Climate Change Impacts on The Uruguayan Dairy Sector by 2050

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This Thesis is submitted in accordance with the regulations of Deakin University in partial fulfilment of the requirements of the degree of Master of Science (Research) in Sustainable Regional Development. I, Pablo Andrés Errazola Anzolabehere, hereby certify that the information presented in this thesis is the result of my own research, except where otherwise acknowledged or referenced, and that none of the material has been presented for any degree at another university or institution.

Signature of candidate: ....

Date: 11/6/2021

Abstract

This thesis analyzed the impacts of climate change on the Uruguayan dairy sector from today to the year 2050. During the thesis's development, the application of Climate-Smart Agriculture (CSA) policies was evaluated to enhance the sustainable intensification of this key sector. The four spheres (or fields) of sustainability were considered: economic, socio-cultural, environmental, and organizational. The primary focus was, however, on the economic and environmental effects of climate change and the adaptation and mitigation to its likely impacts. In this context, a novel Rational Holistic Planning and Decision-making Methodology was used to examine the current situation and future scenarios to 2050. A core component of the methodology was the application of the Land Suitability Analysis (LSA) method to the main pastures in Uruguay - Lucerne, and Ryegrass - for comparing their yields in a baseline scenario with projected yields under the expected climate by 2050. CSA relevant practices were then considered to respond to the likely climate changes and generate an approach for the ongoing adaptation of the dairy sector. Finally, different sustainable development indicators were proposed in order to measure the outcomes of the application of CSA policies.

The LSA results showed that climate changes by 2050 would impact the suitability of the land to produce *Lucerne* in Uruguay. A noticeable projected decline is likely to occur mostly in the northeast and northwest of the country. The LSA modeling also indicated that areas in the south and southeast of Uruguay would experience a slight increase in their potential to grow this pasture. In the case of *Ryegrass*, the LSA modeling indicated that the southeast of the country would be the most benefited by the changes in the rainfall patterns and the increase in temperatures, with some benefits also occurring in the north. On the other hand, the southwest of the country is expected to slightly decrease the suitability for Ryegrass. This demonstrated the diverse impacts of climate change on the two main pastures as well as the possibilities for adaptation; for example, by moving from cultivating one (Lucerne) to the other (Ryegrass) in the southeast and north of Uruguay. These results are an important contribution to the decision-making process of dairy farmers and public institutions promoting the sustainable intensification of the dairy sector towards the future.

While this particular research was focused on the Uruguayan dairy sector, the methodology deployed and its key methods can be applied in Uruguay, or other developing countries or sectors, promoting the sustainable development of other industries and regions.

Keywords: Climate change, Climate-Smart Agriculture (CSA), Land Suitability Analysis (LSA), 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).

Analytic Hierarchy Process (AHP): "A method of breaking down a complex unstructured situation into its component parts; arranging these parts, or variables, into a hierarchical order [or decision tree]" (Saaty, 1994).

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).

Climate Change and Variability: "The changes in the mean and/or the variability of its properties and that persists for an extended period, typically decades or longer" (IPCC, 2014).

Climate-Smart Agriculture (CSA): "An approach that helps to guide actions needed to transform and reorient agricultural systems to effectively support the development and ensure food security in a changing climate" (FAO, 2020).

Earnings Before Interest, Taxes, and Amortization (EBITA): "A metric used to evaluate a company's operating performance. It can be seen as a proxy for cash flow from the entire company's operations" (Corporate Finance Institute, 2021).

Ecological Resilience: "A measure of the persistence of systems and of their ability to absorb change and disturbance and still maintain the same relationships between populations or state variables" (Holling, 1973).

Extreme Weather Event: "An event that is rare at a particular place and time of year. Definitions of rare vary, but an extreme weather event would normally be as rare as or rarer than the 10th or 90th percentile of a probability density function estimated from observations" (IPCC, 2014).

Land Suitability Analysis (LSA): "The mathematical model, developed within a GIS, uses climatic, soil and topographical inputs that determine the growth and production of the commodity of interest. LSA Investigates the biophysical quality of a region for a particular land use" (Sposito et al. 2013).

Land Use: "The total arrangements, activities, and inputs undertaken in a certain land cover type (a set of human actions). The term land use is also used in the sense of the social and economic purposes for which land is managed (e.g., grazing, timber extraction and conservation)" (IPCC, 2014).

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

Multi-Criteria Analysis (MCA): "A very useful method to evaluate a set of alternatives, comparing them with different weight components and trading-off between several criteria" (Sposito, 2013).

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

Net Farm Income: "The income after expenses from production in the current year and is calculated by subtracting farm expenses from gross farm income" (USDA, 2021).

Paradigme: "A set of theories, concepts, methodologies, and methods in relation to a specific field" (Sposito, 2019).

Representative Concentration Pathways (RCP): "Scenarios that include time series of emissions and concentrations of the full suite of greenhouse gases (GHGs) and aerosols and chemically active gases, as well as land use/land cover" (IPCC, 2014).

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).

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).

Sustainable Intensification: “A process or system where agricultural yields are increased without adverse environmental impact and without the conversion of additional non-agricultural land” (Pretty, J and Bharucha, Z, 2014).

Vulnerability: “The degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes” (IPCC, 2001).

List of abbreviations

AHP: Analytical Hierarchy Process

ArcGIS: Aeronautical Reconnaissance Coverage Geographic Information System

CCSM: Community Climate System Model

CH_4: Methane

CONAPROLE: Cooperativa Nacional de Productores de Leche

CO_2: Carbon Dioxide

CSA: Climate-Smart Agriculture

EBITA: Earnings Before Interest, Taxes, and Amortization

FAO: Food and Agriculture Organization

GDP: Gross Domestic Product

GHGs: Greenhouse Gases

GIS: Geographic Information System

INALE: Instituto Nacional de Leche

IPCC: Intergovernmental Panel on Climate Change

LSA: Land Suitability Analysis

MCA: Multi-Criteria Analysis

MERCOSUR: Mercado Común del Sur

MGAP: Ministerio de Ganadería, Agricultura y Pesca

NAP: National Adaptation Plan

N_2O: Nitrous Oxide

RCP: Representative Concentration Pathways

SATS: Sustainability Assessment Tools

SDG: Sustainable Development Goals

SIs: Sustainability Indicators

UN: United Nations

UNFCCC: United Nations Framework Convention on Climate Change

USDA-NAL: United States Department of Agriculture - National Agricultural Library

WCED: World Commission on Environment and Development

CHAPTER 1. INTRODUCTION

This first chapter includes the background of the thesis' research and the key characteristics of the problem that is analyzed. It also includes the research aim and research questions, which were formulated after an exhaustive literature review (discussed in Chapter 2), and the expected outcomes of the thesis. Lastly, a diagram of the outline of the thesis is included.

1.1. Research Context

Several demographic projections are indicating that by 2050, there will be a human population of 9 billion people on Planet Earth and over 70% of them would live in urban areas. In this likely setting, the agriculture sector will be critically challenged to produce enough food to feed humanity (FAO, 2013). Furthermore, the consumption of dairy products is expected to surge due to a larger and wealthier urban population (FAO, 2010). Although world milk production has been increasing over the last 15 years (International Dairy Federation, 2020), some countries that depend on dairy imports will put additional pressure on net exporters countries such as New Zealand, Australia, Argentina, and Uruguay (World´s Top Exports, 2020).

Uruguay is the 7th largest exporter of dairy products in the world –see appendix I-, and despite having a population of 3.5 million people, in only 5% of its territory produces enough milk for more than 18 million people (INALE, 2020). Moreover, agriculture represents 6% of the Gross Domestic Product (GDP) and over 80% of the country´s exports which means more than U$S 7,000 million of income (World Bank, 2015). In recent years, however, agriculture has been impacted by climate change, climate variability, and extreme weather events. These climate-related (environmental) effects have been compounded by socio-economic challenges such as a reduction in international milk prices and a decline in the number of producers since more than 10% of dairy farmers left the sector (Barboza, 2017).

In this complex situation, the national Ministry of Livestock, Agriculture, and Fisheries (MGAP) of Uruguay, considering that agriculture is one of the most vulnerable sectors to climate change, developed the *National Adaptation Plan to Climate Variability and Change for the Agriculture Sector of Uruguay* – NAP (NAP-ag, 2019).

As defined by the Intergovernmental Panel on Climate Change (IPCC, 2014a, p. 120), adaptation to climate change is “the process of adjustment to actual or expected climate and its effects”. In other words, the capacity of a region or country to adapt to climate change depends on the ability to introduce adjustments to the projected climate.

In this sense, the NAP promotes a holistic approach to ensure rural development and food security, focusing on climate change management. The main strategies of the NAP are: (i) develop and adopt animal and plant production systems less vulnerable to the impacts of variability and climate change; (ii) conserve agro ecosystems and their services; (iii) improve the livelihoods of rural populations; and (iv) strengthen institutional capacities for the management of these sustainable and adapted production systems (Nap-ag, 2019).

Several actions stated in the NAP are aligned with *Climate-Smart Agriculture* (CSA) policies – CSA is a novel approach that provides guidance on how agricultural systems can be transformed into sustainable systems (see Section 2.5). Moreover, CSA policies have very similar aims to the NAP, including increasing productivity while protecting natural resources and enhancing farmers' lives, and promoting adaptation and mitigation to climate change (FAO, 2018).

Therefore, encouraging the implementation of CSA practices can both promote the sustainable development of the Uruguayan dairy sector and tackle climate change and variability impacts. Uruguayan farmers have already adopted some CSA policies, especially those related to soil erosion protection (World Bank, 2015). An example is the already implemented ´Plan for Sustainable Dairy Production´ which aims to prevent soil erosion by regulating crop sequences and fertilizations (MGAP, 2017).

Nevertheless, numerous other CSA practices can be introduced in Uruguay. For instance, FAO (2010) enumerated several CSA practices for the dairy sector that include: decreasing methane emissions, producing organic fertilizers, and generating clean energy utilizing anaerobic digesters for manure treatment. In particular, carbon stocks can be increased by improving grazing systems which in turn promotes resilience and enhance nutrients management (Global Dairy Agenda, 2019).

In conclusion, there is great potential for the application of more CSA practices that promote the sustainable development of the Uruguayan dairy sector in the years towards 2050. This project thus intends to understand which strategies/actions would be appropriate to unlocking that potential in the years ahead, hence contributing to the achievement of a sustainable dairy sector.

1.2. Research Aim and Questions

The aim of the thesis is to understand the potential impacts of climate change on the Uruguayan dairy sector towards 2050 in order to generate pertinent information for the decision-making process of farmers and the stakeholders involved in the dairy sector, especially related public institutions[1]. Furthermore, a specific purpose is to identify the most appropriate areas for the location of dairy farms, based on the land suitability for pastures, for the sustainable intensification of the sector. It is considered that this research will contribute to the strategic planning of the Uruguayan Government, which has already started via the *National Adaptation Plan to Climate Variability and Change for the Agriculture Sector of Uruguay* (NAP).

After an exhaustive literature Review (refer to Chapter 2), the following research questions have been posed:

i) In the context of climate change and variability: is it possible to intensify the production of the Uruguayan dairy sector to increase profitability[2] while protecting natural resources and promoting a high quality of life for farmers and the community involved in the region of concern? ´;

ii) Can the promotion of CSA practices lead to a more sustainable and resilient system throughout the Uruguayan dairy sector by 2050? ´;

iii) Is it possible to measure the outcomes of sustainable development of the Uruguayan dairy sector using a system of indicators? ´.

1.3. Expected Outcomes

The main expected outcomes of the project are: to understand (a) the impacts of climate change and the viability of the sustainable intensification of the Uruguayan dairy sector by 2050; (b) how to intensify dairy production, while at the same time protect the

[1] The large group of stakeholders of the dairy sector in Uruguay include: dairy farmers, cooperatives, private industries, public institutions and its agencies, technicians and researchers, transporters, sales and marketing groups, exporters and consumers. Although the research in the thesis will benefit all of them, the primary focus is on dairy farmers and the related public institutions and agencies.
[2] Farm profitability can be measured using Earnings Before Interest, Taxes and Amortization (EBITA), or other indicators such as Net Farm Income (Langemeier, 2017)

natural resources and improve farmers' quality of life; and (c) the effects of applying CSA practices to promote adaptation and mitigation to climate change and its variability in this sector. It is considered that this will contribute to the decision-making process of dairy farmers and the key stakeholders involved in the dairy sector. Another expected outcome is to contribute to the investigation of climate change adaptation in the agriculture sector by generating a strategic framework to analyze different activities in different regions. The structure of the thesis is divided into six parts, which also correspond to its development plan, as described in table 1.

Table 1. Thesis outline

1	Introduction	In the first chapter, the problem is analysed and the objectives are established.
2	Literature Review	This chapter includes a description of the theoretical background of the research, including sustainable development and Climate-Smart Agriculture.
3	Methodology	A description of the different methods used in the study. The main methodology is the Rational-Holistic Model.
4	Results	In this chapter, the main results of the project are described.
5	Discussion	This chapter includes a discussion of the results drawing the main findings together.
6	Conclusion	A summary of the contribution of the research and further studies.

Source: Elaborated by the author

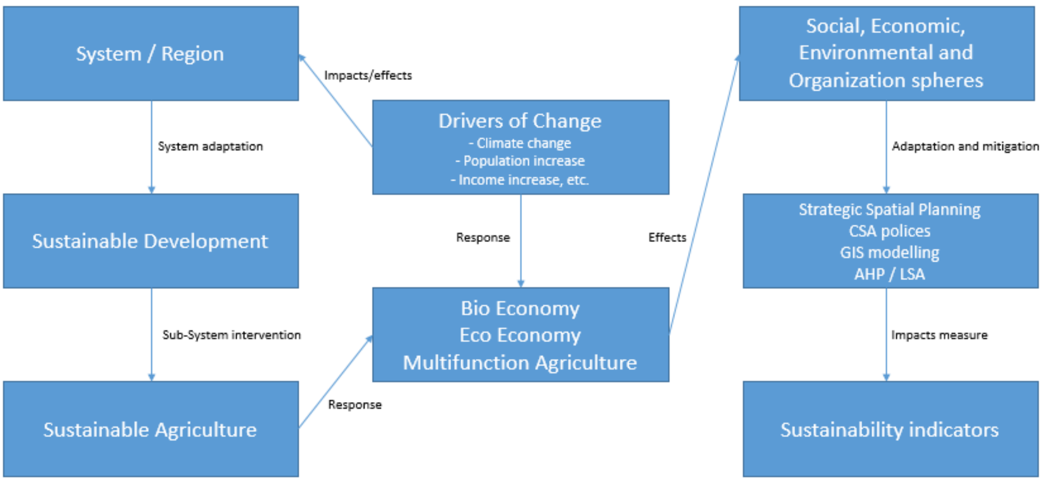
CHAPTER 2. LITERATURE REVIEW

This chapter discusses the most relevant literature related to the topics of climate change, sustainable development, sustainable agriculture, Climate-Smart Agriculture, and measures of sustainability. The pertinent information emerging from the analysis is essential to understand the research conducted in this thesis.

2.1. Initial remarks

This chapter provides the foundation for the thesis by examining the relevant literature in the main topics discusses during its development. Figure 1 summarizes the topics covered in the study and their relationships – see figure 1.

Figure 1. Literature Review Framework



Source: Elaborated by the author

2.2. Sustainable Development

According to Holden et al. (2014), the concept of sustainable development has been used for several attributes but the definition has lost its original meaning. The authors suggested a return to the first definition proposed in the Brundtland Report: “Humanity has 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 p.15). Moreover, Holden et al. (2014) highlighted that so far, no country meets the four dimensions of sustainable development proposed by the World Commission on Environment and Development (WCED). These four dimensions are: ecological sustainability, the satisfaction of human basic needs, and intra-generational and inter-generational equity (Holden et al. 2014).

The Brundtland Report stated that economic development can be undermined by environmental degradation if the natural resources upon which development is based are eroded (WCED, 1987). Furthermore, the report highlighted that humanity has been focused on economic growth without considering the finite resources that are the base for that growth. However, the authors emphasized the importance of the ecological impacts in soils and water resources, landscapes, forests, and the atmosphere over the economic profits (WCED, 1987). Thus, in order to protect the environment, it is extremely necessary to consider it as important as the socio-economic aspects.

Daly (1991) has also consistently argued that the false premise of the environment being part of the economy, is the origin of poor planning. The author claimed that the economy can grow in a physical measure whereas the environment does not. Thus, the economy becomes greater in relation to the ecosystem. The theory elaborated by Daly (1991) Steady-State Economics (SSE) proposes that the large of the economy should be related to the ecosystem, with an optimal allocation and flow of the natural resources amid alternative uses, while population (stock of people) and capital (stock of physical wealth) remain constant.

According to Sposito (2019), a holistic view of sustainable development implies a global perspective that considers the *four spheres* of sustainable development: economic, ecologic, organizational, and socio-cultural. The author states that sustainability is at the core of the four spheres, and therefore, it is not possible if one of them is not considered. Furthermore, as depicted in figure 2, Sposito (2019) highlighted that Sustainable Development is at the intersection of the four spheres. In addition, it is stated that a vision of the long-term development of a region, will be a key component of the strategic framework of Sustainable Development (Sposito et. al 2014). Thus, planning is an extremely important part of sustainable development, maintaining a vision or goal for the long term and actions for the short term that tackle the four spheres of sustainable development.

Figure 2. Four Spheres of Sustainable development

Source: Sposito (2019)

Regarding the socio-cultural sphere, the concept of equity is fundamental. The Brundtland Report stated that not only economic growth is required, but also an assurance that low-income sectors receive their share to sustain growth (WCED, 1987).

In this sense, the decision-making process should consider intra-and-inter-generational equity for the sustainable development of a region. Moreover, sustainable development must consider present as well as future needs in the way of using natural resources, technology, investments, and organizing institutions (Holden et al. 2014).

Sustainable development is in the end, a flux or a path for achieving the final goal that is sustainability. In this sense, if a sustainable food production system is intended, the sustainable development of the agriculture sector is extremely important. This process may be conducted in the four dimensions of sustainability, which could be directly linked to Sposito´s four spheres. As explained, the economic sphere must be understood under the intergenerational equity dimension. Furthermore, the satisfaction of basic human needs can be related to the sociocultural sphere; while ecological sustainability is directly appointed as the environmental sphere; and the organizational sphere (which is represented by institutions) can be connected with intra generational equity (WECD, 1987; Holden et al. 2014; Sposito, 2019).

In addition, Rockström and Sukhdev (2016) highlighted that sustainable and healthy food are linked directly or indirectly to all the Sustainable Development Goals (SDGs). In this sense, the United Nations (UN) has defined the most important goals for the next 30 years as the *Sustainable Development Goals*. The 17 SDGs - see figure 3 - were accepted by all the countries members of the UN in 2015, as a united call for action by all the nations despite their level of development. There is a recognition that coping with climate change is needed while protecting natural resources, reducing poverty and inequalities, and improve health and economic growth (UN, 2020). An aspiring sustainable agriculture and [regenerative] food system must be in line with the SDGs and reflect radical changes to meet these ambitious but essential goals (Duncan, et al. 2020). These authors emphasized the importance of a sustainable agriculture system and defined that all the SDGs are related to a regenerative food system.

Figure 3. Sustainable Development Goals

Source: United Nations (2020)

2.3. Sustainable Agriculture

The National Research Council (2010, p. 1) defines Agricultural Sustainability as the agriculture system that pursues the following goals: (i) provide humanity with food and fiber needs; (ii) protect the natural resources and enhance the environment; (ii) ensure the economic viability of the agriculture sector; and (iv) improve the quality of life of farmers, their communities and the whole society. According to the United States Department of Agriculture - National Agricultural Library (USDA-NAL, 2007) a sustainable agriculture system is one that not only provides food and fiber, but also biofuel and other products and services for societies with reasonable profits for farmers, good animal welfare practices while protecting and enhancing the ecological resources.

The National Research Council (2010) stated that since the end of the 1980s, there has been a significant advance in technology and innovations leading to a sustainable agriculture sector. However, the authors highlighted that in order to adapt to the challenges of climate change and population growth, new technologies and innovations are going to be required (National Research Council, 2010). Moreover, due to the increasing pressure of production costs and the reduction of commodities prices, farmers have declined in number and many are tempted to ease the control on sustainable practices (Sposito, 2019).

In this sense, Wilson (2007) proposed a change of paradigm[3] from traditional agriculture to *Multifunction Agriculture*; meaning that agriculture has the potential to not only satisfy the needs of food and fiber but also provide other services including the protection of natural resources and biodiversity, the conservation of natural landscapes while enhancing farmers´ quality of life. This concept is by far more aligned with the sustainable development of the agriculture sector than traditional farming. Sustainable agriculture is capable of supporting regional economies and rural communities, maintaining their lifestyles and culture. A holistic approach, consisting of high-quality niche´ products, clean energy, nature, and landscapes management, and connections beyond the rural space, is proposed by the author (Sposito, 2019).

Wilson (2007) stated that there is a *broad spectrum of decision-making opportunities*, which has to be narrowed into tangible policymaking. Thus, a distinction between *weak, moderate, and strong multi-functionality* was proposed by the author, with different levels of *productivist* tendencies. The first one is the worst case of multi-functionality

[3] Paradigm is a set of theories, concepts, methodologies and methods in relation to a specific field (Sposito, 2019).

and it is very close to productivist agriculture (low environmental sustainability), whereas strong multi-functionality must be the goal for all societies, because of the synergies that it poses between actions and processes (Wilson, 2007). For instance, the author highlights the positive relation between landscape conservation, high-quality food production, and the participation of local rural communities. Figure 4- represents the different levels of multi-functionality proposed by Wilson.

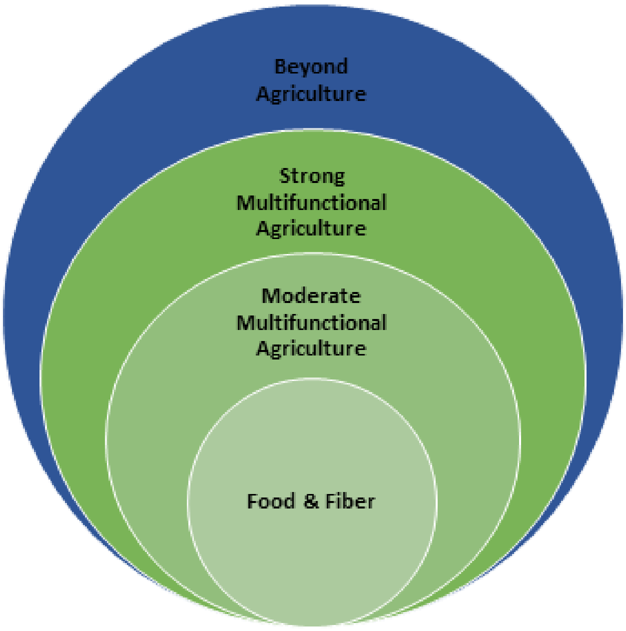


Figure 4. Multifunctional Agriculture

Source: adapted from Sposito (2019)

The *Beyond Agriculture* sphere is the maximum level of multi-functionality and can be related to the concept of *Eco-economy* (Kitchen and Marsden, 2009). This model links the innovative production of agricultural products under sustainable development practices and the endogenous consumption of the communities. This movement includes organic production and short supply chains, adding value to the products in the region. According to Sposito (2019), the Eco-economy model and Multifunctional agriculture have many aspects in common. For instance, both models state that agriculture provides a wide-ranging of needs for the community that not only include food and fiber production, but also the creation of jobs and wealth, protection of natural resources and ecosystems, and provision of tourism attractions.

