff: 360 (Inumet); CPS: 1.43 (De Lucca 2020)
Erosion	Mg soil/ha/year	Erosion 6.0	Using the program Erosion 6.0 (FAgro UDELAR) for the case study farm situation: ´Tambo´: 4.7 Mg soil/ha/year Whole farm 6.3 Mg soil/ha/year
P Soil analysis	ppm Pbray	Farmer record	Average ´Tambo´ 41 ppm Pbray Average whole farm: 30 ppm Pbray

Source: elaborated by the author.

A.5. NPM agent-based model

Table 12. Entities and States Variables of NPM model.



Entity	Variables
Patch-own	Centroid; paddock-id; no-id-paddock; biomass-my-pasture-kgDM-ha; surface-my-paddock; forage-species; biomass-plant-kgDM-ha; biomass-plant-total-kgDM; biomass-growth-rate; surface; coefficient-absorption-N; absorption-N-patch; pool-N-patch-total; pool-N-patch-kg-ha; pool-N-total-my-paddock; pool-N-kg-ha-mi-paddock; coefficient-absorption-P; phosphorus-fertilizer-ha; nitrogen-fertilizer-ha; ppm-phosphorus; ppm-phosphorus-my-paddock; P-soluble; P-particulate; P-total; Fact-Estrat; P-estrat-2.5; CPS; Concentration-P-soil; FBN-kgDM: pool-N-mobile-patch-total; pool-N-mobile-patch-kg-ha; pool-N-immobile-patch-total; pool-N-immobile-patch-kg-ha; pool-N-mobile-patch-total-mi-potrero; pool-N-mobile-patch-kg-ha-mi-paddock; pool-N-immobile-patch-total-mi-potrero; pool-N-immobile-patch-kg-ha-mi-paddock; direct-loss-parcel; loss-volatiliz-plot; lost-leachate-plot; contribution-N-excretion-cows; daily-N-immobile excretion; daily-N-mobile excretion
Cow-own	Weight; milk-production; protein-milk; daily-protein-production; N-milk; N-live-weight; N-retained; daily-consumption-DM; daily-consumption-DM-pasture; daily-consumption-DM-reserve; daily-consumption-DM-concentrate; daily-protein-pasture-consumption; daily-consumption-protein-reserve; daily-protein-concentrate-consumption; daily-total-protein-consumption; daily-consumption-total-N; efficiency-use-N; daily-N excretion; daily-N-feces excretion; daily-N-urine excretion; profile-diet-% pasture; profile-diet-% reserve; profile-diet-% concentrate; P-milk; daily-production-phosphorus; daily-consumption-phosphorus-pasture; daily-consumption-phosphorus-reserve; daily-consumption-phosphorous-concentrate; daily-consumption-total-phosphorus; efficiency-use-P; excretion-daily-P
Effluent Syst.-own	Stock-N-effluents; stock-N-effluents-immobile; stock-N-effluents-mobile; direct-N-loss; loss-N-volatiliz; loss-N-leaching; stock-P-effluents; loss-P-leaching

Source: elaborated by the author.

A.6. Dairy farm case study

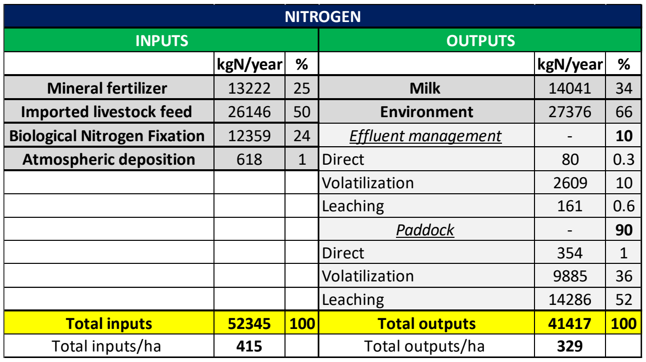
Table 13. Case study summary and comparison with typology INALE.