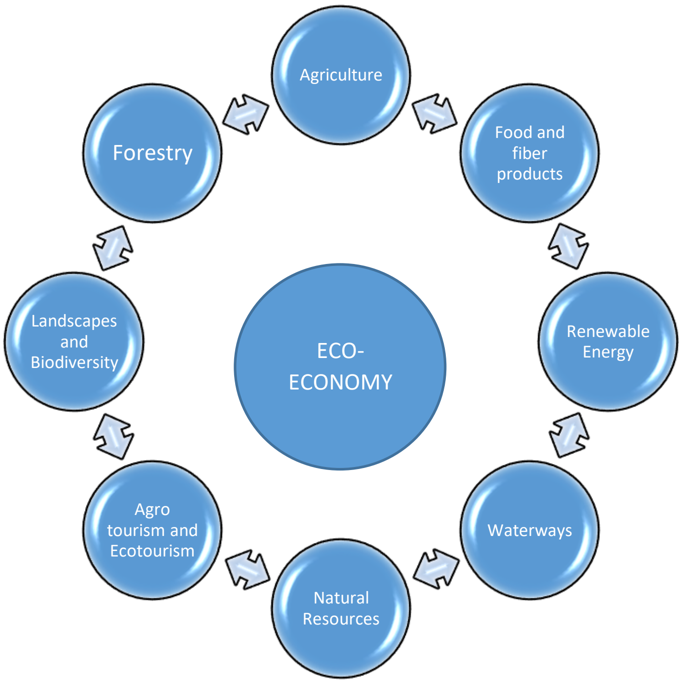


Figure 5. Eco-economy model

Source: adapted from Sposito (2019)

2.4. Drivers of Change and Planetary Boundaries

The models described above have the potential to increase the profitability of farms, while protecting the natural resources, ensuring the viability of the sector, and improving farmers´ lives, thus promoting sustainable development. Farm profitability can be measured using Earnings Before Interest, Taxes, and Amortization (EBITA), or other indicators such as Net Farm Income (Langemeier, 2017). For a farm or region to be sustainable, it is essential that it generates profits without depleting the environment and affecting negatively the community.

However, the sustainable development path may suffer important pressures from different sources or drivers of change (Sposito, 2019). In this sense, the development of humanity has overstepped several planet boundaries, affecting the natural processes of the Earth (Rockström and Karlberg, 2010; Rockström et al. 2015). These authors have described four main factors which are defined as *Quadruple Squeeze* that threaten the achievement of sustainable development. These factors are: overpopulation, human-induced climate change, anthropogenic ecosystem erosion, and unexpected tipping points that could arise. Rockström and Karlberg (2010) hence stated that a change of paradigm is needed if food production and humanity intend to operate within safe planetary boundaries.

Steffen (2015) defined the *Planetary Boundaries* as the limits which if surpassed, there is no return to stability in the Earth system – see Figure 6. The author stated that this concept is different from a *tipping point* or *global threshold*. The Planetary Boundaries Framework aims to advance biophysical science-based marks that the Earth system must not trespass (Steffen, 2015). Thus, the agriculture sector needs to shift from the current paradigm to one in which sustainable development is possible without the risk of exceeding these boundaries.

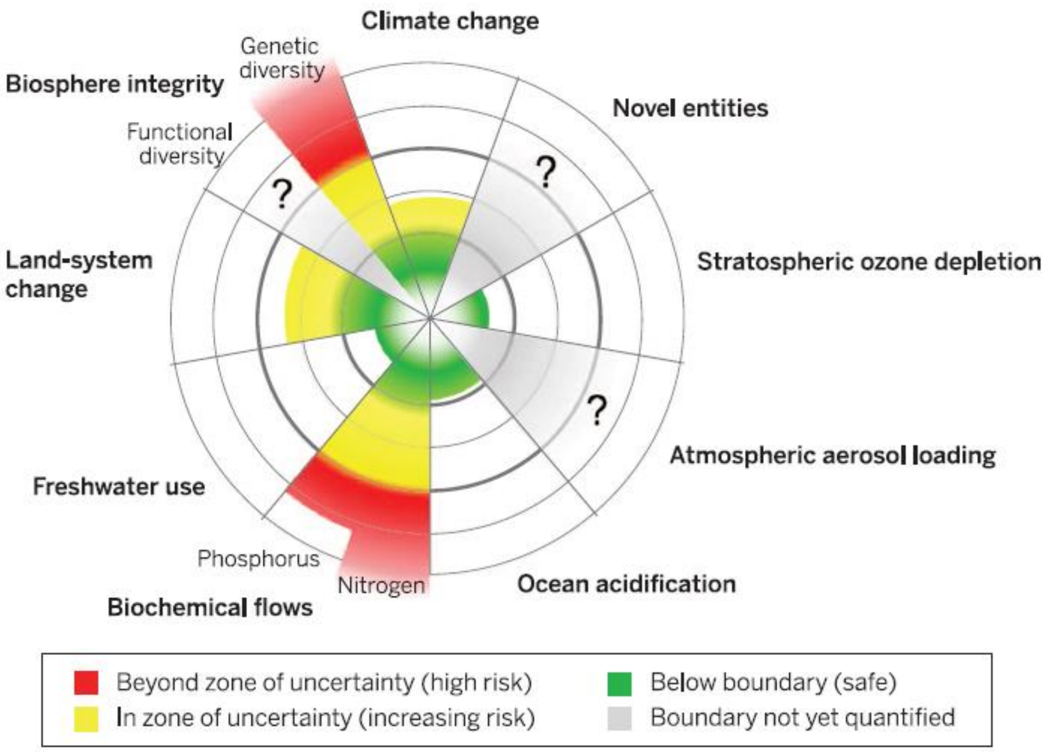


Figure 6. Planetary Boundaries

Source: Steffen, W et al. (2015)

This new paradigm of sustainable development, within the planetary boundaries, is possible under the framework of multifunctional agriculture and the eco-economy model. In this sense, Wilson (2007) highlighted that strong multifunctional agriculture intends: high environmental sustainability, low farming intensity, strong non-productivist tendencies, and open mind farmers and communities that understand that agriculture is in a process of change. For instance, this level of multifunctionality can contribute to the reduction of the usage of chemical fertilizers, helping to keep the phosphorus and nitrogen levels below the safe boundary. Furthermore, both multifunctional agriculture and eco-economy intend to generate short supply chains and local embedded communities, which promote local sustainable development (Wilson, 2007; Sposito, 2019). Generating a sustainable agriculture sector, which trails the SDGs and promotes adaptation and mitigation to climate change is required to not surpass these planetary boundaries.

2.5. Climate Change and Adaptation

The agriculture sector is one of the most vulnerable to climate change and the impacts of its variability affect food security. The UNFCCC (1992 p. 7) described climate change as: “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”. In addition, climate change is defined by the IPCC (2014a p. 120) as: “Changes in the mean and/or the variability of its properties and that persists for an extended period, typically decades or longer”. These changes are related to external forces like variations in the solar cycle, volcanos as well as persistent human-induced impacts generating changes in the atmosphere´s composition. In fact, the UNFCC has agreed that Climate Change is strongly influenced by anthropogenic actions (UNFCCC, 2011).

Therefore, adaptation to climate change is an important challenge for the agriculture sector. Adaptation is defined by the IPCC (2014a p. 118) as “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”. This definition clearly expresses that adjustments in the systems are needed to cope with climate change.

In Uruguay, the NAP-ag (2019) was elaborated, understating that the challenges of climate change demand a holistic approach. This includes food security, rural development, and climate risk management. The adaptation plan is part of the *National*

System of Response to Climate Change and Variability, aiming to fulfill the commitment of Uruguay to the Paris Agreement. Some of the measures of the plan include Climate-Smart Agriculture (CSA) practices.

2.6. Climate-Smart Agriculture

In the context of climate change and a growing population that will demand an increase of 70% in food production by 2050, food security needs a shift in the way of farming, towards more resilient and sustainable systems (FAO, 2013). In relation to this, *Climate Smart Agriculture* seeks the improvement of farmers' lives, increasing productivity, profitability and promoting adaptation to climate change, contributing to the mitigation of Greenhouse Gasses (GHGs) emissions (FAO, 2018)

According to FAO (2020, p. 1), Climate-Smart Agriculture (CSA) is "an approach that helps to guide actions needed to transform and reorient agricultural systems to effectively support the development and ensure food security in a changing climate". CSA aims to tackle three main objectives: 1) sustainably increasing agricultural productivity and incomes; 2) adapting and building resilience to climate change; and 3) reducing and/or removing greenhouse gas emissions, where possible (FAO, 2020).

Furthermore, CSA has the potential to improve food security under the pressure of climate change and its variability. It recognizes that the involvement of the different stakeholders is essential to identify strategies more suitable for local and regional conditions (FAO, 2020). In this sense, changes in the management of natural resources (for instance: land and water resources, biodiversity, genetic resources, and soil nutrients) are required, and more efficiency in their use is needed (FAO, 2010). Transformations of the system could lead to mitigation benefits, reducing the GHGs emissions of the sector. In this sense, Duncan et al. (2020) propose a shift to rebuild the food system and the practices related to agriculture, to contribute to the regeneration of soils, unity of communities, integration of policies, and generate more sustainable diets. The authors propose a focus shift to regenerate the whole food system under the umbrella of *Regenerative Agriculture*.

Uruguay has been undergoing important changes during the last decade, working towards more sustainable natural resources management, particularly concerning soil (MGAP, 2017). Uruguayan farmers, supported by the national Ministry of Livestock, Agriculture, and Fisheries (MGAP) have applied several CSA practices such as: direct seeding in the cropping sector, grazing natural pastures for beef cattle, and sheep, and improving water harvesting and management (World Bank, 2015). Yet, there are many more opportunities to apply more CSA practices, further contributing to the sustainable development of agriculture, particularly the dairy sector.

Within this area specifically, CSA practices that are well suited include: the treatment of manure using anaerobic digesters, decreasing methane emissions of the system while producing clean energy and organic fertilizers (FAO, 2010). In this sense, a *circular [food] economy*[4] proposes that nutrients can be recovered after feeding animals, extracting water, phosphorus, and nitrogen from urine and manure using biotechnology (Pascucci S, 2020). Moreover, improving grazing management can increase carbon stocks enhancing mitigation and resilience, and improve nutrients management. In this sense, technology plays a fundamental role and innovations like remote sensing or satellite

[4] Circular Economy is defined by the Ellen MacArthur Foundation (2013) as: 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.

imagery of pastures growth could generate a huge impact on the system (Global Dairy Agenda for Action, 2019).

Additionally, the formalization of the proposed *Plan for Sustainable Dairy Production* is another opportunity for Uruguay (World Bank, 2015). This plan, already implemented for the agriculture sector with excellent results, aims to prevent soil erosion by regulating crop rotation and pasture successions and to improve fertilizers management (MGAP, 2017). Overall, Uruguay has the potential to enhance the application of CSA practices, promoting sustainable development. The application of these policies will contribute to the adaptation and mitigation of the sector to climate change and its variability. In this sense, the sector would be more resilient to disturbances being able for instance, to cope with extreme weather events such as droughts and floods.

The term *resilience* was first described by Holling (1973, p. 14) as “a measure of the persistence of systems and of their ability to absorb change and disturbance and still maintain the same relationships between populations or state variables”. It is important to clarify that this definition refers to *ecological resilience* which is substantially different from *engineering resilience*. The latter was described by the author as a steady-state of stability near equilibrium, and it is used for economic theory (Holling 1996). In the case of *ecological resilience,* “the magnitude of disturbance that can be absorbed before the system changes its structure by changing the variables and processes that control behavior” is what is measured (Holling, 1996 p, 33).

Building on Holling’s concept, the IPCC (2014a p. 127) defines resilience as “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". According to Sposito (2019), this definition could be adapted at the regional level, expressing how local economies and businesses react to shocks and adapt after disturbances. This research has a particular focus on ecological resilience, analyzing how an ecosystem or a whole sector can respond to perturbations.

2.7. Measuring Sustainability through Indicators

Since the beginning of the century, there has been a strong promotion of sustainability targets across different sectors. In order to measure the progress to realize sustainability, it is important to develop *Sustainability Indicators* (SIs) that facilitate the decision-making and monitoring processes (Coteur et al. 2020; Reid and Rout, 2020). These indicators focus on measurable aspects of the four spheres of sustainability: environmental, economic, social, and institutional. The decision of which indicators are more relevant in a socio-ecological system is substantially based on subjective judgments (Reid and Rout, 2020). Furthermore, as it is complex to deal with a large number of indicators, it is important to prioritize the most relevant and build dashboards that summarize the performance of a farm or industry (Reid and Rout, 2020; Sposito, 2020b).

Sustainability Assessment Tools (SATs) aim to facilitate the decision-making process of farmers, directing them to more sustainable management (Coteur et al. 2020). The authors generated a framework that is farmer-oriented and promotes sustainable practices management and the use of SATs - see table 2. This framework is flexible and adaptable for different farms and changing needs of farmers, in order to help them to choose the best tool for a specific application in a particular moment.

Table 2. SAT's characteristics, complexity, and management dimensions

GENERAL CHARACTERISTICS	
	The goal, primary purpose
	Sector Scope
	Level of assessment
	Applying user (the person performing the assessment)
	End-user of the results
COMPLEXITY DIMENSIONS	
(1) Time required	Preparation by the farmer and assessor
	On-site data collection (interview, contact with farmer)
	Assessment phase, calculating results
	Reporting, communicating
(2) Type of assessment	Qualitative, semi-quantitative, or quantitative data
	Qualitative, semi-quantitative, or quantitative assessments
	Type of indicators
	Details on method for data collection
(3) Coverage within each	Number of themes within each dimension
sustainability dimension	Which themes and subthemes
	Number of indicators
(4) Complexity of calculation	Data intensity: Amount of data needed per
	Dimension/length of the questionnaire
	Model complexity: Number of calculations, weighting,
	allocation of questions
MANAGEMENT DIMENSION	
Step 1: Assessment	Method of reporting results to the farmer
Step 2: Interpretation of results	Whether support is provided to interpret the SAT results
Step 3: Improvement strategies	Whether support is provided to develop improvement
	Strategies
Step 4: Implementation of	Whether support is provided on how to implement the
strategies	Strategies
Step 5: Monitoring and	Whether the improvement strategies are evaluated after
benchmarking	Implementation

Source: Coteur et al. (2020)

In Uruguay, there have been some attempts to generate indicators to evaluate sustainability. In the dairy sector, the development of a system of indicators for the social, economic, and environmental dimensions was conducted for family farmers (Tommasino et al. 2012). These authors developed a system of 15 indicators to be applied at the farm level for the conditions of Uruguay -see table 3-. Each indicator is measured either by a survey conducted by the farmer or by direct measurements on the farm and has a maximum value that contributes to a particular dimension, which is then evaluated separately. However, there is not a global index of sustainability calculated (Tommasino et al. 2012).

Table 3. System of indicators of Sustainability for the Uruguayan Dairy Sector

DIMENSION	**INDEX**	**VARIABLES CONSIDERED**	**MAX VALUE**
SOCIAL	General participation	Level of participation in collective spaces	20
	Productive participation	Participation in joint asset management	20
	Education	Productive and non-productive training in the last 3 years	20
	Subjective quality of Life	Personal satisfaction evaluation	12
	The structural quality of life	Housing, locomotion, health	8
	Succession	Age and successors willing to continue in the farm	20
ECONOMIC	Farm income	Farm income and number of people living on the farm	40
	Production support	Breeding field, joint machinery, joint sowing	15
	Financial autonomy	Cattle bank, microcredits, total property debt	30
	Transmissibility	Number of heirs	15
ENVIRONMENTAL	Water	Sources of pollution, animal access, state of the structure	20
	Effluents	Number of cows, risk of contamination	20
	Soil	Land use management	20
	Biodiversity	Native forest record and use, state of conservation	20
	Agrochemicals	Personal prevention measures, environmental conditions for application, a place for washing and loading the products	20

Source: Tommasino et al. (2012)

This system of indicators is a useful and practical framework to measure sustainable development in the dairy sector, considering the different dimensions of sustainability at the same level of importance. Yet, a global index of sustainability would be an interesting measure to compare different farms or regions.

All things considered, this literature review leads to several research questions about the potential of CSA practices towards the sustainable development of the dairy sector in Uruguay. A brief description of the study area is included in the next section to understand the context of this research.

2.8. Study Area: Uruguay

This section provides a brief description of the country of study, Uruguay. Special emphasis is placed on the historical and current situation of the agricultural sector to understand the impacts of climate change on this important segment of the Uruguayan economy. Particularly, the impacts of climate change on the dairy sector and the adaptation and mitigation policies will be analyzed.

The Oriental Republic of Uruguay is located in the eastern region of the southern cone, bordering Brazil to the northeast and Argentina to the west, as depicted in figure 7. According to the last census of the *Instituto Nacional de Estadística (INE)*, It has a population of approximately 3.2 million inhabitants, on an area of 176,000 km2 of which approximately 160,000 km2 have agricultural potential. Its capital is Montevideo and it is located in the south of the country, with a population of 1.3 million inhabitants according to the last national census (INE, 2011).

Figure 7. Location of Uruguay in South America

Source: Google Maps (2021)

Uruguay has a temperate and humid climate and four defined seasons. Rainfall is distributed evenly throughout the year and has an annual average of approximately 1,200 mm. It presents a hydrographic network of rivers and streams that extend throughout the country, nourishing the soil and making it suitable for planting crops and growing native pastures that are the basis for fattening animals (World Bank, 2015). It has coasts to the Uruguay River to the west, Río de la Plata to the south, and the Atlantic Ocean to the southeast, where various important ports are located such as Nueva Palmira, Colonia del Sacramento, Montevideo, and La Paloma. Regarding the transport of agricultural products, it is done by trucks using a network of highways that cover all the country and the railroad to a lesser degree. The country is divided into 19th departments as depicted in figure 8.

Figure 8. Political map of Uruguay

Source: Maps - Uruguay (2021)

The natural characteristics of the country make livestock production from natural pastures favorable, which has distribution in its production with peaks in spring-summer. The Uruguayan economy is dominated by the agricultural-livestock sector - see figure 9-, oriented to exports, and by a developed agro-industrial sector (World Bank, 2015). Cattle are raised in open air, under natural conditions within a temperate climate, fertile soils, and a great abundance of water generated in its numerous rivers and streams, ensuring the well-being of animals. Investment in technology, added to the sanitary status and the quality of its products, converted Uruguayan meat and dairy products attractive to the most demanding markets (MGAP, 2017).

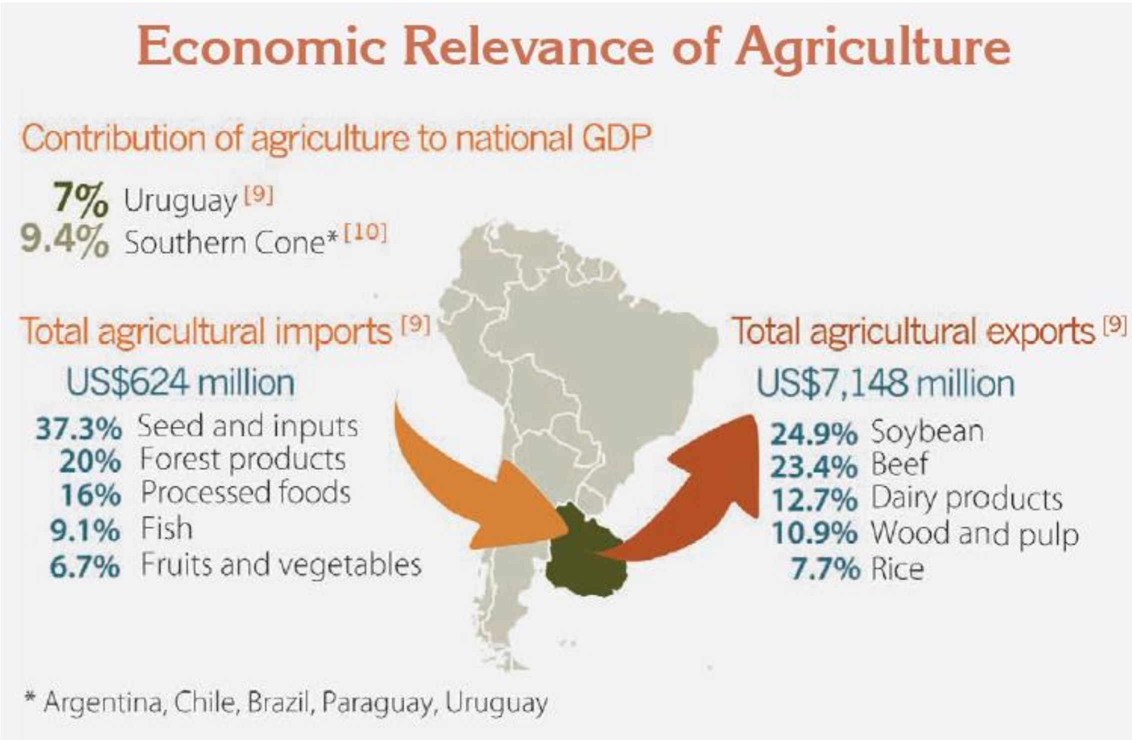


Figure 9. Economic Relevance of the sector

Source: World Bank (2015)

The dairy sector concentrates the highest technological development and seeks the greatest productive efficiency through the adoption of new feeding technologies. As depicted in the following map - see figure 10 -, Dairy farming is practiced mainly in the south and southwest, on 890,000 hectares. This area represents only 5% of the total agricultural land but accounts for 12.7% of the total Uruguayan exports or U$S 900 million/year approximately (INALE, 2020).

Figure 10. Main location of the Dairy farms in Uruguay

Source: INALE (2020)

Currently, 10% of the Uruguayan farmers are dedicated to dairy production, representing 3,800 farmers -see figure 11. Moreover, 73% of these farmers are dedicated to milk remission (2,200 million liters/year) while 27% are cheese producers. Uruguay has a consumption of 230 liters of milk per capita per year, a fact that makes it the largest consumer of dairy products in Latin America (INALE, 2020). However, domestic consumption represents only 30% of the annual remission, while the remaining 70% is exported to various markets (with projections of an increase to 90% in the next 10 years). It destines its production to more than 60 countries, where the Mercosur[5] has main relevance but also other markets as Asia, Europe, and Africa (INALE, 2020).

[5] MERCOSUR: the *Mercado Comun del Sur*, or Southern Common Market, is a trading bloc established in 1991 by neighboring countries Argentina, Brazil, Paraguay and Uruguay.

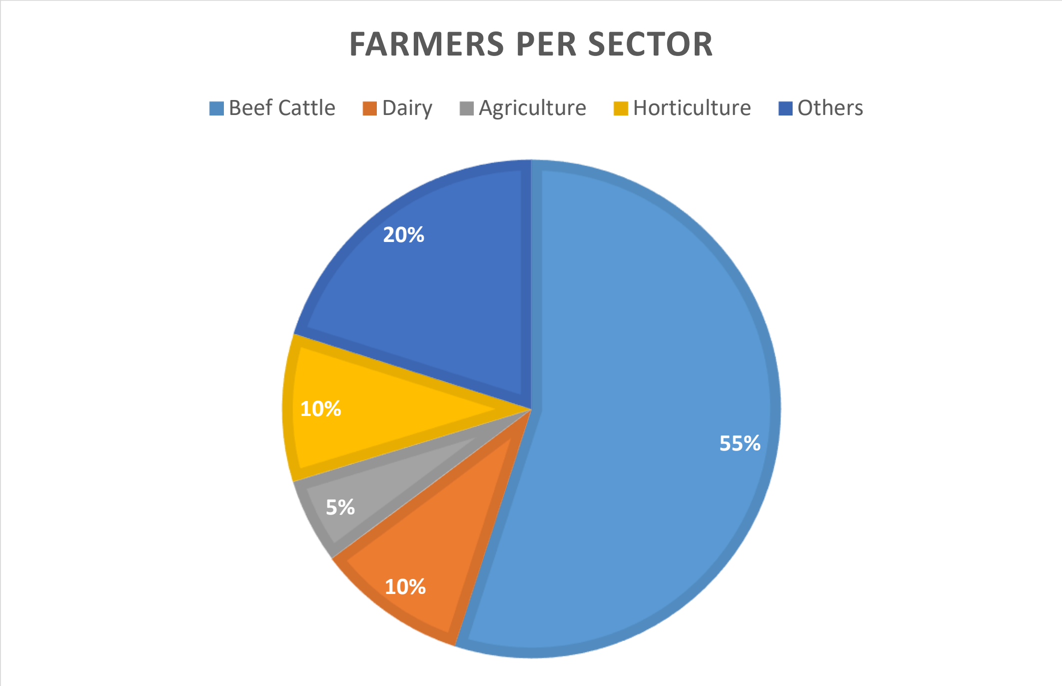


Figure 11. Farmers per sector

Source: INE (2011)

Farms between 50 and 199 hectares represent 50% of the total number of farms and 21% of the surface dedicated to milk production of the country; those of 200 to 499 hectares represent 22% of the total and 26% of the surface, and those of 2,500 hectares and more are the 0.8% of farms and 11% of the surface. One of the main phenomena that occurred in the sector is the reduction in the number of farmers. However, agricultural production has had a constant increase due to a rise in productivity per hectare maintaining a relatively constant stock of cows (INALE, 2020).

Table 4. Dairy cow's stock evolution (expressed in thousands)

YEAR	TOTAL	MILKING COWS	DRY COWS	OTHERS	CALVES
2010	764	296	134	430	60
2011	793	320	130	450	61
2012	755	320	121	441	61
2013	782	331	114	445	62
2014	772	297	127	424	57

Source: INALE (2020)

Main facts of the Dairy Sector in Uruguay (INALE, 2020):

- Uruguayan producers work with extensive, intensive, and semi-intensive systems. The extensive system is based on an almost purely pastoral diet; the intensive or enclosure system uses a grain-based diet and energy concentrates and finally, the semi-intensive system where grass and grains are used proportionally.
- 70% of Uruguayan dairy producers are associated with the National Cooperative of Dairy Producers, better known by its acronym in Spanish CONAPROLE. It was founded in 1936 and since then operates under a cooperative regime.
- The dairy industrial sector is comprised of national and multinational companies that have continuously expanded their installed capacity.
- The demand for dairy products by the domestic market is widely covered, leaving an exportable balance of 70% of production. The main exported products, ordered by annual volume, are whole milk powder, cheese, skim milk powder, and butter.

Due to the importance of this sector in the Uruguayan economy and society, it is imperative to determine and analyze the possible impacts of climate change and its variability. In this sense, the National Adaptation Plan was created with the objective of the "development, design, coordination and prioritization of policies, programs, and projects which support the vulnerability[6] to climate change of the different agriculture sectors, generating a change of paradigm towards sustainable development. The final aim is to enhance farmers' lives through sustainable farming systems" (NAP-ag, 2019 p. 17). The plan integrates adaptation and mitigation to climate change policies with actions to increase food security. Some of the policies are Climate Smart Agriculture outputs, such as: increase productivity, increase net return, improve inputs use and efficiency, reduction of emissions, increase resilience, increase gender and social inclusion (NAP-ag, 2019).

[6] Vulnerability is defined as "The degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes" (IPCC, 2001 p. 995).

CHAPTER 3. METHODOLOGY

This chapter contains a description of the methodology applied in the thesis. Firstly, a Rich Picture method was conducted to understand the main actors involved in the dairy sector and their relations. Secondly, the Land Use Analysis method was applied to make a diagnosis of the situation in Uruguay. Thirdly, Land Suitability Analysis was used to determining a solution to the impact of climate change on the dairy sector; this part of the methodology utilized a Geospatial Information System (ArcGIS) software.

3.1. Rational Holistic Planning and Decision Making Model

The research approach applied different methods to implement a generic methodology in order to understand the impacts of key drivers of change, particularly climate change on the Uruguayan dairy sector by 2050 and develop future scenarios applying CSA practices. The approach uses the *Rational Holistic Planning and Decision Making Model* formulated by Sposito (2020b). This is a six-step multi-methodology (see below) that allows the user to apply different methods on each step (or stage). The steps are: 1) Problem Formulation; 2) Situation and Diagnosis; 3) Solution; 4) Decision-taking; 5) Implementation and 6) Monitoring. The model is iterative and cyclical, meaning that the user can start at different points and go back to other steps if necessary -see figure 12. Furthermore, it aims the promotion of sustainable development at different levels of analysis, in this case, the regional level, and the adaptation to different drivers of change such as population growth or climate change.

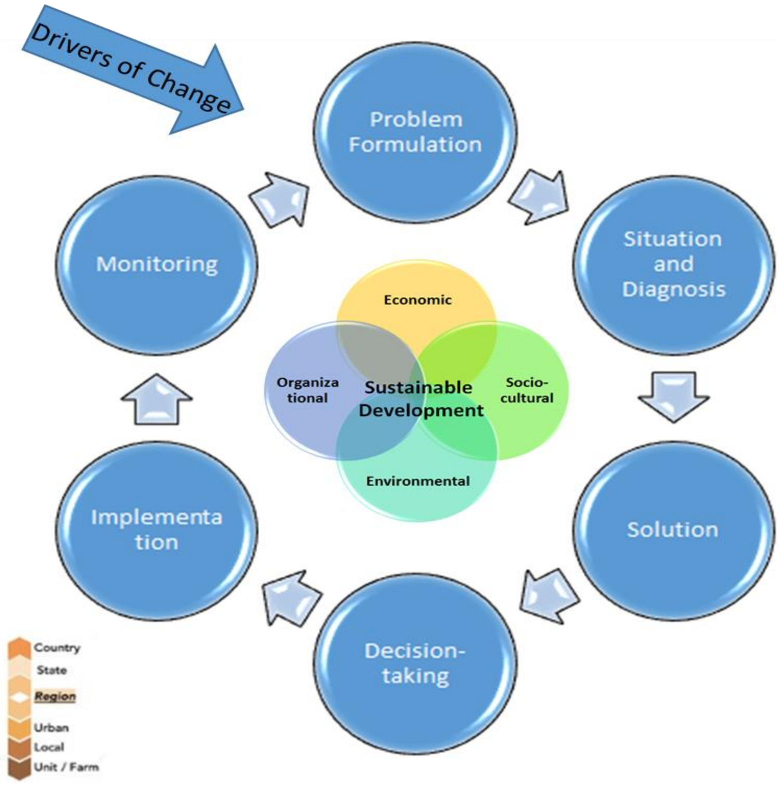


Figure 12. Rational Holistic Model

Source: adapted from Sposito (2020a)

Jackson (2019, p. 531) stated that multi-methodological approaches have several advantages, especially when dealing with complex problems under uncertain and risk environments. The author highlighted that "multi methodology is the combinations of methodologies (possibly from different paradigms) and methods together in a single intervention".

Table 5. Jackson´s advantages of using multi-methodological approaches.

1	The complex problems we are trying to solve are part of a multidimensional system, the world. Thus, using different methods to understand different paradigms (specially in the social field) is extremly useful.
2	The interventions of decission makers and the planning proces involve different phases. Each phase or stage involves a variety of tasks, so using different methods could be very helpful.
3	Any oberserver or methodology knows the truth about a complex problem. In this sense, a holistic approach including different points of views and a range of methods is required.
4	The lack of succes of other approaches (such as hard systems) in tackling wicked problems, encorages new approaches like MM in order to cope with complexity.
5	Finally, ovserving the problem from different perspectives (specially when they differ) is extremly valuable in order to understand the complexity of the issue.

Source: adapted from Jackson, MC (2019, pp. 531-540)

As a multi-methodological approach, different methods were applied in the thesis's research in the different stages of the model. These include quantitative, qualitative, soft systems, and hard systems methods. In systemic inquiries, Checkland (1981) considers that Hard Systems Thinking (HST) is a useful approach *to analyze the world itself*, while Soft Systems Thinking (SST) involves a shift *to analyzing the process of dealing with the world*. Sposito (2020a) stressed that SST is a cyclic learning system, which is very useful to analyze real-world problem situations in the absence of concrete (or fuzzy) definitions where the objective of the study is a problem itself; while hard systems are appropriated for dealing with well-structured problems and defined objectives. As depicted in figure 13, each step in the application includes different methods detached from several methodologies, which is very important in a holistic approach that aims to tackle complex problems (Sposito 2020b).

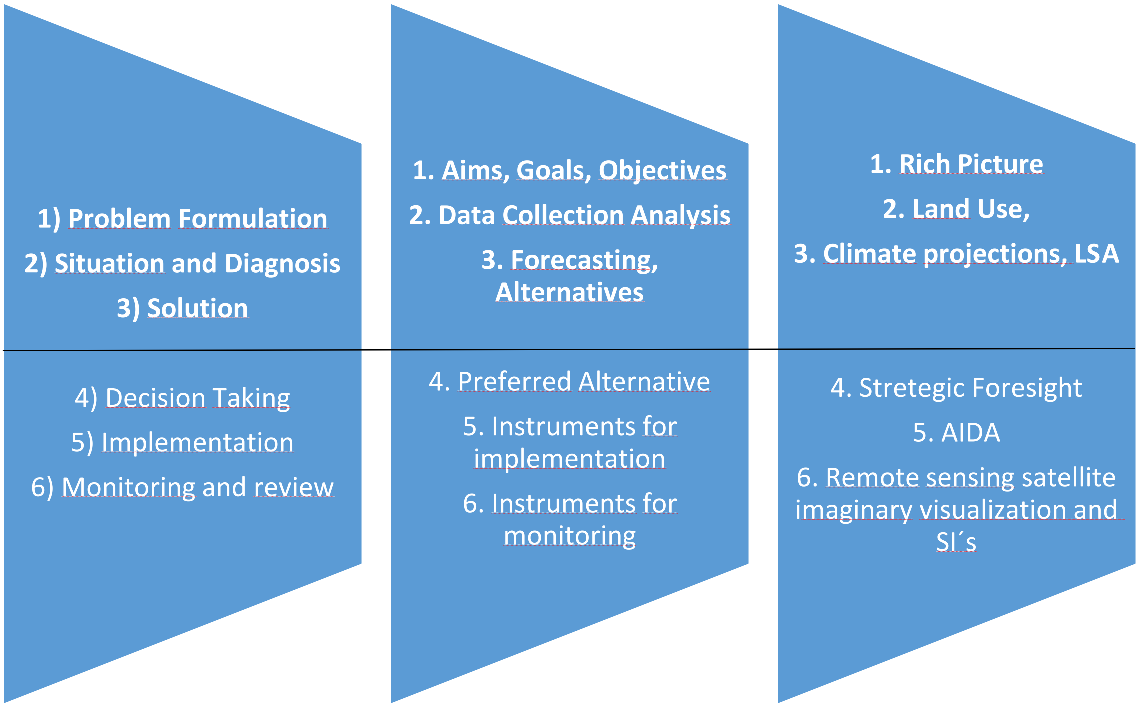


Figure 13. Rational Holistic model and the methods to be applied[7]

Source: Adapted from Sposito (2020b)

Although this thesis analyzes the situation in the whole country, the area where the research is focused is where the majority of the dairy farms are located in Uruguay. The dairy sector is concentrated in the southwest of the country, mainly in the departments of Florida, San José, Colonia, and Canelones (see figures 17 and 18).

3.2. Rich Picture Building

In the first stage of the multi-methodological approach, *problem formulation*, the proposed method to be deployed is Checkland´s *Rich Picture* which is a key component of his Soft System Methodology – SSM (Checkland, 1981). This method is very useful to understand a complex problem, analyzing how the system operates, which are the main parts of that system, and how the different parts are related (Checkland and Poulter,

[7] The black line represents a distinction between decision-making and decision-taking. Commonly, politicians are responsible for the implementation and monitoring of policies, but planners must be part of this process too (Sposito, 2020b).

2006). Checkland (2012, 9:10) described the Soft System Methodology as an "epistemology which enables you to learn your way to taking action to improve a problematical situation or a wicked situation". According to this author, the only way to cope with complex problems is with the same level of complexity in the way of dealing with them (Sposito, V. 2020a). A typical example is when two soccer teams plan their strategies to win the game. To deal with the complexity of the rivals´ strategies, the other team also needs the same number of players and the same level of strategy. Checkland (1981 p. A10) defined that "…the use of the word ´system´ is no longer applied to the world, it is instead applied to the process of dealing with the world" stating that SSM implies a shift from examining the world to studying the process of examination of the world.

3.3. Land Use Analysis

In the second step of the multi-methodological approach, *situation and diagnosis*, the focus is on Land Use Analysis. Land Use Analysis contributes to the understanding of a particular region and the diagnosis of the baseline situation. The resultant land use map is a thematic cartography that characterizes the different forms of occupation of the territory (geographic space) according to a variable number of categories. In other words, the map shows how the different sectors are distributed across a region and where the main cities and infrastructure are located (Sposito, 2020b). In the case of the thesis, the spatial distribution of the dairy farms and farmer's concentration is presented, as a baseline to demonstrate where the areas of high suitability for the production are represented.

3.4. Land Suitability Analysis

Yields for different pastures were used in the research as a proxy to determine likely milk production under the current and projected climate for Uruguay by 2050. It was assumed here that the more environmentally suitable land areas for growing pastures are more likely to sustain more milk cows per hectare thus increasing milk production with relatively low feed costs and generating more profits for farmers (Chilibroste and Battegazzore, 2015). However, higher levels of supplementation per hectare (implying more external inputs to the system) might be required to manage imbalances between pasture supply and demand during certain times of the year.

Land Suitability Analysis (LSA) is thus deployed to determine the land suitability for pasture growth in Uruguay. The building of a LSA model is based on the use of Multiple Criteria Analysis (MCA) in a Geographic Information System (GIS) platform or environment (Johnson et al. 2018). MCA is a very useful method to evaluate a set of alternatives, comparing them with different weight components and trading-off between several criteria (Sposito, 2013). In the LSA modeling, the MCA deployed is the *Analytic Hierarchy Process*.

GIS software is an excellent spatial representation tool that helps the user to visualize different problems and contextualize complex spatial analysis. For instance, the relationship between the problem and the solution can be analyzed both spatially and temporally, even in different time horizons.

The description of the Analytical Hierarchy Process by its creator Saaty (1995 p. 4) is "Basically the AHP is a method of breaking down a complex unstructured situation into its component parts; arranging these parts, or variables, into a hierarchical order [or decision tree]; assigning numerical values to subjective judgments on the relative importance of each variable…”.

The application of MCA-AHP allows for the evaluation of *ranges* of land suitability rather than *absolute* values of suitable or unsuitable. The modeling process includes the participation of experts in creating the LSA model, thus including them in the overall decision-making process. The inclusion of experts is extremely important to understand the system under consideration and ensure experts from different fields, such as soil scientists and agronomists, provide their authoritative input (Johnson et al. 2018). It is in this sense that LSA building is considered as an *expert systems modeling*. As shown by Mrazova et al. (2017) in building a LSA model, weights (numerical values) are assigned to each component or criterion, using experts’ knowledge. The authors stated that the weights demonstrate the importance of each criterion and the relativity between them.

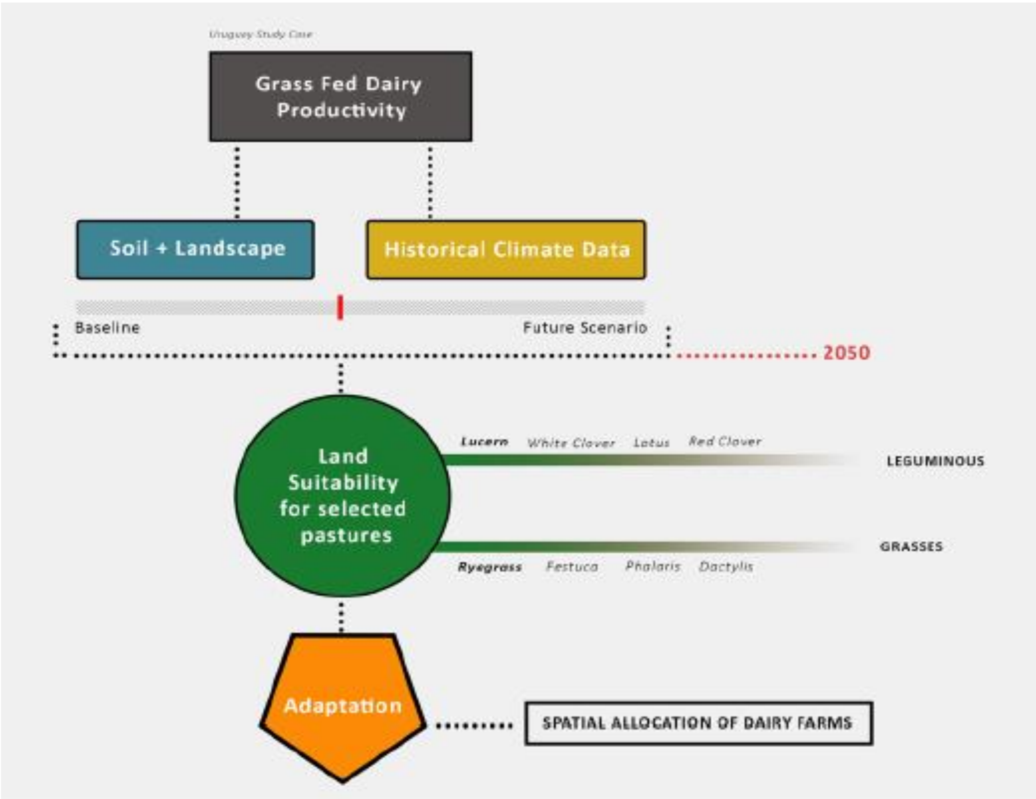


Figure 14. Land Suitability Analysis Methodology

Source: Jhonson et al. (2018)

The LSA models developed and applied in this thesis were for Lucerne and Ryegrass since they are some of the main species used in the Uruguayan dairy systems. The main inputs of the model are soil data, landscape data, and climatic data - see Figure 14. Climate projections by 2050 are compared to the current/base climate to understand future pastures' suitability and the impact of climate change. It is possible in this way to understand how the dairy sector might adapt to global warming, particularly changes in temperature and rainfall patterns. This analysis is henceforth paramount to validate a future spatial allocation of dairy farms and examine mitigation/adaptation strategies to tackle unfolding climatic changes.

As depicted in Figure 14, the models use historical climate information, which is then replaced by projected climate data to obtain estimations of the land suitability variations. The other components of the model remain stable to understand the impact of climate change separately. Once the model is run, Land Suitability projections for the different species, under dissimilar climate change scenarios, can be obtained and adaptation measures can be assessed. Measures that can be assessed include the use of CSA practices such as diversification of crops and pastures, irrigation and water recycling, precision agriculture techniques, and so on. (Johnson et al. 2018). As previously mentioned, GIS is a very powerful tool to support the decision-making process for regional development strategies. It is however essential that clear criteria, factors, and constraints are selected and correctly weighted. Therefore, the LSA model will only be reliable if the decision rules introduced allow trade-offs and truthful combinations.

Based on the decision models for Lucerne and Ryegrass in Australia, the Analytical Hierarchy Process (AHP) of those two species was generated for Uruguay. The main variations (adjustments) were in the weighting of the variables and the rates associated with them following the experts' recommendations. In this sense, the participation of experts from the National Institute of Agricultural Research (INIA) and the Faculty of Agronomy from the University of the Republic (Fagro – UdelaR) was extremely important (see appendix II).

In terms of climate, the parameters of temperature and water tendencies for Uruguay were obtained from the historical data and future projections from www.worldclim.org. Consequently, two decision trees were generated to describe Lucerne land Suitability and Ryegrass land suitability –see appendix III.

As mentioned, the soil and landscape data for both pastures were maintained (assuming that there is no impact of erosion and changes in fertility to simplify), but the historical climate baseline[8] was modified by the 2050 climate forecast. Therefore, two additional decision (AHP) trees were generated for 2050. Essentially, once the hierarchy and weight criteria were specified, the next steps were the data value rating, the database development, and finally the model development using the Model Builder Tool[9].

The final results of the models are for (a) historical baseline climate, and (b) projected climate by 2050, maintaining, as mentioned, soil and landscape data constant. Relevant maps were used as inputs to generate the historical baseline land suitability and projected land suitability by 2050 for both pastures.

[8] Data from 1960-1990 assumed to be in line with global standards for historical baselines.
[9] Graphical representation of the sequence of geo-processing tools used in ArcGIS.

3.5. Drivers of Pastures Productivity

This section includes a revision of the current literature related to the drivers of productivity both for Lucerne and Ryegrass. A description of the main factors affecting the potential of the species is presented, aiming to understand the impact of climate change on pastures' productivity. This information is also extremely valuable to construct the Analytical Hierarchy Process for the selected pastures and to decide the weighting criteria.

3.5.1. Lucerne

Alfalfa (Medicago sativa L.) is a perennial summer legume that has high yield potential and persistence, due to the reserves on its crown (Rebuffo, 2000). This pasture can grow and a wide range of climates because it has a great phenotypic and genetic variation and is adapted to drought conditions (Ovalle et al. 2015). These characteristics make Lucerne a very good option as a persistent and productive pasture in Uruguay (Formoso, 2000; Otero and Castro, 2018).

According to Otero and Castro (2018) temperature, solar radiation, evapotranspiration, and rainfall patterns are, among others, the most important variables that determine the growth rate of Lucerne. The authors stated that the balance between the last two determines the water excesses or deficits which affect the productivity potential (Otero and Castro 2018). The climatic conditions of Uruguay, with a temperate subtropical climate, allows a good performance of Lucerne (Rebuffo, 2000). Also in other similar climatic conditions like central Chile, Argentina, and Southern Australia, the use of perennial legumes is a priority to improve forage distribution and cope with environmental issues (Ovalle et al. 2015).

According to Otero and Castro (2018), the optimal temperature for Lucerne is from 25 to 30 °C, but it is considered that there is a wide range between 5 -30 °C for a germination rate (Rebuffo, 2000). Furthermore, frosts during winter and spring and water deficits in spring and summer can affect the productivity of Lucerne (Otero and Castro, 2018). Moreover, the authors stated the annual production varies between genetic materials and pasture age, influenced by climatic conditions. Also, Growth Rates (GR) vary according to the age of the pasture and climatic conditions, which differently affect the GR according to the season of the year (Otero and Castro, 2018). The following table summarizes the optimal conditions for Lucerne's maximum GR - see table 6.