	Case study (2020)	H1 (2019-2020)	H2 (2019-2020)
Milking and Dry cows (VM)	**343**	460	367
Milking cows (VO)	**283**	354	296
VO / VM ratio	**0.83**	0.77	0.81
Hectare VM	**214**	491	306
Total area (ha)	**261**	883	569
Property (%)	**46**	37	46
Stocking rate (VM/ha VM)	**1.6**	0.94	1.2
Animal productivity (l/VO/day)	**23.4**	19.5	20.1
Land productivity (l/ha VM)	**11439**	5132	5916
Milk production (l/year)	**2447875**	2517695	2168103
Milk production (l/day)	**6707**	6898	5940
Pasture intake (Kg DM/ha VM)	**4452**	2026	3954
Silage intake (Kg DM/ha VM)	**1858**	2237	1942
Concentrate intake (Kg DM/ha VM)	**3279**	1868	2118
Pasture intake (Kg DM/VO/day)	**9.1**	7.7	11.2
Silage intake (Kg DM/VO/day)	**3.9**	8.5	5.5
Concentrate intake (Kg DM/VO/day)	**6.7**	7.1	6
Total intake (kg DM/VO/day)	**19.7**	23.3	22.7
% Pasture	**46%**	33%	49%
% Silage	**20%**	36%	24%
% Concentrate	**34%**	30%	26%

Source: elaborated by the author. Information H1 and H2 from INALE 2020.

A.7. Scenarios

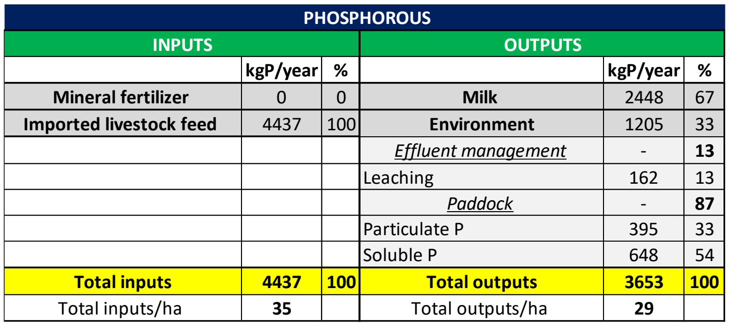
Table 14. Scenario 1 ´Tambo´ nitrogen budget.



NITROGEN					
INPUTS			OUTPUTS		
	kgN/year	%		kgN/year	%
Mineral fertilizer	13222	25	**Milk**	14041	34
Imported livestock feed	26146	50	**Environment**	27376	66
Biological Nitrogen Fixation	12359	24	*Effluent management*	-	**10**
Atmospheric deposition	618	1	Direct	80	0.3
			Volatilization	2609	10
			Leaching	161	0.6
			Paddock	-	**90**
			Direct	354	1
			Volatilization	9885	36
			Leaching	14286	52
Total inputs	**52345**	**100**	**Total outputs**	**41417**	**100**
Total inputs/ha	**415**		Total outputs/ha	**329**	

Source: elaborated by the author.

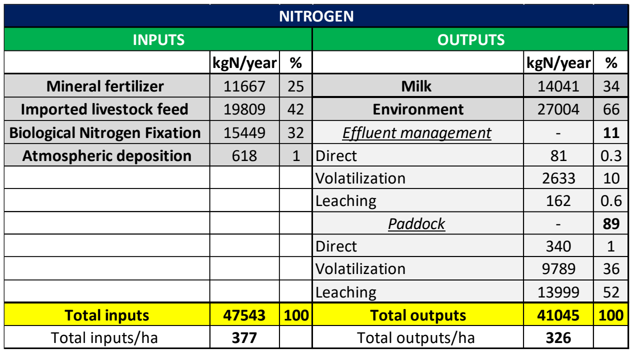
Table 15. Scenario 1 ´Tambo´ phosphorous budget.



PHOSPHOROUS					
INPUTS			OUTPUTS		
	kgP/year	%		kgP/year	%
Mineral fertilizer	0	0	**Milk**	2448	67
Imported livestock feed	4437	100	**Environment**	1205	33
			Effluent management	-	**13**
			Leaching	162	13
			Paddock	-	**87**
			Particulate P	395	33
			Soluble P	648	54
Total inputs	**4437**	**100**	**Total outputs**	**3653**	**100**
Total inputs/ha	**35**		Total outputs/ha	**29**	

Source: elaborated by the author.

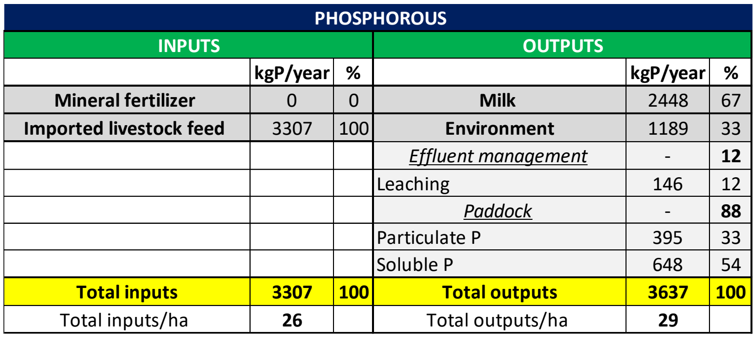
Table 16. Scenario 2 ´Tambo´ nitrogen budget.