Table 6. Lucerne requirements according to Uruguayan and Australian authors

VARIABLES	ATRIBUTES	SUB CATEGORY	Otero and Castro, 2018	Mrazova et al. 2017
CLIMATE	TEMPERATURE	SUMMER	20 - 25°C	15 - 25°C
		AUTUM	8 - 20 °C	10 - 18°C
		SPRING	22,5°C	10 - 30°C
		WINTER	7,5 - 8,5°C	10 - 25°C
	RAINFALL	ANNUAL	1200	500 - 700
		SUMMER	Eta: Etm = 1	50 - 75
	RADIATION		20 Mj / m2 / day	
TOPOGRAPHY	SLOPE			5% or less
	ALTITUDE			E, SE, S, SW, W
SOIL	PH TOPSOIL			6,5-7,5
	PH SUBSOIL			6,5-7,5
	DEPTH			100 cm
	TEXTURE	OPTIMAL		LS,CS,S,SL,FSL
		SUBOPTIMAL		L, ZL, CL, SCL
	DRAINAGE			Well rapid
	SODICITY			Not sodic
	SOC			High
	WATER LOGGIN			Low rating
POTENTIAL (ha/year)			14 ton	6,5 - 12 ton

Source: Mrazova et al. (2017) and Otero and Castro (2018)

The optimal climatic conditions for Lucerne are consistent in both countries, showing that high summer precipitations (Australia) and no water stress during this period (Otero and Castro, 2018) are critical for high growth rates. Moreover, optimal temperatures during the different seasons are required to express the potential of the pasture for both countries. Concerning soil and topography data, soil PH, texture and depth are the most important variables affecting potential yield. This information is critical to building the AHP model for Lucerne, and expert participation is essential (see appendix IV).

3.5.2. Ryegrass

Lolium multiflorum (Annual *Ryegrass*) is an annual grass mainly used for pasture, hay, or silage production in high precipitation areas (>650mm), between 0 – 30°C and in high fertility soils (Grassland Society of Southern Australia Inc. 2008). This densely tillered pasture always has only 3 live leaves and the rest start to die after 21 days in spring and 90 in winter (DairyNZ, 2008). Ryegrass varieties are adapted to different rainfall requirements and environmental conditions. However, in general, requires at least 600 mm of annual rainfall to be productive and persistent (Smith, 2012).

In Uruguay, *Ryegrass* is used as a winter crop to cover natural grasses' growth rate which is usually low during cold seasons (Berruti, 2018). It is well adapted to different environmental and soil conditions and it is very productive in fertile soils (Carambula, 2007). According to the author, Ryegrass grows in well-drained soils, but it also tolerates very humid conditions and is adapted to heavy soils, although grows well in well-fertilized sandy soils (Carambula, 2007).

Consistently, Smith (2012) states that ryegrass is not recommended in soils with low/poor fertility. The author highlights that ryegrass has a good response to applications of Nitrogen (Smith, 2012; Carambula, 2007). The optimal pH level is between 5,6 and 7,0 to maximize pasture growth (Smith, 2012). Moreover, this pasture tolerates waterlogging and also tolerates acid soils and salinity (Smith, 2012). According to DairyNZ (2006), extreme temperatures would affect pasture growth. Ryegrass grows better in template temperatures varying on the season. In this sense, Romeijn et al. (2014) determined a LSA model for perennial Ryegrass based on the following criteria – see table 7.

Table 7. Ryegrass requirements

Criteria	Weight (%)	Suitability Category		Index Value	
1st 2nd 3rd	1st 2nd 3rd	High	Low	High	Low
Landscape	15				
Slope	40	< 4,5 °	> 31,5°	1.0	0.0
Aspect	35	E,S,W	N	1.0	0.5
Altitude	25	< 400 m	> 400 m	1.0	0.7
Soil	25				
pH	25	5,5 - 6,5	<4,0 and >8,5	1.0	-1
Water Holding	50				
Coarse Fragments	10	None to Slight	Very High	1.0	-1
Depth to Bedrock	20	> 1,2m	<0,5m	1.0	0.5
Texture	70	CL, L, SCL, FS	HCL, HC	1.0	0.2
Drainage	10	Well, Moderate	Vey Poor	1.0	0.2
ECe	15	Very Low, Low	Very High	1.0	-1
Climate	60				
Mean Temperature	40				
Mar - May	25	15- 20°C	> 30°C	1.0	-1

Source: Romeijn et al. (2017)

3.6. Decision-taking process

The final three steps in the Rational Holistic Model are: decision-taking, implementation, and monitoring – refer to Figure 13.

The *decision-taking step* (or process) is usually conducted by decision-takers and politicians who have the role of assigning resources to different projects and implementing them (Sposito 2020a). However, to determine which method could be adopted for each of the final steps in the model, it is also briefly considered here.

Therefore, to support the decision-taking process, an interesting main methodology is *Strategic Foresight* (Mrazova et al. 2016[10]). This methodology focuses on three types of scenarios: *"*Predictive Scenarios that try to determine the likelihood of future events (…) Explorative Scenarios, that investigate a range of plausible events (…) and Normative Scenarios, which are a target driven" (Mrazova et al. 2016 p.3).

The *implementation step* can be conducted using the A*nalysis of Interconnected Decision Areas* (AIDA), which is a useful method to identify the attributes of a problematic situation and how these could affect the possible solutions, using different actions (Sposito, 2020a). Sposito mentions that this method is particularly useful for avoiding spending resources on unfeasible solutions.

Finally, for the *monitoring step*, Sustainability Indicators (SIs) are proposed as the best method to measure the policies´ outcomes. Moreover, remote sensing satellite imagery could be used as a visualizing method to determine the achievements resulting from the CSA appellation.

Nevertheless, it is important to state that due to the scope of this research and the time available for developing it, these three steps were not conducted and they are simply described to show their contribution to the whole process.

[10] Mrazova's PhD thesis applied Strategic Foresight in the Glenelg-Hopkins Region of the State of Victoria.

CHAPTER 4. RESULTS

This chapter contains the results of applying the different methods described in the previous methodology chapter. Firstly, a *Rich Picture* analysis is shown aimed to understand the problem and its environment. Secondly, *Land Use Analysis* is conducted as a diagnosis of the actual situation. Finally, *Land Suitability Analysis* is applied - the different scenarios are described and all the models and inputs are shown. Although the next chapter is dedicated to the discussion of the results, the key findings resulted from the maps for the LSA of both Lucerne and Ryegrass are shown in this one.

4.1. Rich Picture

The Rich Picture method was applied to understand how this system works and which are the main actors and their relationships. The picture has boundaries in order to make the illustration simpler and aims to represent the real situation of the system, its actors, processes, and relationships. Climate change is the main driver for the system.

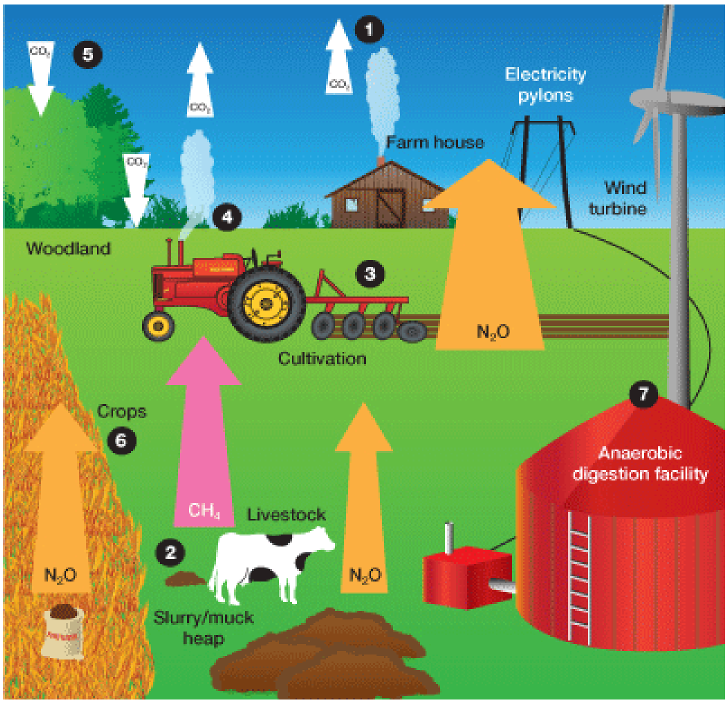


Figure 15. Rich Picture of a Dairy Farm

Source: climatechange-foodsecurity.org (2021)

As depicted in figure 15, the main inputs of the system are CO_2 sequestered by pastures and woodland; water; energy produced by wind turbines; (hydro)electric pumps or anaerobic digesters; and fertilizers and seeds for crops. On the other hand, after processing these inputs to generate feed for the animals to sustain milk production, the outputs generated are CO_2, N_2O, and methane from enteric fermentation; manure and Gasoil used by machinery with the consequent CO_2 emissions. According to the World Bank (2015), the GHG emissions of the agriculture sector represent 75% of the total emissions of the country, from which 56% comes from enteric fermentation (see appendix V). The key process that balances the inputs and outputs of the system is the photosynthesis of pastures which transform CO_2 into energy that is consumed by cows to produce milk generating also a sink of GHGs. Thus, more productive pastures could increase the sequestration of greenhouse gases.

4.2. Land Use Analysis

The Land Use Analysis is the description of the actual land use for the different sectors or activities developed in the region. Despite the actual land use, where some areas are not dedicated to dairy because of the existence of other infrastructure or activity, such as rain-fed extensive crops or horticulture areas, these land could have the potential of being used for dairy which is reflected in the Land Suitability Analysis -see figure 16-. The main area where dairy farms are located based on native grass and pastures is in the southwest of the country, including the departments of Canelones, San José, Colonia, Flores, Florida, and Soriano. The region includes other important sectors such as rain-fed agriculture and extensive crop which also are used for dairy.

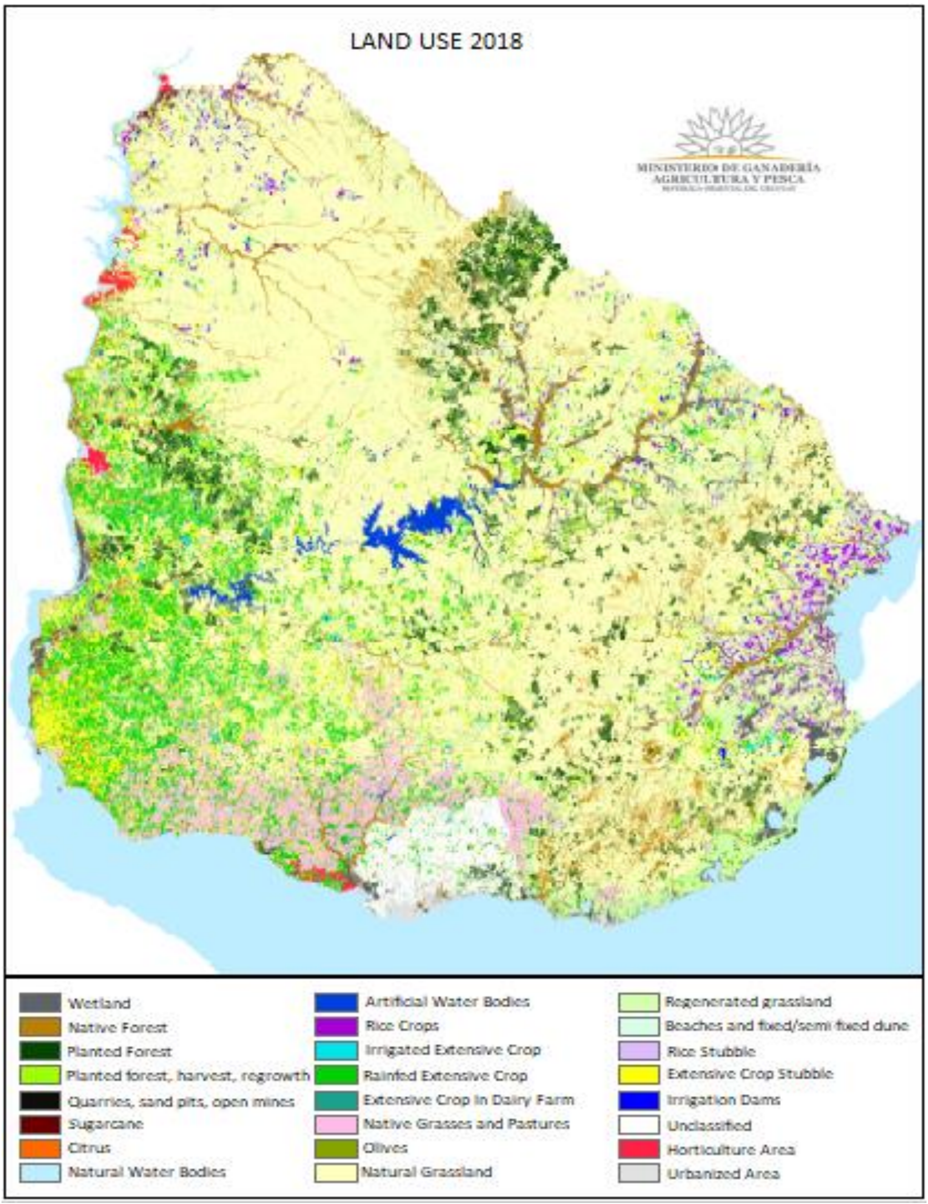


Figure 16. Land Use

Source: MGAP (2018)

The baseline of the actual land use for the dairy sector is presented in figure 17. It includes the spatial allocation of the dairy farms in Uruguay and the percentage of surface dedicated to dairy production. This baseline is very useful to understand if the Land Suitability Analysis is correct or not.

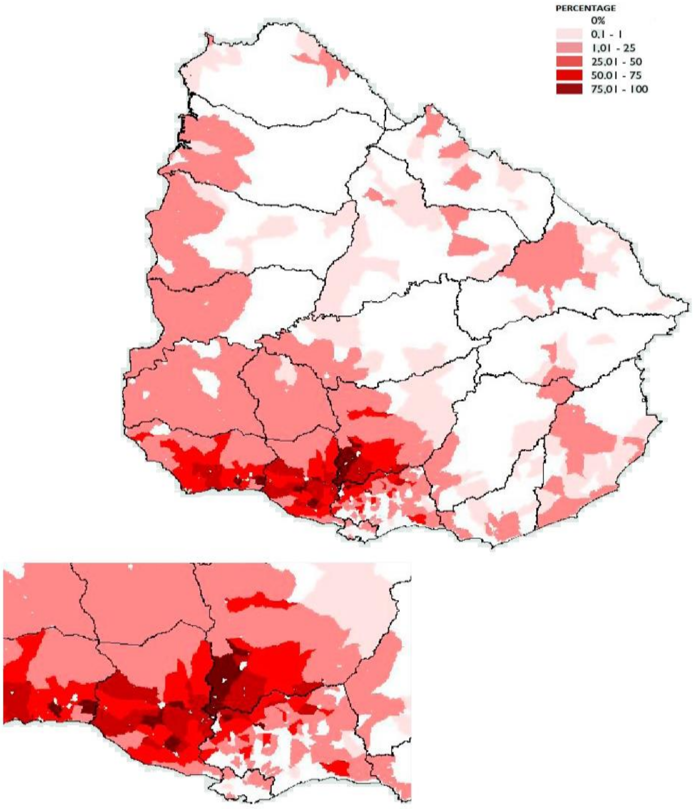


Figure 17. Dairy production by region

Source: Direction of Agriculture Statistics Research (2011)

A map of the spatial distribution of dairy farmers was also included as another input to understanding the special distribution of the sector –see figure 18. Each red dot on the map represents at least two dairy farms in the region. As depicted in the maps, the southwest region concentrates the majority of farms, including the departments of Soriano, Colonia, San Jose, Florida, Flores, and Canelones. There are also other relevant dairy regions, that are often close to the main cities, due to the importance of the proximity to urban areas. Despite the low level of production compared to the southwest, these minor dairy regions are essential to guarantee the supply of dairy products to the related urban areas.

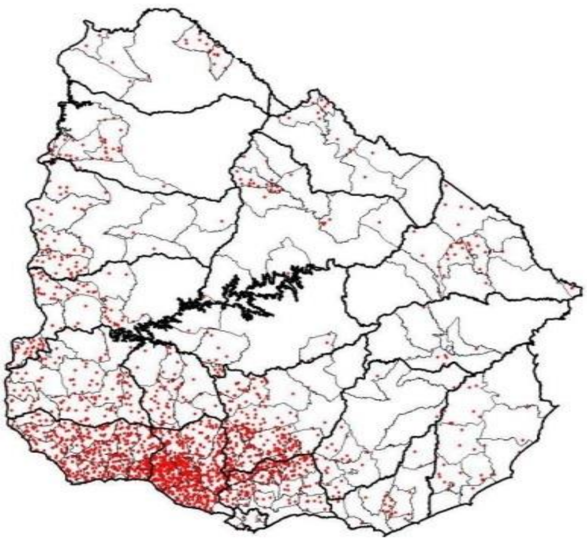


Figure 18. Dairy farmers' spatial allocation

Source: Direction of Agriculture Statistics (2011)

4.3. Land Suitability Analysis

4.3.1. Baseline Scenario

The baseline scenario for the historical climate data is the 1960- 1990 series. This is the starting point for the Land Suitability Analysis. Despite not being a current baseline, it continues to be used to be in line with global standards for historical baselines in general. Changes in Land Suitability are analyzed by changing the historical climate data for projected climate data while leaving the other factors constant.

4.3.2. Projected Scenario

Both the baseline and projected climate data were obtained from WorldClim´s website. The Representative Concentration Pathways (RCP) 8.5 (Community Climate System Model, CCSM4) model was considered to represent a high CO_2 emissions scenario (IPCC, 2014). These projections estimate that under the current trend, there will be a considerable variation in average mean temperature and precipitation rates if the current GHGs emissions are not considerably reduced. The RCP 8.5 was selected because it is intended to understand the impacts of the worst-case scenario, to generate possible adaptation and mitigation measures if it occurs -figure 19-. Hopefully, the actual trend is diminished in the future, reducing the impacts of climate change and its variations on the agricultural sector.

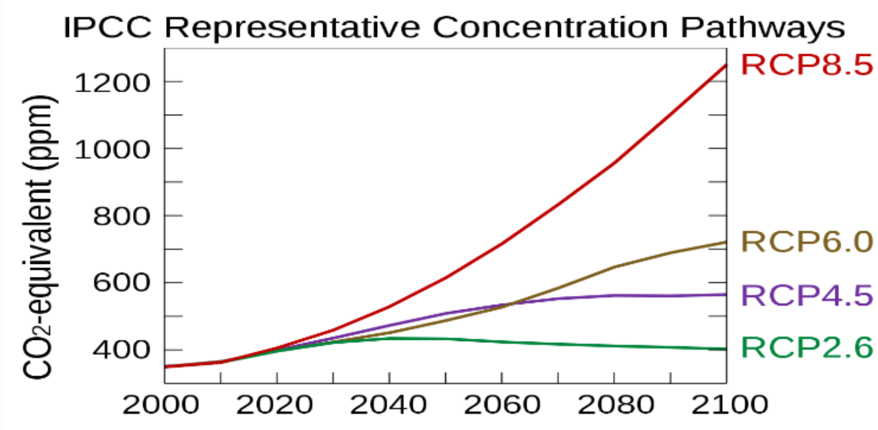
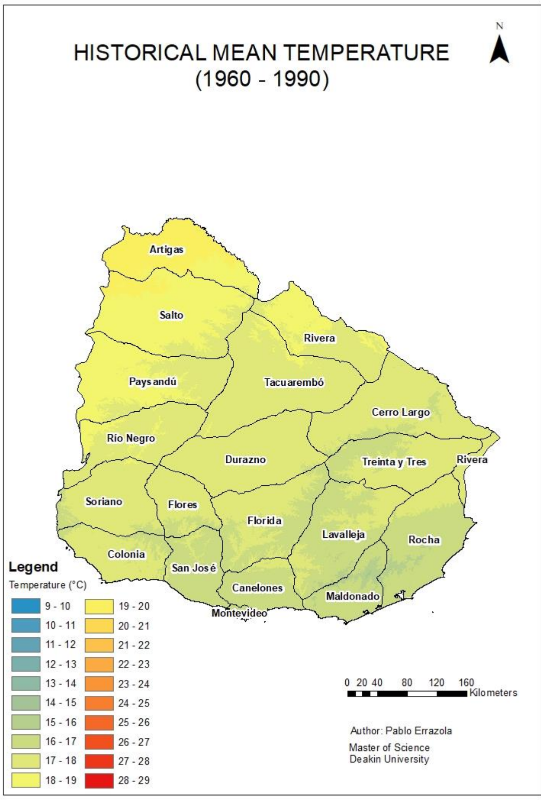
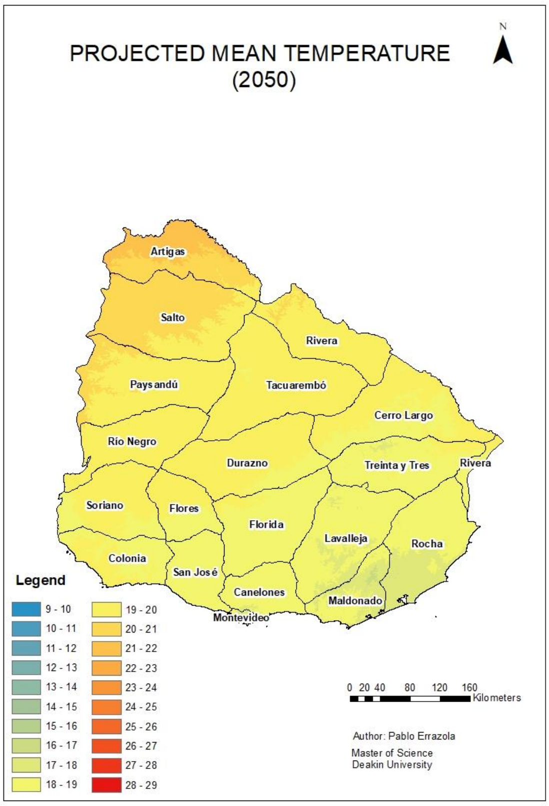


Figure 19. Representative Concentration Pathways

Source: IPCC (2014)

Under this scenario, as depicted in figures 20 and 21, an average rise of almost 2°C is expected for 2050. This phenomenon will occur within a range of 1.8°C and 2.2°C across Uruguay, compared to the baseline scenario. In particular, the northwest of the country shows the greater temperature surges.

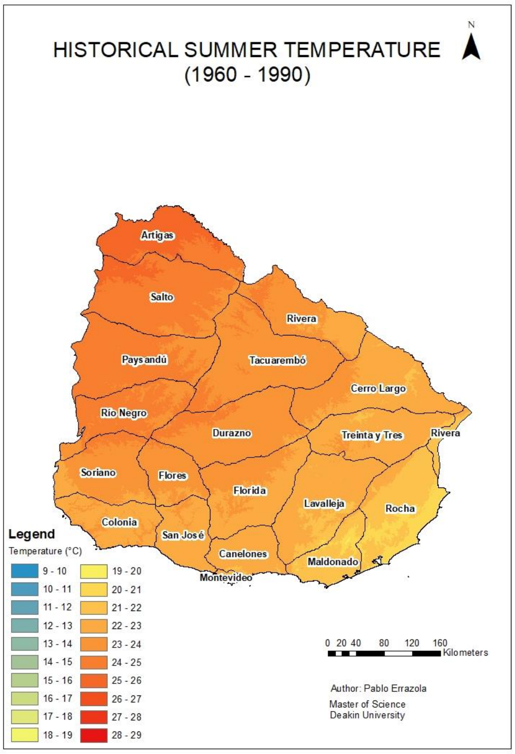




Figures 20. And 21. Historical and Projected Mean Temperature

Source: Elaborated by the Author

When analyzing the temperature by season, there is a clear increase in the projected mean temperature in the north and northwest of the country. There is also an increase in the south, however, this effect is considerably less intense, due to the effect of the proximity to the ocean. According to Agrawala et al. (2004), the ocean has the effect of tempering warm temperatures, reducing the impact of global warming.


HISTORICAL SUMMER TEMPERATURE
(1960 - 1990)
N
Artigas
Salto
Rivera
Paysandú
Tacuarembó
Cerro Largo
Río Negro
Durazno
Treinta y Tres
Rivera
Soriano
Flores
Florida
Lavalleja
Rocha
Colonia
San José
Canelones
Maldonado
Montevideo
Legend
Temperature (°C)
9 - 10
10 - 11
11 - 12
12 - 13
13 - 14
14 - 15
15 - 16
16 - 17
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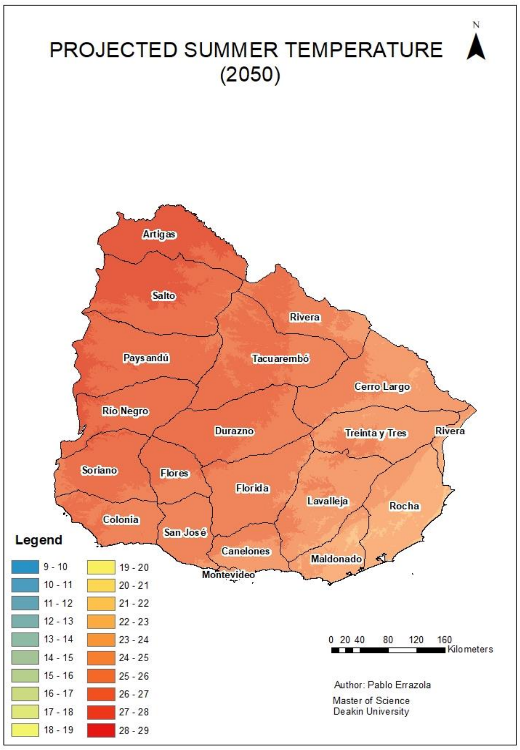
0 20 40 80 120 160
Kilometers
Author: Pablo Errazola
Master of Science
Deakin University


PROJECTED SUMMER TEMPERATURE
(2050)
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Artigas
Salto
Rivera
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Tacuarembó
Cerro Largo
Río Negro
Durazno
Treinta y Tres
Rivera
Soriano
Flores
Florida
Lavalleja
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Kilometers
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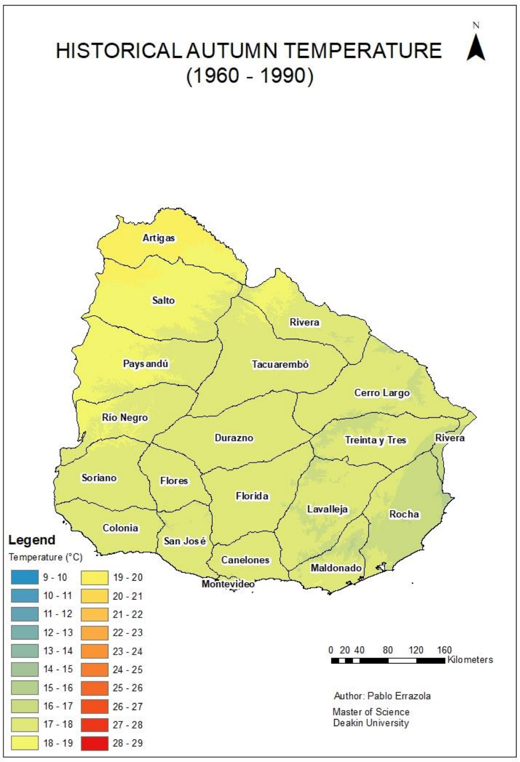
HISTORICAL AUTUMN TEMPERATURE
(1960 - 1990)
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Artigas
Salto
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Tacuarembó
Cerro Largo
Río Negro
Durazno
Treinta y Tres
Rivera
Soriano
Flores
Florida
Lavalleja
Rocha
Colonia
San José
Canelones
Maldonado
Montevideo
Legend
Temperature (°C)
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Kilometers
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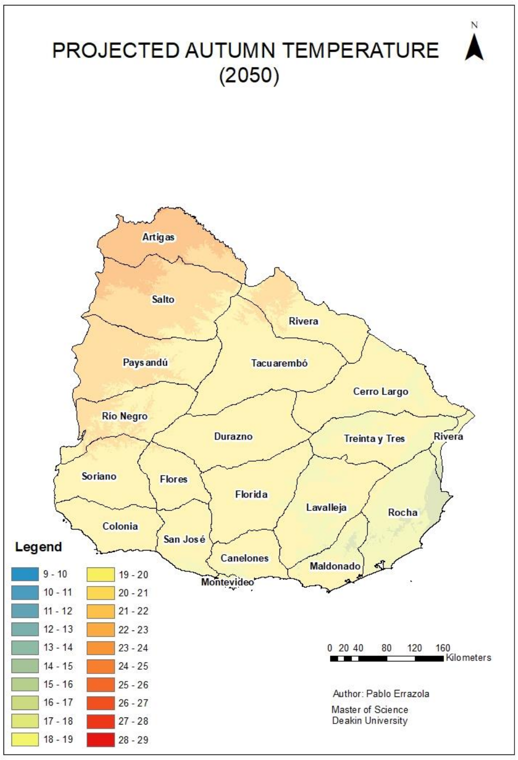
PROJECTED AUTUMN TEMPERATURE
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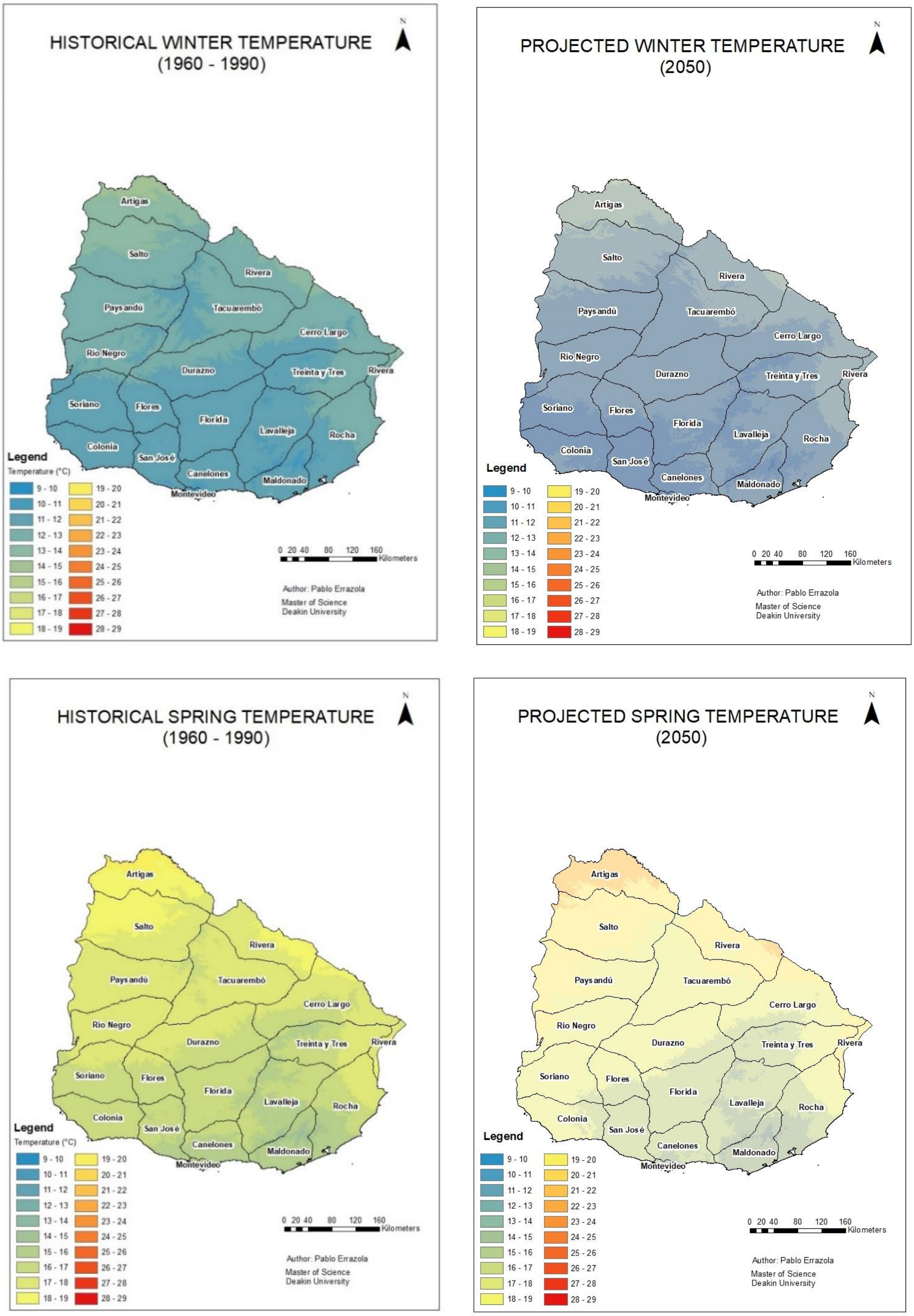
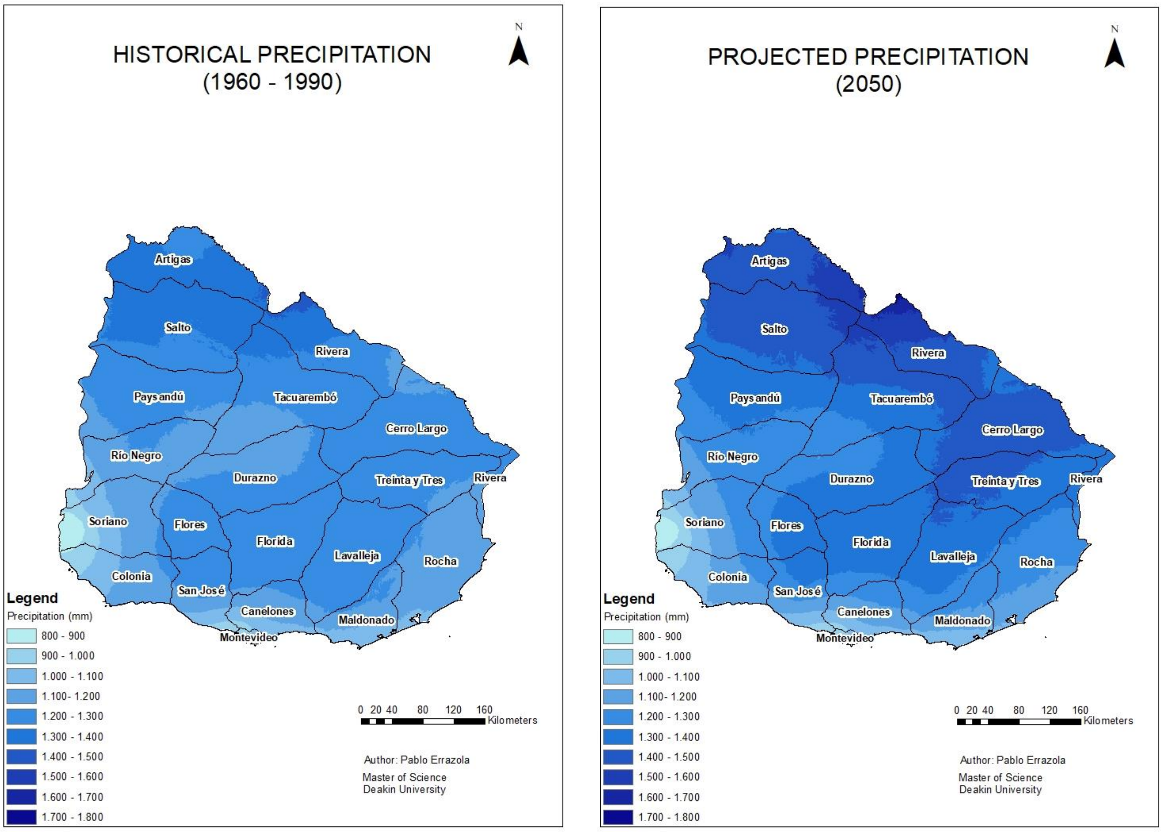
Kilometers
Author: Pablo Errazola
Master of Science
Deakin University



Figures 22 to 29. Historical and Projected Mean Temperature by season

Source: Elaborated by the Author

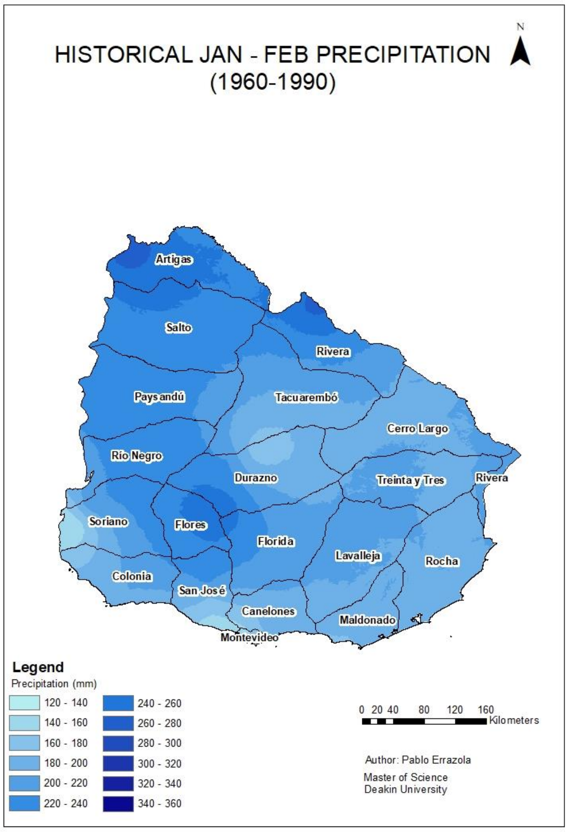
In terms of rainfall, despite maintaining similar distribution patterns, the cumulative annual average will increase by 200 mm. The range of this variation will be between 170 mm and 230 mm in different areas of the country. In this case, the northeast is the area where the greatest change will occur, while the southwest is not expected to receive considerable additional precipitations. This difference could affect pasture growth with variable degrees.

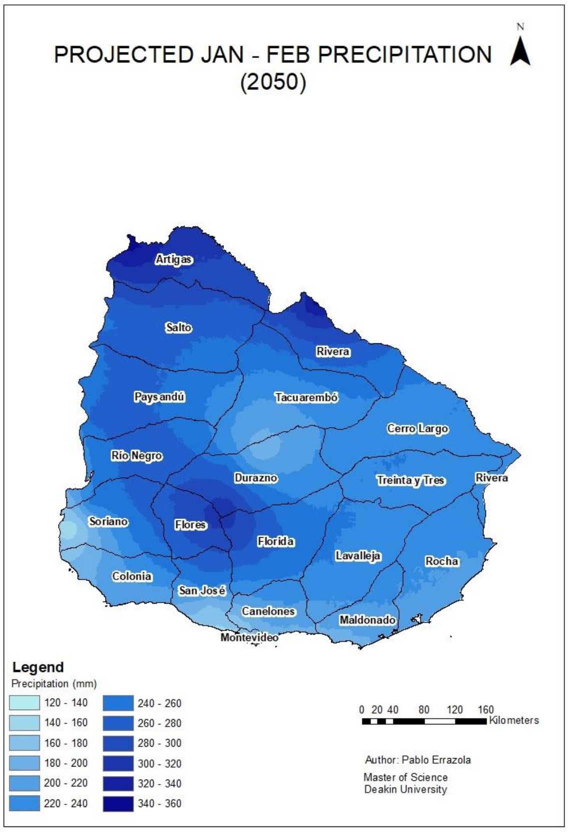


Figures 30. And 31. Historical and Projected Annual Precipitation

Source: Elaborated by the Author

When analyzing the precipitation during January and February, the increments are smaller but the pattern remains very similar. There is also an area in the center of the country that will accumulate more rainfall during this period of the year. This period is very important for pasture growth because it is when the evapotranspiration is higher due to higher temperatures and radiation. For instance, Lucerne has shown its maximum growth rate in Uruguay during summer, when water is not limiting the potential. The solar radiation was not included in this analysis as it is considered to remain constant over the period of study.





Figures 32. And 33. Historical and Projected Summer Precipitation

Source: Elaborated by the Author

The most important findings for soil data were included in this chapter. Firstly, a topographic map was used for the model, to determine the suitability of the different crops. Secondly, the CONEAT data was extracted from the Uruguayan Ministry for Agriculture, Livestock, and Fishery. This data includes homogeneous areas defined by their production capacity. Organic content, water holding capacity, soil classes, PH, and fertility are some of the key elements considered when categorizing the CONEAT groups. In the case of this thesis, the model used the information contained in these groups as the input for the land suitability analysis. The collaboration of experts in the field was extremely valuable (appendix VI). Using this contribution from the experts, the CONEAT groups were then reclassified according to their suitability for the different pastures. The landscape slope and aspect reclassification maps for both pastures were included in appendices (appendix VII).

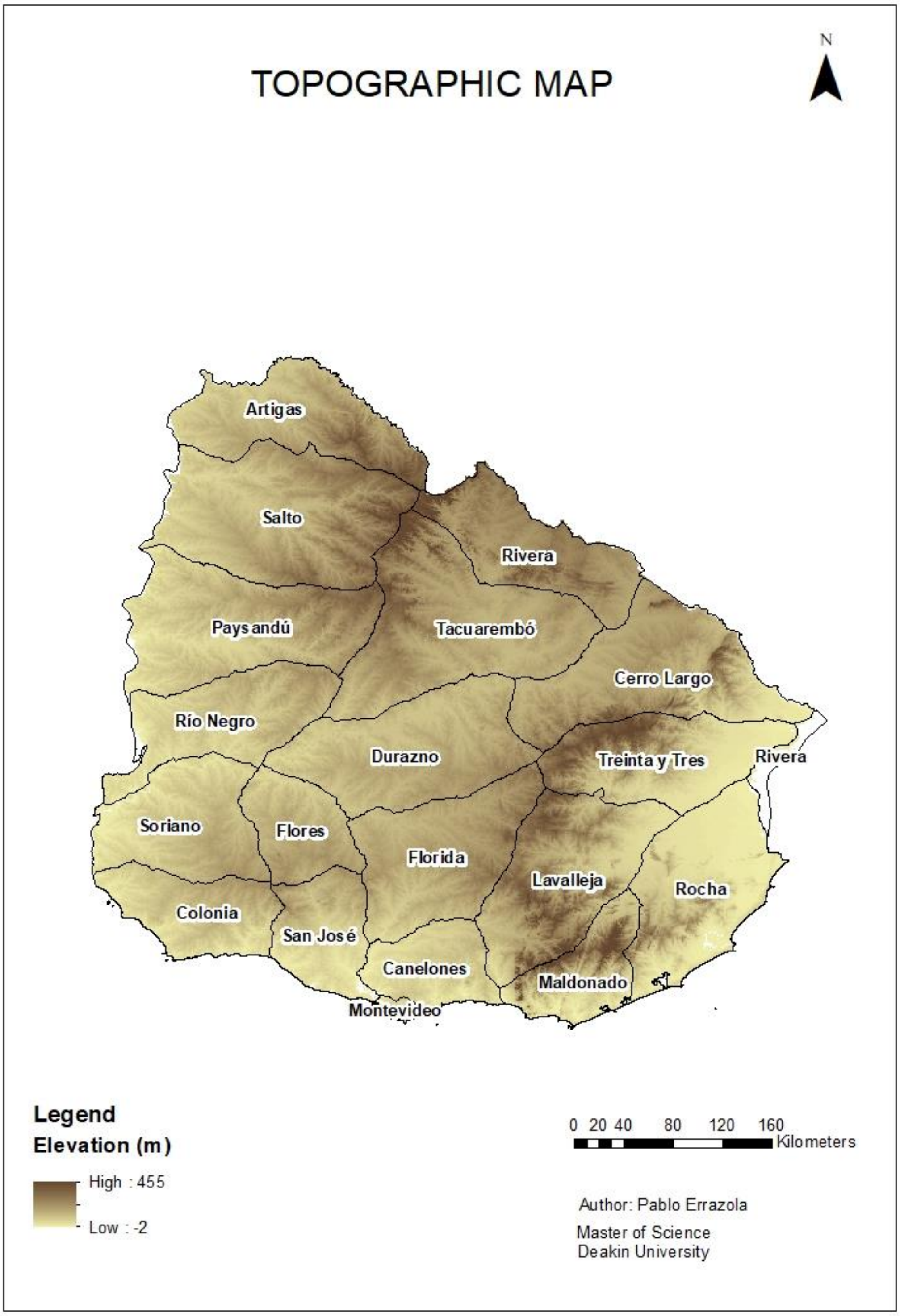


Figure 34. Topographic map

Source: Elaborated by the Author

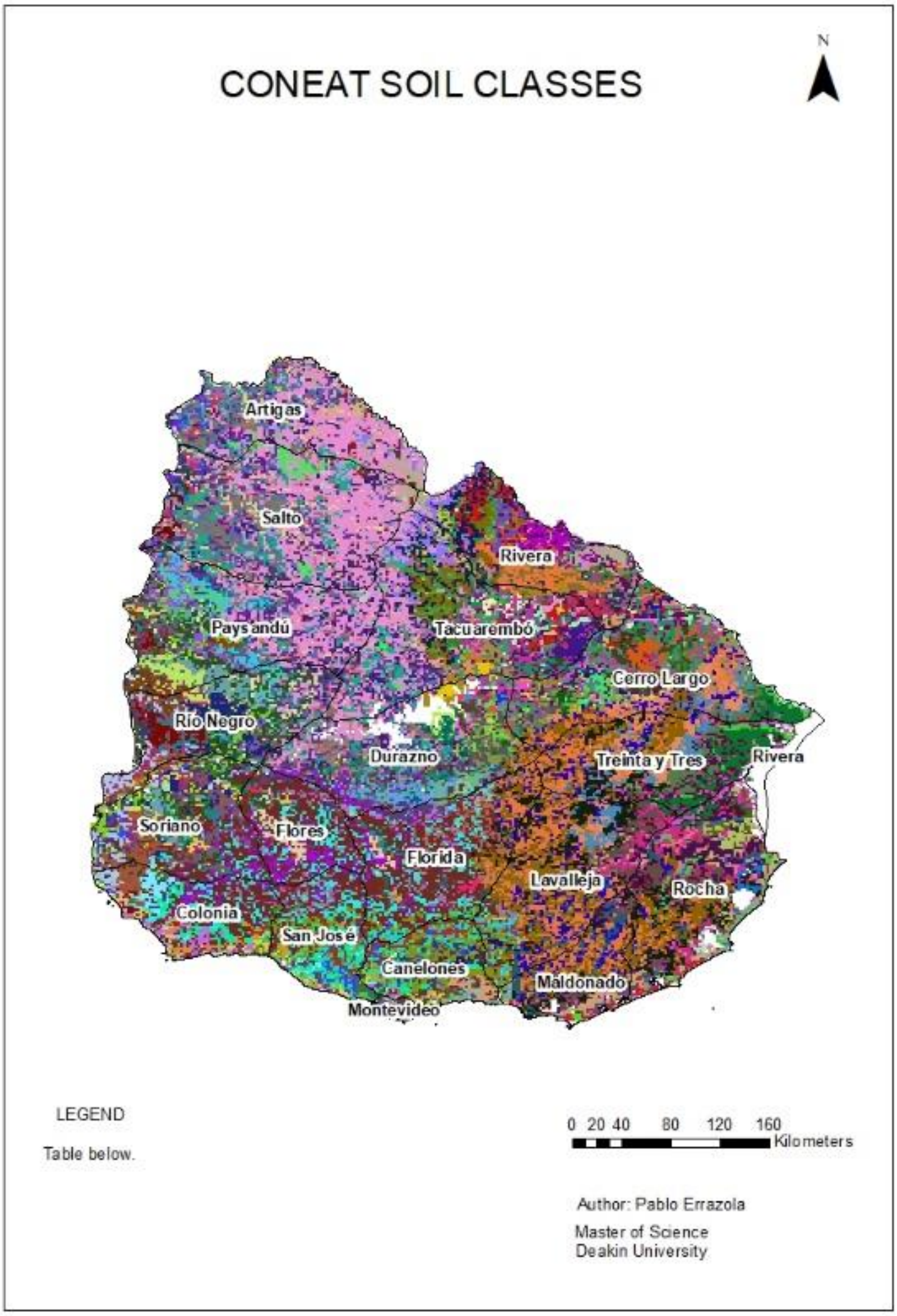


Figure 35. CONEAT map

Source: Elaborated by the Author

The CONEAT classes were then reclassified from 1 to 10 according to their suitability for growing Lucerne. As described, expert knowledge was fundamental to the range of the different soil classes. The resulting map shows the soil suitability for Lucerne in Uruguay –see figure 36.