NITROGEN					
INPUTS			OUTPUTS		
	kgN/year	%		kgN/year	%
Mineral fertilizer	11667	25	**Milk**	14041	34
Imported livestock feed	19809	42	**Environment**	27004	66
Biological Nitrogen Fixation	15449	32	*Effluent management*	-	**11**
Atmospheric deposition	618	1	Direct	81	0.3
			Volatilization	2633	10
			Leaching	162	0.6
			Paddock	-	**89**
			Direct	340	1
			Volatilization	9789	36
			Leaching	13999	52
Total inputs	**47543**	**100**	**Total outputs**	**41045**	**100**
Total inputs/ha	**377**		Total outputs/ha	**326**	

Source: elaborated by the author.

Table 17. Scenario 2 ´Tambo´ phosphorous budget.



PHOSPHOROUS					
INPUTS			OUTPUTS		
	kgP/year	%		kgP/year	%
Mineral fertilizer	0	0	**Milk**	2448	67
Imported livestock feed	3307	100	**Environment**	1189	33
			Effluent management	-	**12**
			Leaching	146	12
			Paddock	-	**88**
			Particulate P	395	33
			Soluble P	648	54
Total inputs	**3307**	**100**	**Total outputs**	**3637**	**100**
Total inputs/ha	**26**		Total outputs/ha	**29**	

Source: elaborated by the author.

Table 18. Scenario 3 ´Tambo´ nitrogen budget.

NITROGEN					
INPUTS			OUTPUTS		
	kgN/year	%		kgN/year	%
Mineral fertilizer	11667	24	**Milk**	11233	33
Imported livestock feed	20917	43	**Environment**	22601	67
Biological Nitrogen Fixation	15449	32	*Effluent management*	-	**10**
Atmospheric deposition	618	1	Direct	64	0.3
			Volatilization	2087	9
			Leaching	128	0.6
			Paddock	-	**90**
			Direct	307	1
			Volatilization	8027	36
			Leaching	11986	53
Total inputs	**48650**	**100**	**Total outputs**	**33834**	**100**
Total inputs/ha	**386**		Total outputs/ha	**269**	

Source: elaborated by the author.

Table 19. Scenario 3 ´Tambo´ phosphorous budget.

PHOSPHOROUS					
INPUTS			OUTPUTS		
	kgP/year	%		kgP/year	%
Mineral fertilizer	0	0	**Milk**	1958	63
Imported livestock feed	3550	100	**Environment**	1173	37
			Effluent management	-	**11**
			Leaching	130	11
			Paddock	-	**89**
			Particulate P	395	34
			Soluble P	648	55
Total inputs	**3550**	**100**	**Total outputs**	**3131**	**100**
Total inputs/ha	**28**		Total outputs/ha	**25**	

Source: elaborated by the author.

Table 20. Scenario 4 Whole Farm nitrogen budget.

NITROGEN					
INPUTS			OUTPUTS		
	kgN/year	%		kgN/year	%
Mineral fertilizer	17863	24	**Milk**	14041	27
Imported livestock feed	23455	31	**Meat**	1778	3
Biological Nitrogen Fixation	32212	43	**Environment**	36778	70
Atmospheric deposition	1278	2	*Effluent management*	-	**8**
			Direct	80	0.2
			Volatilization	2609	7
			Leaching	161	0.4
			Paddock	-	**92**
			Direct	551	1
			Volatilization	13196	36
			Leaching	20180	55
Total inputs	**74808**	**100**	**Total outputs**	**52596**	**100**
Total inputs/ha	**287**		Total outputs/ha	**202**	

Source: elaborated by the author.

Table 21. Scenario 4 Whole Farm phosphorous budget.

PHOSPHOROUS					
INPUTS			OUTPUTS		
	kgP/year	**%**		**kgP/year**	**%**
Mineral fertilizer	1436	29	**Milk**	2448	48
Imported livestock feed	3552	71	**Meat**	529	10
			Environment	2113	42
			Effluent management	-	**8**
			Leaching	162	8
			Paddock		**92**
			Particulate P	1013	48
			Soluble P	938	44
Total inputs	**4988**	**100**	**Total outputs**	**5089**	**100**
Total inputs/ha	**19**		Total outputs/ha	**20**	

Source: elaborated by the author.