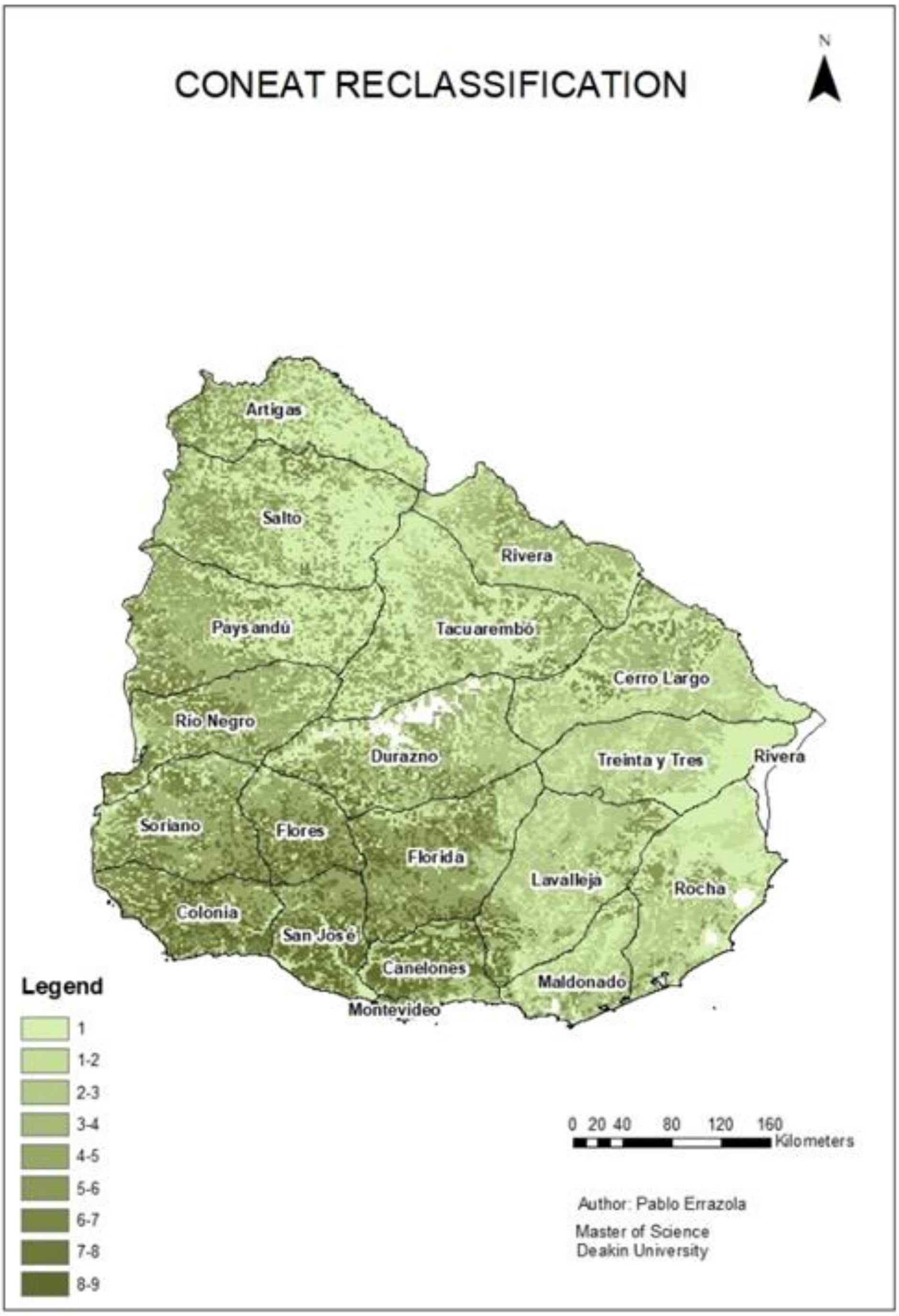


Figure 36. Lucerne CONEAT Soils reclassification

Source: Elaborated by the Author

After integrating the above information on the Lucerne model and applying the Analytical Hierarchy Process (see AHP in Appendix III) and multi-criteria analysis; the land suitability analysis (LSA) was conducted. The historical LSA uses the baseline climate scenario whereas the Projected LSA uses the 2050 climate scenario, resulting on the following maps –see figures 37 and 38.

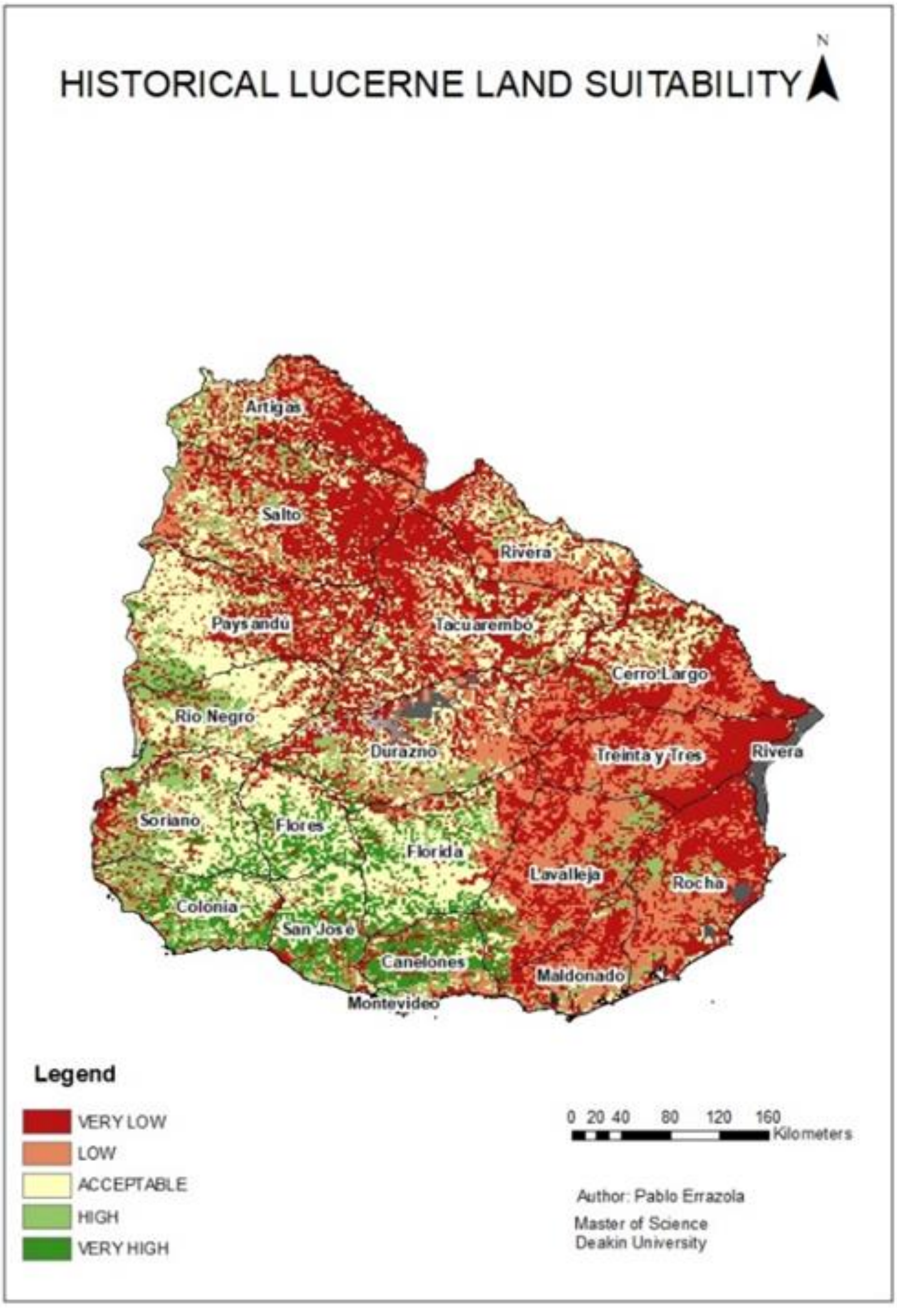


Figure 37. Historical Lucerne Land Suitability Analysis

Source: Elaborated by the Author

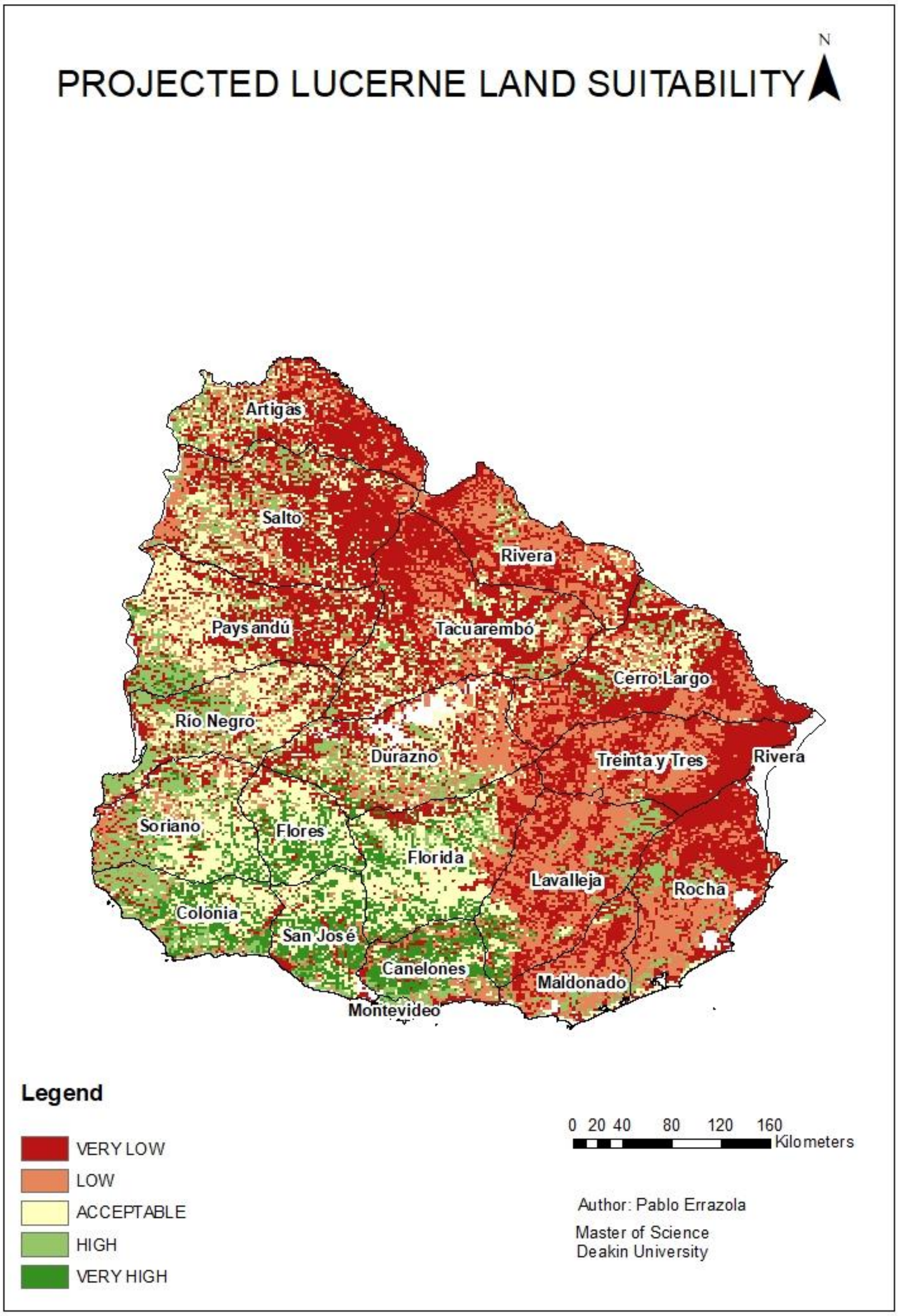


Figure 38. Projected Lucerne Land Suitability Analysis

Source: Elaborated by the Author

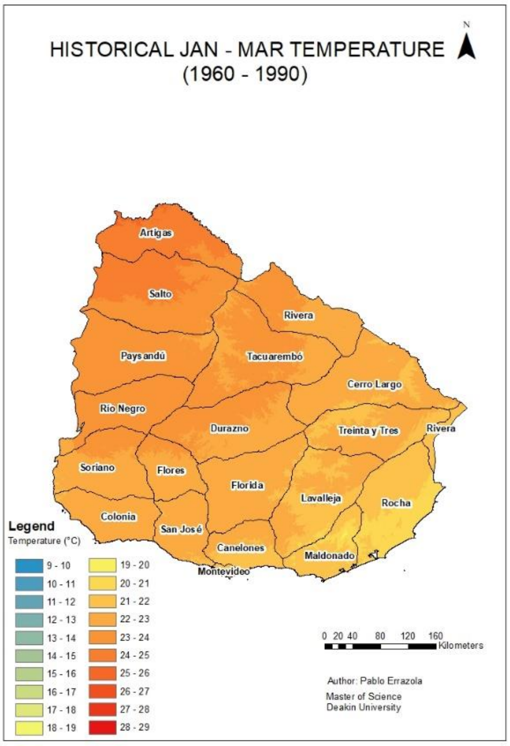
From the maps above, the difference in percentage for each class between the baseline and the projected LSA index value was calculated. It is important to understand that the different classes of suitability include a range of values among them (for instance: very low suitability includes values ≤2). Table 8 describes this variation per region and value.

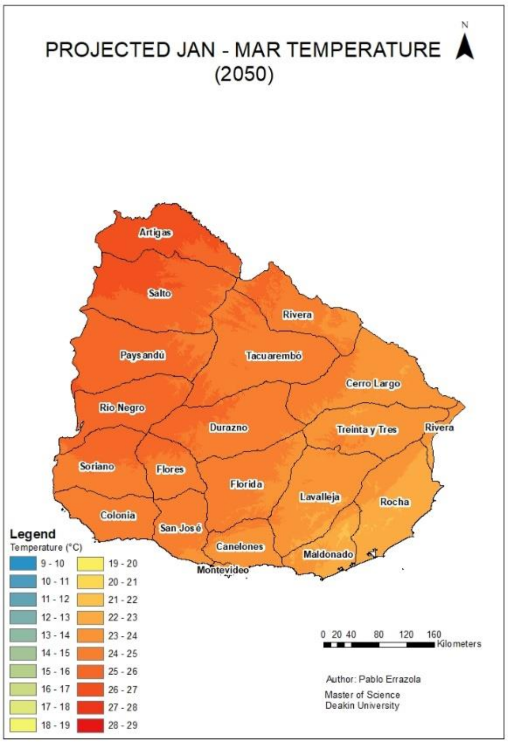
Table 8. Variation in LSA index values per department

DEPARTMENT	VALUE_2	VALUE_3	VALUE_4	VALUE_5	VALUE_6	VALUE_7	VALUE_8	VALUE_9
Artigas	9	-34	0	8	-11	-1	0	0
Canelones	-1080	25	0	-18	22	-10	-41	72
Cerro Largo	48	-50	1	8	-89	0	0	0
Colonia	-139	21	-21	-29	8	-3	-45	39
Durazno	19	-9	0	4	-5	-2	2	-3
Flores	13	-4	0	13	-11	0	3	-20
Florida	14	-2	0	1	0	0	-2	10
Lavalleja	-16	3	0	-8	2	0	-6	24
Maldonado	-442	27	0	-3	1	0	-100	100
Montevideo	-150	100	0	-250	13	-12	63	0
Paysandú	64	-64	-1	39	-80	0	0	0
Río Negro	65	-22	0	16	-26	0	0	0
Rivera	40	-42	45	-24	-71	0	0	0
Rocha	-157	19	0	0	0	0	0	0
Salto	34	-146	1	23	-27	-1	0	0
San José	-300	41	-14	-2	4	-2	-40	64
Soriano	-29	8	-138	14	-12	-2	16	-88
Tacuarembó	49	-68	34	0	-31	0	0	0
Treinta y Tres	25	-10	0	0	0	0	0	0

Source: Elaborated by the Author

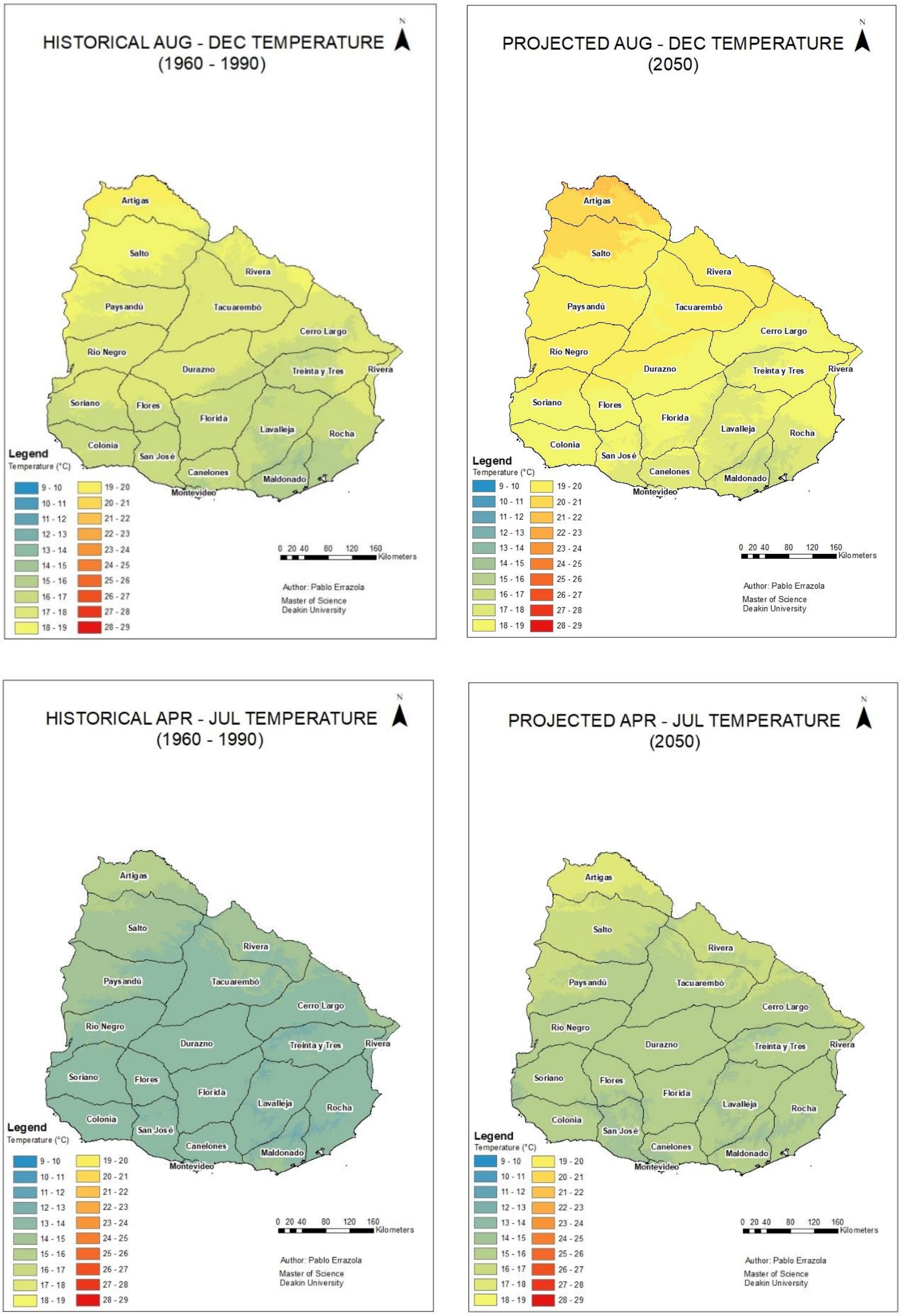
In the case of Ryegrass, the mean temperatures were divided differently regarding the most important months for the low and high pasture growing seasons. This occurs between January – March (for biannual varieties) and August – December respectively. The period between April and July is considered the Autumn break (implantation on April for annual varieties). In this sense, the historical and projected mean temperature for these periods is presented. A temperature increase is expected for the 3 seasons in the order of 2°C according to the high emissions scenario (RCP 8.5.).





Figures 39. And 40. Historical and Projected Mean January – March Temperature

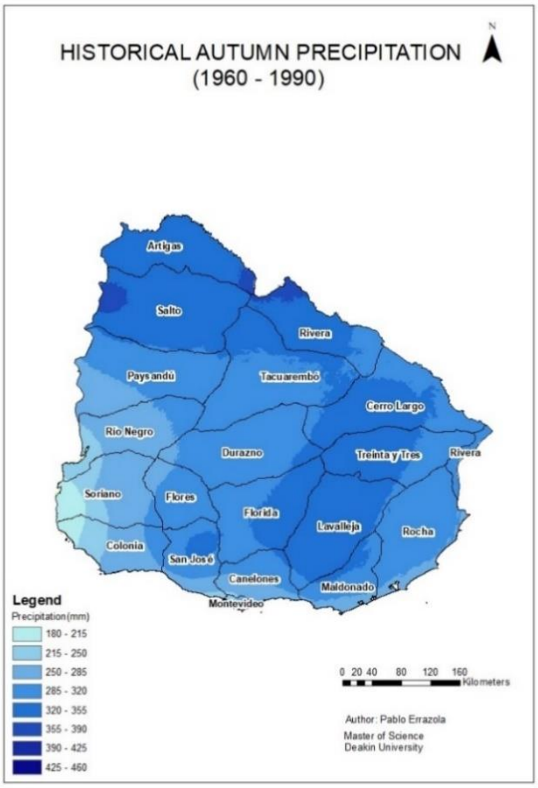
Source: Elaborated by the Author

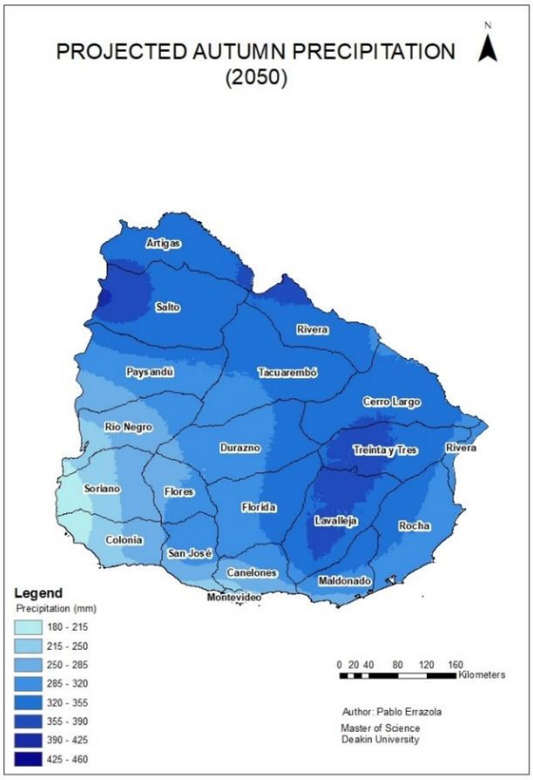


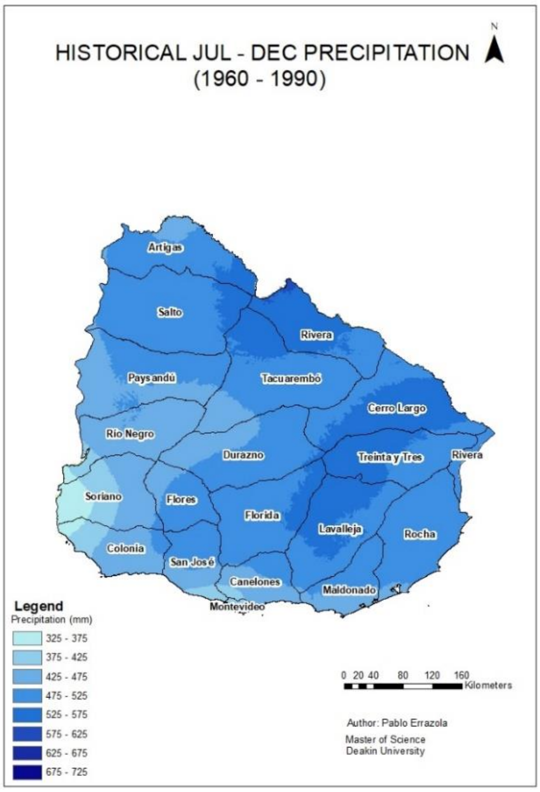
Figures 41. to 44. Historical and Projected Mean Aug - Dec / Apr - Jul Temperature

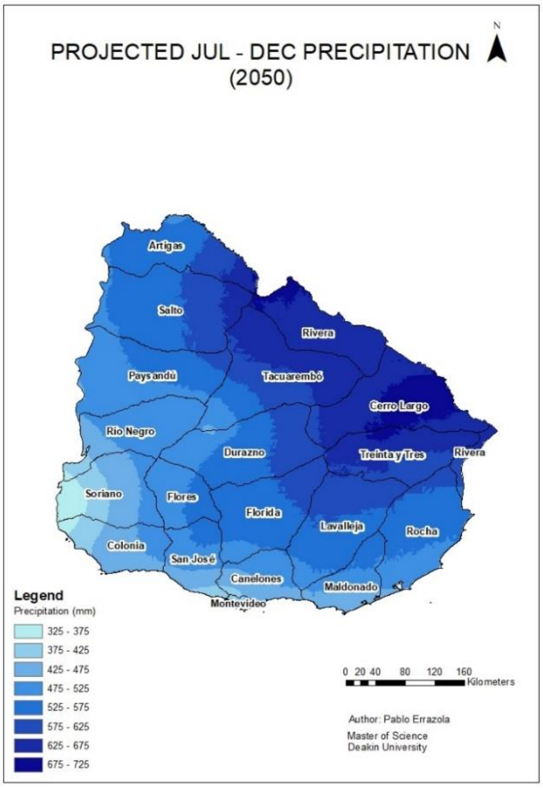
Source: Elaborated by the Author

In the case of the rainfall, the model considers the annual precipitations (already presented for Lucerne) and the Autumn break, and High growth seasons. According to the model, the most relevant season in terms of water availability is Spring, representing 50% of the model input.









Figures 45. to 48. Historical and Projected Autumn and July - December Precipitation.

Source: Elaborated by the Author

The model also uses soil data as an input, considering topographic and soil maps. As per the Lucerne LSA, the CONEAT classes were also reclassified from 1 to 10 according to their suitability for growing Ryegrass (AHP fin in appendix III). Experts´ knowledge was also fundamental to the range of the different soil classes. The resulting map shows the soil suitability for Ryegrass in Uruguay.

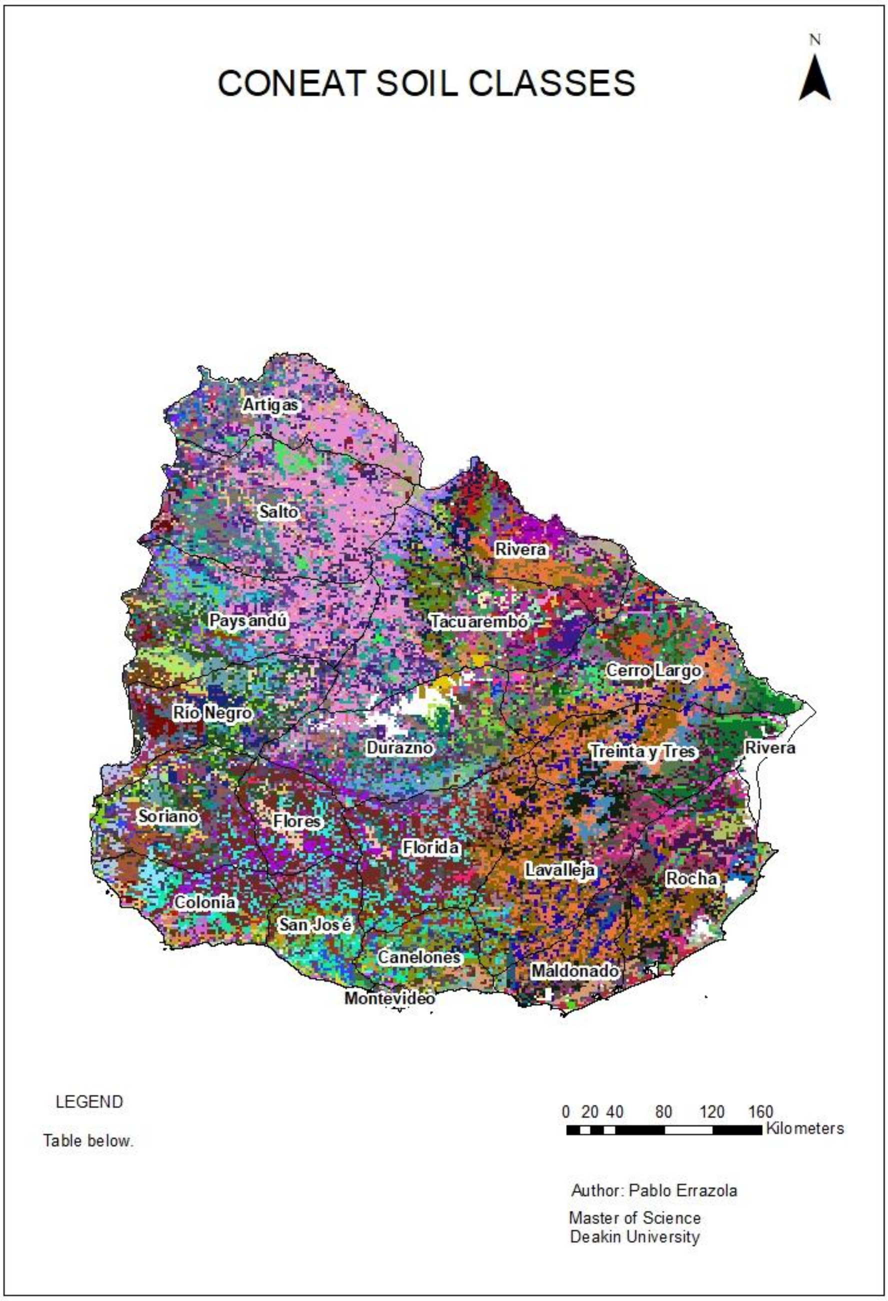


Figure 49. CONEAT soil classes

Source: Elaborated by the Author

There is a clear difference with the Soil Suitability map for Lucerne, showing the different adaptations for the species. Ryegrass has fewer fertility requirements, making it able to grow in more restricted areas such as the northeast of Uruguay. This difference is also translated into the Land Suitability Map, showing a wide range of soils where Ryegrass can thrive. Furthermore, the impacts of receiving more precipitations and warmer weather, show that Ryegrass could be also grown with high suitability in a vast area of Uruguay.

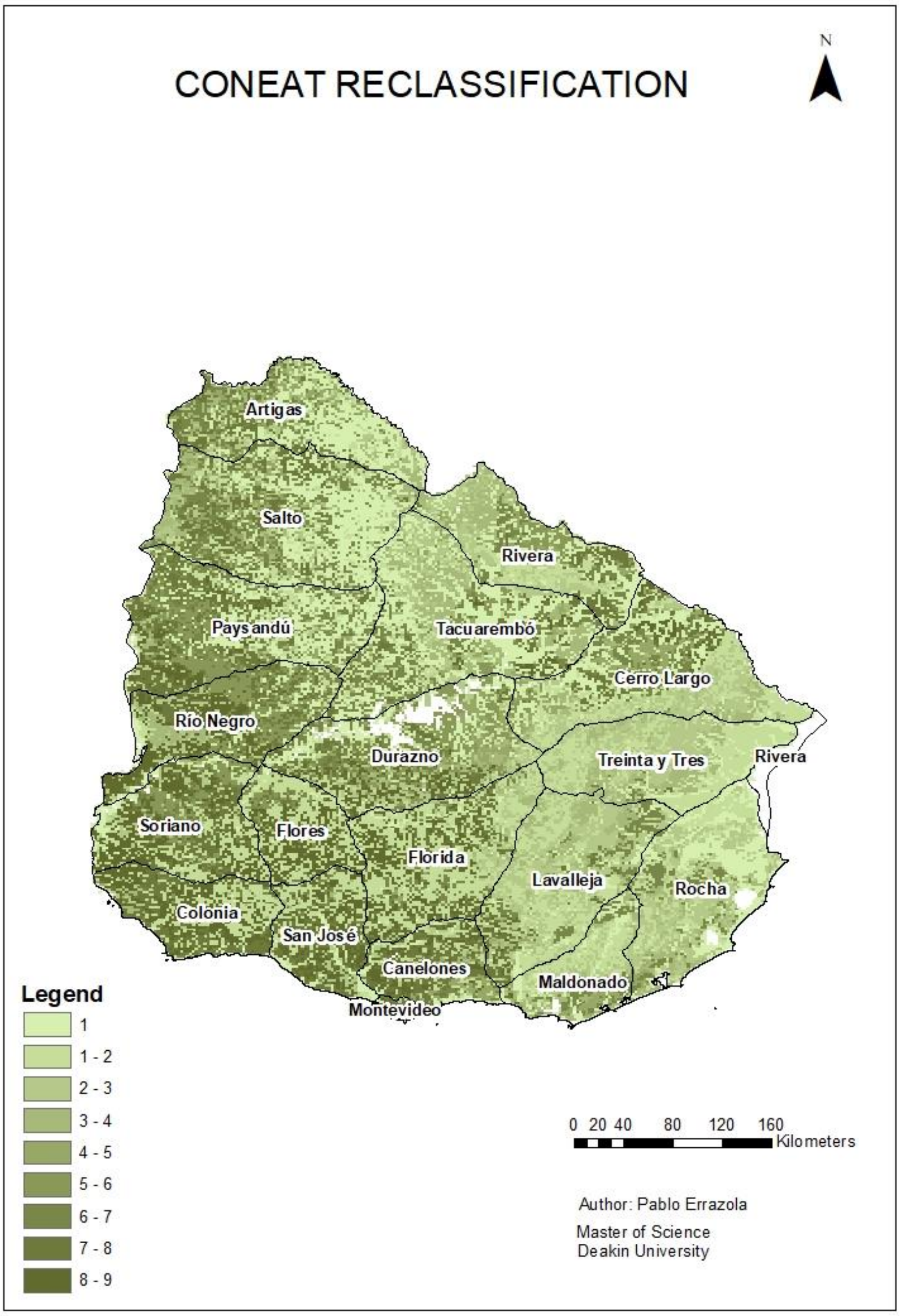


Figure 50. Ryegrass CONEAT Soils reclassification

Source: Elaborated by the Author

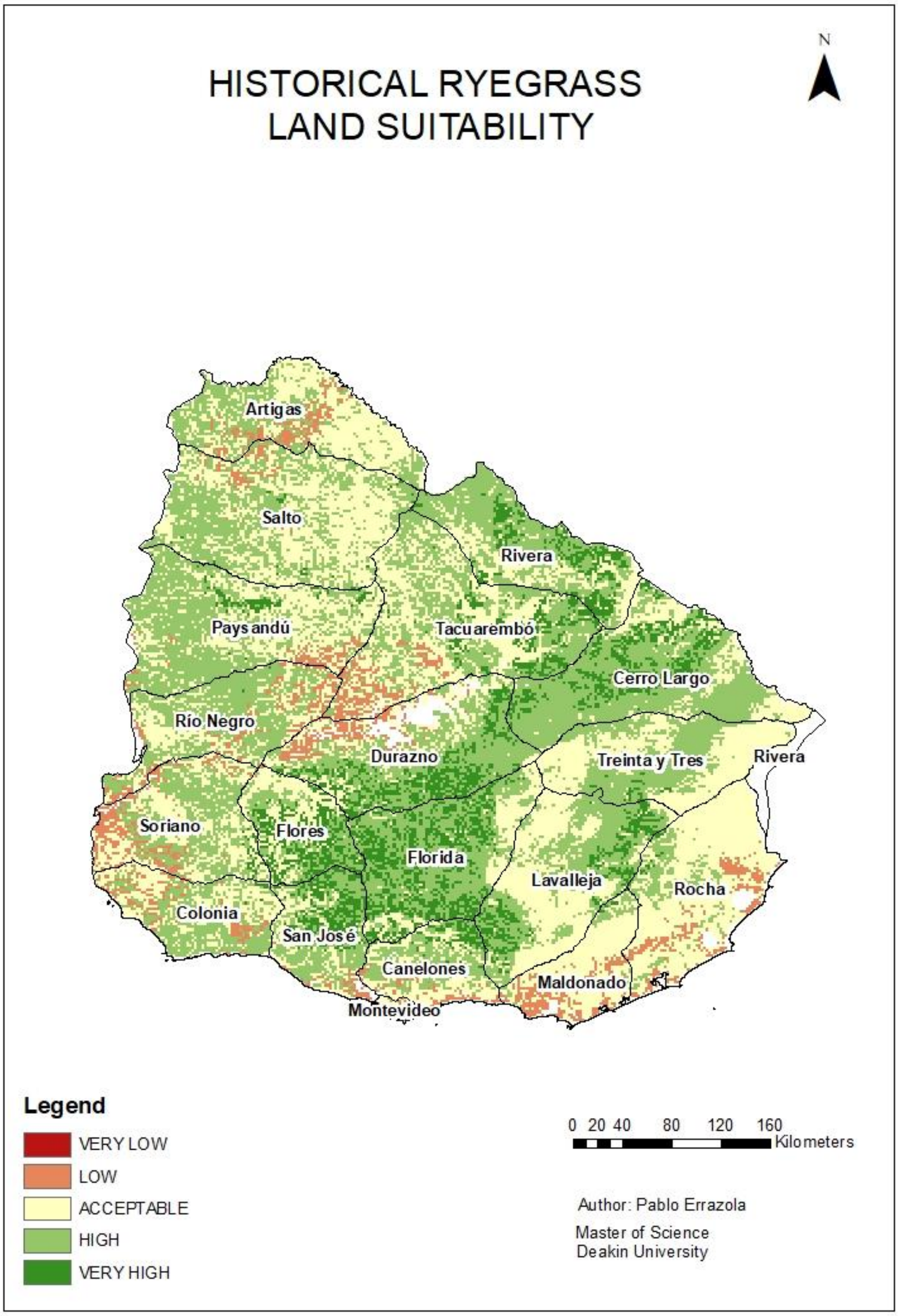


Figure 51. Historical Ryegrass Land Suitability Analysis

Source: Elaborated by the Author

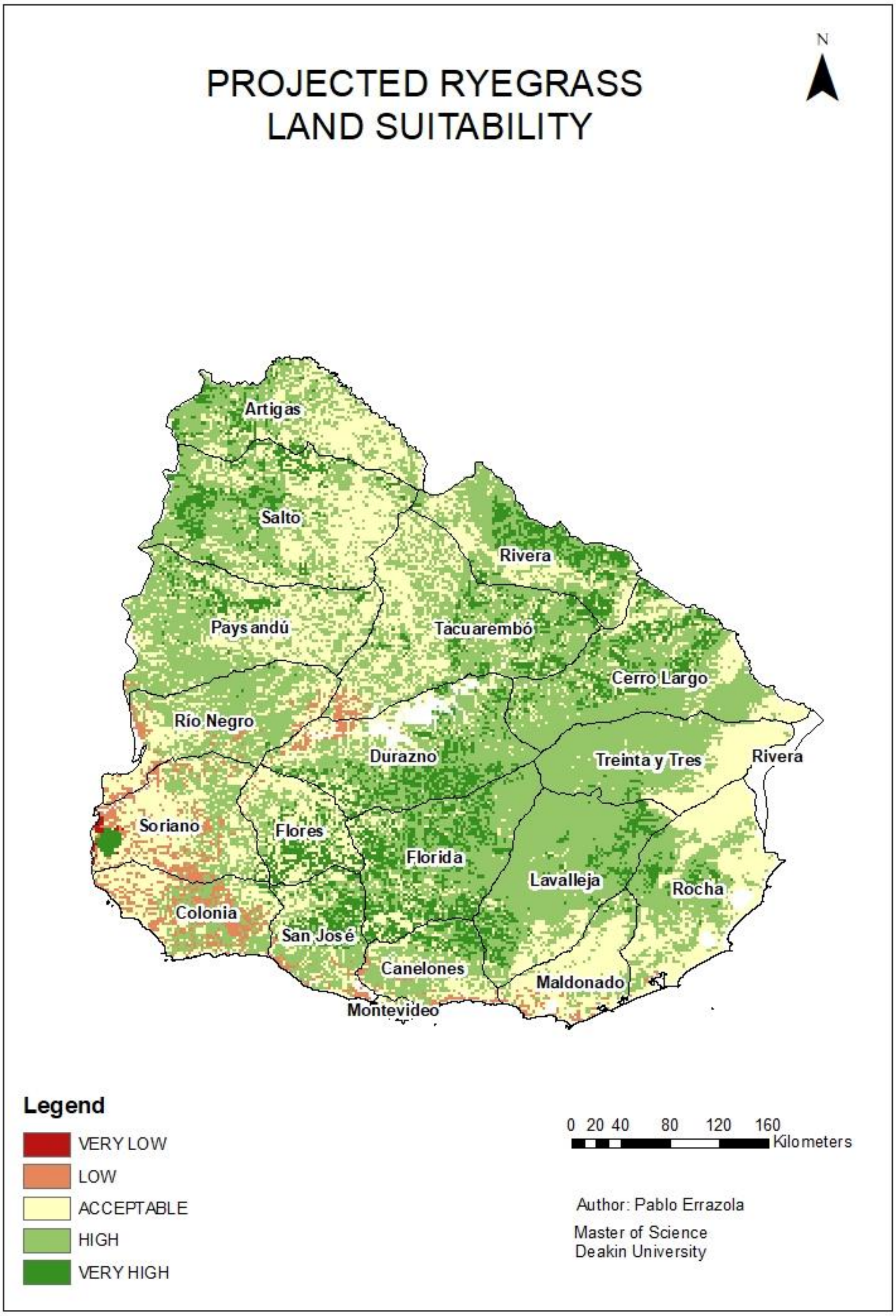


Figure 52. Projected Ryegrass Land Suitability Analysis

Source: Elaborated by the Author

As for the case of Lucerne, the difference between the historical and project LSA index was calculated for Ryegrass. Table n°9 shows the variations in percentage for each department in Uruguay. Again, each LSA class includes several values on the table.

Table 9. Variation in LSA index values per department

DEPARTMENT	VALUE_3	VALUE_4	VALUE_5	VALUE_6	VALUE_7	VALUE_8	VALUE_9
Artigas	0	0	-2186	40	39	100	0
Canelones	-100	-28	-9	-7	5	36	0
Cerro Largo	0	0	-17	-4	10	-6	0
Colonia	100	74	-32	20	-127	71	0
Durazno	0	-149	-12	-15	29	-27	100
Flores	0	0	11	6	30	-77	0
Florida	0	0	-90	-31	51	-3	14
Lavalleja	0	0	-1900	-23	59	11	0
Maldonado	0	-359	-103	69	42	73	0
Montevideo	0	-33	-125	37	100	0	0
Paysandú	0	-1220	-42	8	16	26	0
Río Negro	100	-2	-7	-30	24	100	0
Rivera	0	0	-13	14	-33	6	0
Rocha	0	0	-284	52	64	77	0
Salto	0	0	-764	22	16	94	0
San José	0	8	6	1	1	-9	0
Soriano	58	34	21	-8	-120	-475	0
Tacuarembó	0	-187	-40	0	29	-2	0
Treinta y Tres	0	0	-173	-15	41	-7	0

CHAPTER 5. DISCUSSION

As previously described, the main driver of change analyzed for the Uruguayan dairy system is climate change. In this chapter, the main results of the application of Land Suitability Analysis (LSA) and findings are discussed. The analysis is focused on the variations of the LSA per region for each crop – Lucerne, and Ryegrass - to understand the possible impacts of climate change and its variability on the dairy sector over the next thirty years. The application of CSA practices and the possibility of measuring the outcomes are also analyzed.

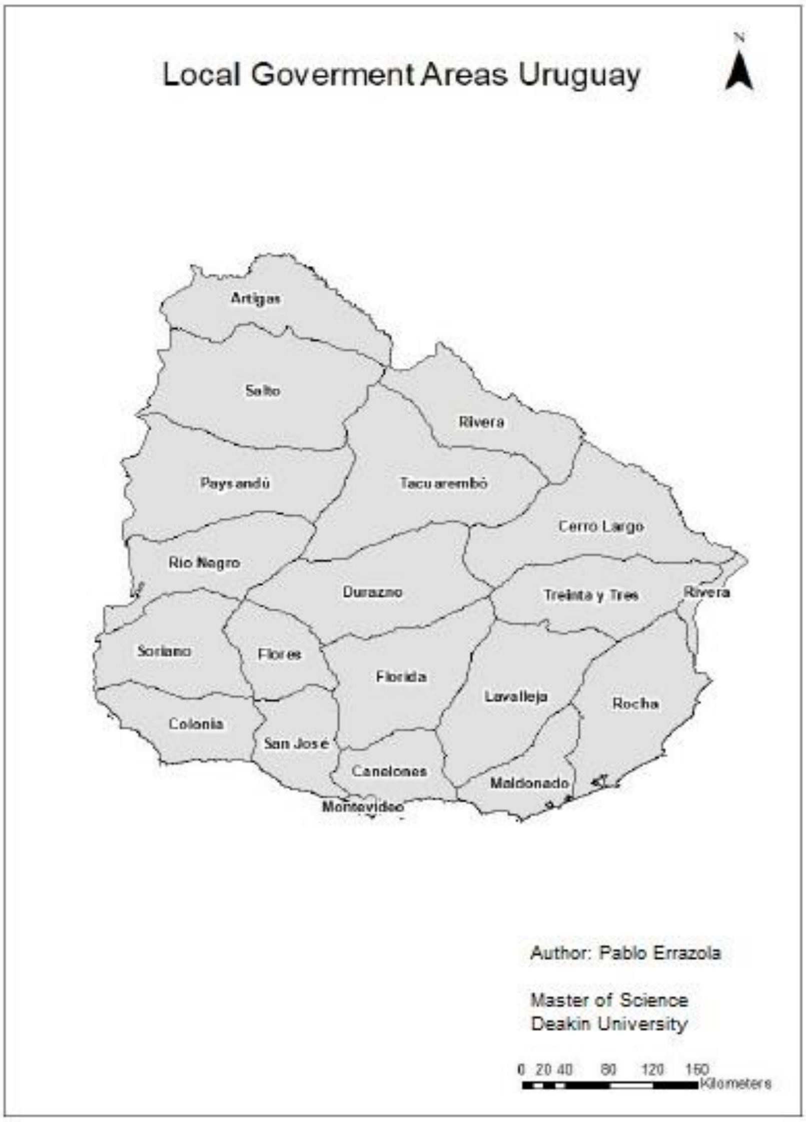


Figure 53. Local Government Areas in Uruguay
Source: Elaborated by the Author

5.1. Lucerne

When comparing the historical LSA (1960-1990) for Lucerne with the projected LSA (2050), it is important to describe the main changes. The annual rainfall is expected to rise 200 mm per year across the country, with a monthly increase of approximately 70 mm/month. Yet, the main factor affecting Lucerne LSA would be an increase in the mean temperature that has an important weight in the model, showing the impacts of global warming on this pasture. Reflecting the combined effects of temperature and rainfall on Lucerne, the average suitability value for Uruguay shows a slight decrease from 5,21 to 5,19 (out of a total of 9,00), demonstrating the negative impacts of climate change on the crop. However, as depicted in Figure 54 , this variation will be heterogeneous around the country. Luckily, some of the main dairy departments in Uruguay, such as Colonia, San José, Soriano, or Canelones (located in the southwest), will experience an increase in the suitability for growing Lucerne. On the other hand, the departments located in the northeast and northwest, such as Artigas, Rivera, Paysandú, and Salto, are likely to decrease their land suitability for this pasture, affected by the increasing mean temperature and precipitation rates. Interestingly, the projected suitability for the center of the country (departments of Flores, Florida, and Durazno) will remain almost equal to the historical projections. Another variation that is interesting to analyze is the land suitability for the departments of Maldonado and Rocha. Two non-traditional areas for dairy production will experience an increase in their capacity for growing Lucerne.

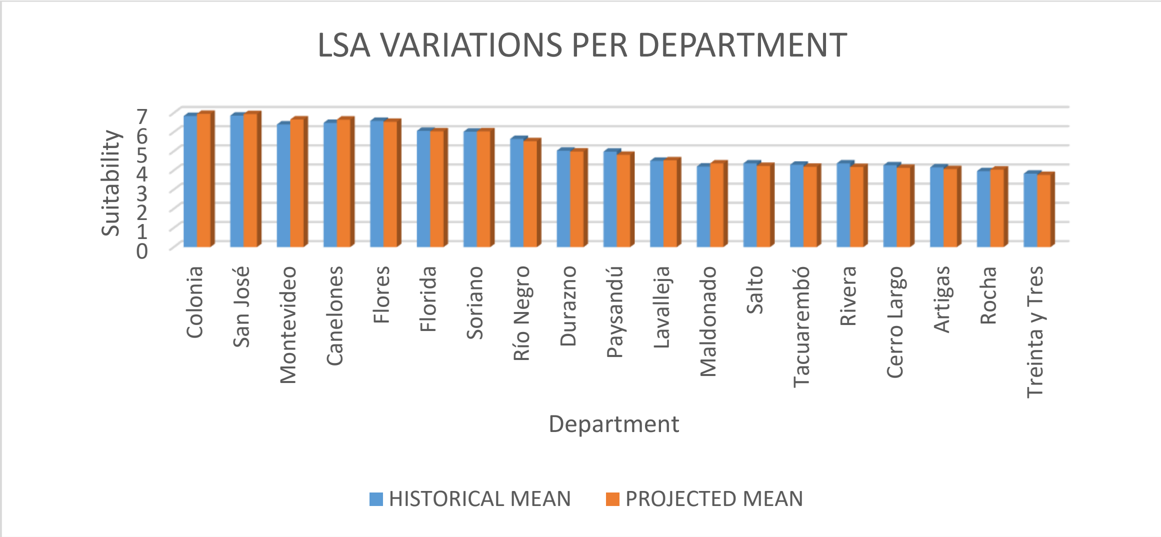


Figure 54. Lucerne Land Suitability Variations per Department

Source: Elaborated by the Author

Understanding these results is extremely important for decision-makers to take action for climate change and its impact. Adaptation and mitigation plans are required if sustainable development of the dairy sector is intended. Furthermore, dairy farms' location could change according to the suitability for growing different pastures under the projected climate for 2050.

In terms of adaptation, one of the measures that could be considered is to use other pastures more suitable to the projected climate scenario. In this sense, pastures adapted to more rainfall and higher temperatures could be planted. Moreover, genetic modifications or guided selection are strategies that can generate Lucerne varieties more adapted to the projected climate conditions. In terms of mitigation, there is an alternative pasture being studied in western Australia (Banik et al. 2013) *Biserrula sp.* That has the potential for producing 90% fewer methane emissions than other pastures when consumed by cows. Loi et al. (2014) highlighted that *Biserrula pelecinus* also have other important ecological trails: tolerating acidic soils, regenerating degraded soils, and resisting low summer precipitations. This is an interesting Climate Smart Agriculture measure that promotes a more sustainable sector with less GHGs emissions and assists farmers in adapting to climate change. Further studies of this pasture in Uruguay's actual and projected conditions would be very interesting.

In the case of the areas that will be more affected by climate change (northeast and northwest of Uruguay), diversifying the production could be a good measure. This measure can include using different pastures or crops for dairy or even producing other goods such as beef, wool, horticulture, or timber. Diversification reduces the risk of being affected by climate change and decreases the susceptibility to economic crises of the sector (FAO, 2013). On the other hand, the areas that showed more potential for growing Lucerne in the southeast of the country (Maldonado and Rocha) under the projected climate could be fomented by stimulating policies for the sector. For this to be possible, strong institutional coordination with public policies is needed. To sum up, understanding the effects of climate change is extremely important for decision-makers and for enhancing the decision-making process.

5.2. Ryegrass

The impacts of climate change on Ryegrass suitability in Uruguay are not expected to be as negative as for Lucerne. When analyzing the mean LSA index per department, the majority of the country is likely to experience an increase in the mean suitability value. The projected (2050) mean average is 6,76 while the historical (1960-1990) is 6,56 out of 9,00. Similar to Lucerne, the southeast of the country (represented by the departments of Maldonado, Rocha Treinta y Tres, and Lavalleja) will be the most benefited by the changes in the rainfall patterns and the increase in temperatures. Thus, the suitability for growing Ryegrass in these areas will be higher. On the other hand, the southwest of the country (mainly the department of Colonia) is expected to slightly decrease the suitability for Ryegrass, while the north of Uruguay will also benefit.

Interestingly, the differences between Ryegrass and Lucerne on their impacts of climate change demonstrate that the intensity of the combined effects of temperature and rainfall patterns variations will not be the same for different species. In the case of Ryegrass, it is clear that an increase in annual precipitation will impact positively on the annual yield. However, extreme temperatures could impact this pasture's productivity negatively.

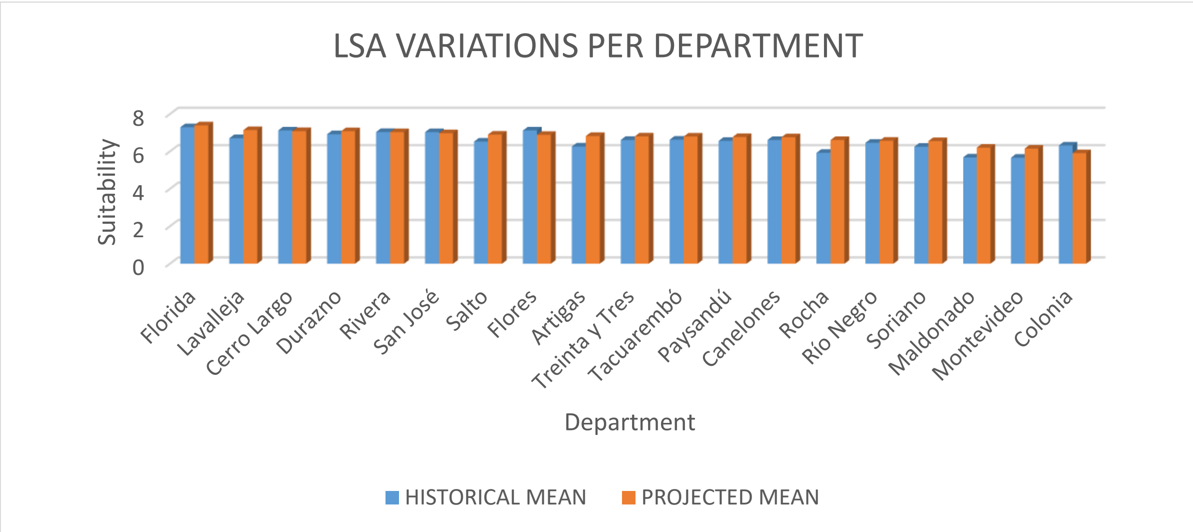


Figure 55. Ryegrass Land Suitability Variations per Department

Source: Elaborated by the Author

Summarizing the analysis of the impacts of climate change on Ryegrass and Lucerne LSA, it is clear that Ryegrass will experience an increase in the overall suitability while Lucerne will be affected in some areas. However, the two pastures can be used as a complement for different regions, knowing how they will produce under the projected weather conditions. In this sense, the LSA maps are a very important input to support the decision-making process of dairy farmers and technicians. For instance, understanding that ryegrass will be more productive over the next 30 years in the southeast and north of the country could be paramount for dairy farmers.

5.3. Model Validation

In order to validate the model developed, it is interesting to contrast the results of the historical LSA maps to the actual location of dairy farms in Uruguay. A good model would represent the reality of the current spatial distribution of the dairy farms. This comparison was made between the dairy production per region and the Lucerne LSA, understanding that Lucerne is the most productive pasture for dairy production and has higher requirements to be planted.

As depicted in the map on the left - in Figure 56 - the dairy sector is largely located in the south and southwest of the country. The productivity of dairy farms (red intensity) and the high production per region overlaps with the most suitable areas for growing Lucerne (green areas) in the LSA model. Consistently, isolated areas of high suitability for growing Lucerne coincide with areas where dairy production is moderate.

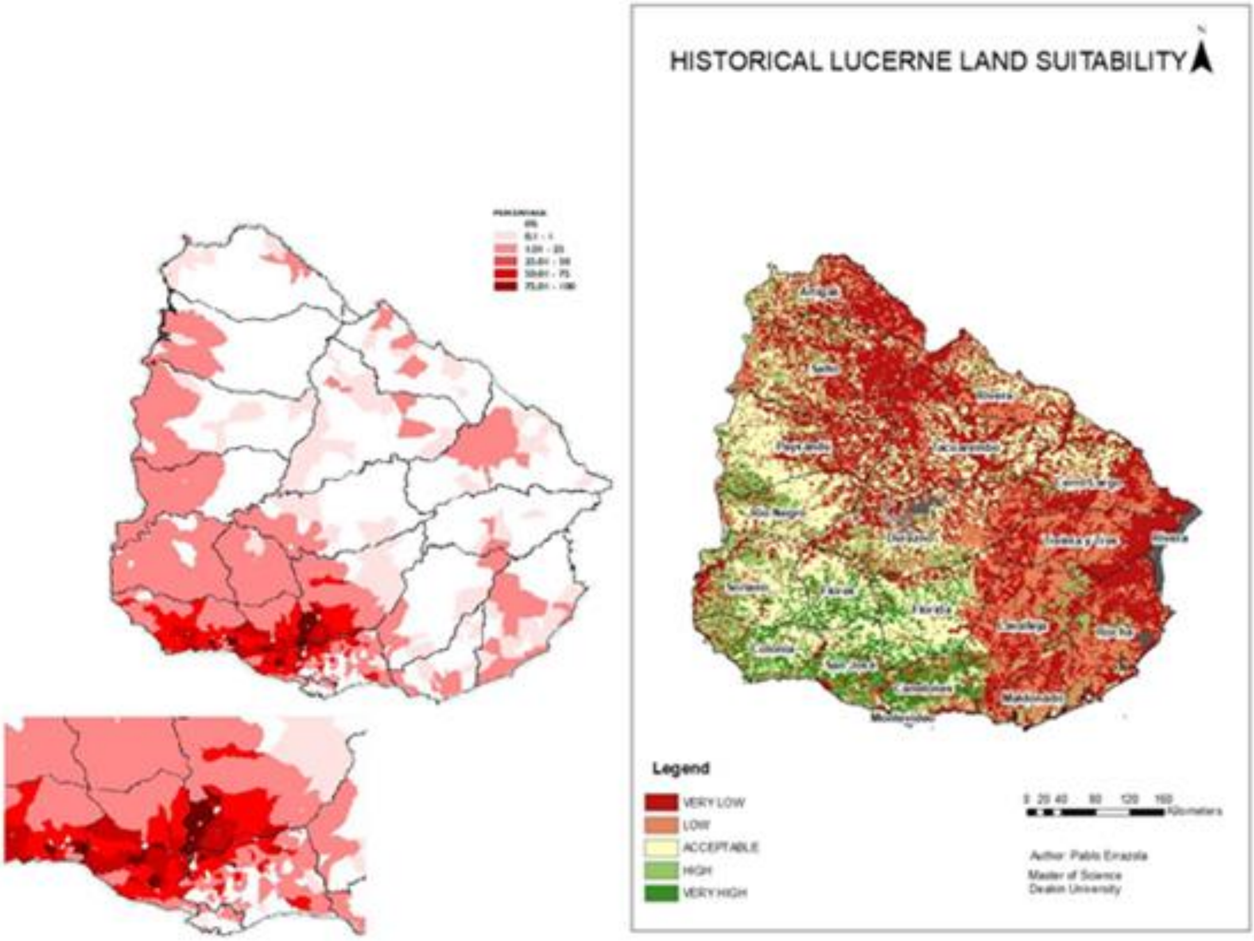


Figure 56. Lucerne Model Validation

Source: Elaborated by the Author

In contrast, areas with very low suitability for growing Lucerne are consistent with regions with very low or no dairy production. To sum up, the land suitability model is a good representation of the actual allocation of the dairy sector. This is a faithful validation for the Lucerne LSA model, thus the projected results can be considered as a viable outcome of the impacts of climate change for the sector.

The Ryegrass LSA model was not compared to the dairy farms distribution because it is a pasture with less specific requirements, so it grows in regions of Uruguay that are not strictly related to dairy regions. For instance, it is used by farmers for feeding beef cattle in many regions. Hence, the validation of the model comparing the dairy farms allocation is not representative, but the model still is a very useful input to understand the impact of climate change on different crops.

5.4. Extreme Weather Events

Despite not being considered in the model due to the scope of this research, the frequency of extreme weather events is another factor to take into consideration. The incidence of severe periods of droughts and extreme storms with high rates of precipitation in a few hours need to be considered. This increase in the frequency of extreme events could negatively affect both pastures and dairy farms' infrastructure. According to Ghofrani et al. (2017), it is unlikely that we can cope with an increase in the frequency and intensity of extreme weather events. This capacity to cope with extreme events in Uruguay could be very low due to poor infrastructure and structural support. Hence, if the frequency of these events is intensified, farmers may lose their coping capacity and their entire businesses.

Ghofrani et al. (2017) highlighted that sustainable methods to cope with extreme weather events can be a solution. The authors proposed that Blue-Green Infrastructure (BGI) can increase resilience under projected climate change while enhancing social and economic wellbeing. The BGI consists of connected natural and designed landscape mechanisms, including green spaces and water bodies, that can control flooding and be used for water harvest and storage for irrigation and provide an ecosystem for wildlife. Another interesting measure for coping with extreme weather events proposed by FAO (2013) is agroforestry. It was proposed that the usage of trees on agricultural systems can contribute to water infiltration, prevent soil erosion and reduce the impacts of extreme weather events (FAO, 2013).

5.5. Climate-Smart Policies

As discussed in the literature review (chapter 2), the application of Climate Smart Policies is essential for the sustainable development of the sector (FAO, 2018). Financial access and technical support are required to pursue the goal of sustainable intensification (World Bank, 2015). In this sense, all stakeholders including farmers, technicians, research, public institutions, and industry, must coordinate the application of these policies. Furthermore, Climate Smart Policies are based on three main principles: increase food security and farmers´ income; promote adaptation to climate change and resilience, and reduce GHGs emissions (FAO, 2010). Some of the most relevant Climate-Smart Policies that could be adopted in Uruguay are sustainable soil management, pasture management improvement, manure management, water conservation, and irrigation efficiency (World Bank, 2015).

The National Adaptation Plan for the agriculture sector (NAP-ag) is a very interesting example of adaptation and mitigation policies for the long term. According to the NAP-ag (2019), several adaptation measures can contribute to the increase of carbon sinks and reduce Greenhouse Gasses emissions. For instance, the sustainable management of natural grasslands generates resilient and more productive agriculture systems while reducing GHGs emissions. This is a vital measure since as described by the World Bank (2015), agriculture is responsible for 75% of total GHGs emissions in Uruguay. In summary, the NAP-ag aims to “improve the livelihoods of rural populations through the adoption of sustainable animal and plant production systems that are less vulnerable to the impacts of climate variability and change” (NAP-ag, 2019 p. 2). However, the application of the NAP is as important as the formulation of the policies. If decision-takers do not follow the steps required to adopt these actions, there is no value in formulating a National Adaptation Plan.

Interestingly, the World Bank (2015) and the Ministry for Livestock, Agriculture, and Fishery elaborated a summary of Climate-Smart Agriculture in Uruguay. This study reveals the importance of applying CSA practices in Uruguay due to its economic importance (7% of the GDP and 71% of total goods export) and the recent impacts of climate change and its variability. As described in the previous section, the frequency and intensity of floods and droughts are increasing. Thus, promoting the adoption of CSA practices can reduce the impacts of climate change, increase resilience and enhance farmers´ lives and profits. For the livestock production system, policies related to pastures, crops, feed, and manure management can contribute to the reduction of GHG emissions in the sector (FAO 2013; World Bank, 2015).

Specifically, for the dairy sector, most practices are related to the use of irrigation, the distribution of water across the farm, and the management of grasses and manure. According to the World Bank (2015), Uruguay needs to improve the responsible management of chemical fertilizers and reuse effluents as biofertilizers to promote the conservation of water bodies and reduce the pollution of rivers. This practice would also be interesting from the point of view of eco-economy and circular food economy (Sposito, 2019; Pascucci, 2020). Regarding the management of pastures, better practices can increase productivity and the utilization of grasses, increasing milk production without incurring extra costs (Chilibroste and Battegazzore, 2015). Furthermore, the efficient use of concentrates and reserves during extreme weather events or low pasture growth periods enhances and maintains the productive structure

(World Bank, 2020). This CSA measure could indirectly reduce the amount of GHGs emissions per unit of product.

In relation to pasture management, as described in the results above, more productive pastures could be used under the projected climate, such as ryegrass. In this sense, FAO (2013) highlighted that carbon sequestration could be promoted by improving grassing management. Regenerative agriculture also proposes a change in farming management to rebuild soil fertility (Duncan et al. 2020). Hence, it is imperative that the dairy sector improves pasture management, promotes the sequestration of carbon, regeneration of soil fertility, and increases farmers' productivity, thus improving their quality of life. If these measures are accompanied by the promotion of the generation of high-quality products, short supply chains, and local embedded communities, the new model of the dairy sector would have strong multifunctionality (Wilson, 2007).

5.6. Measuring Sustainability

Measuring the outcomes of applying Climate-Smart Policies is as important as the application of them. Undoubtedly, it is not possible to manage something that is not measured. Hence, the use of indicators to analyze the impact of the policies is required. For instance, the indicators developed by Tommasino et al. (2012) in Uruguay have the potential of measuring the outcomes of a sustainable development plan –see table 3. However, this system measures the different spheres of sustainability separated and does not include an integrated index. A unique index that indicates the outcome of a particular policy applied at a regional or farm level is to be applied.

In this sense, it is proposed to generate a Sustainability Global Index using the total of each dimension -see table 10. Once this total is obtained for each sphere, a global average index can be calculated as valuable data for comparing Climate Smart Agriculture policies outcomes or contrasting different farms. The maximum global Sustainability Index would be 100 points as an average of the 3 dimensions.

Moreover, it is proposed to add another dimension to the Indicator: the organizational Index. As described by Sposito (2019), there are *four spheres* of sustainable development, and along with the social, economic, and environmental spheres, the organizational sphere is included. The variables considered under the organizational sphere are the relationships with other farmers (for example participating in groups of farmers), the organization of the destination of the dairy products (cooperatives vs. private industries), the participation of technicians in the organization (agronomist, veterinarians, etc.), and the relation with the community (this is partially described in the *level of participation in collective spaces* in the social sphere).

Table 10. System of indicators of Sustainability for the Uruguayan Dairy Sector Adapted.

DIMENSION	INDEX	VARIABLES CONSIDERED	MAX VALUE	SPHERE INDEX
SOCIAL	General participation	Level of participation in collective spaces	20	Total of the Social Indicators = x/100
	Productive participation	Participation in joint asset management	20	
	Education	Productive and non-productive training in the last 3 years	20	
	Subjective quality of Life	Personal satisfaction evaluation	12	
	The structural quality of life	Housing, locomotion, health	8	

	Succession	Age and successors willing to continue in the farm	20	
ECONOMIC	Farm income	Farm income and number of people living on the farm	40	Total of the Economic Indicators = x/100
	Production support	Breeding field, joint machinery, joint sowing	15	
	Financial autonomy	Cattle bank, microcredits, total property debt	30	
	Transmissibility	Number of heirs	15	
ENVIRONMENTAL	Water	Sources of pollution, animal access, state of the structure	20	Average of the Environmental Indicators = x/100
	Effluents	Number of cows, risk of contamination	20	
	Soil	Land use management	20	
	Biodiversity	Native forest record and use, state of conservation	20	
	Agrochemicals	Personal prevention measures, environmental conditions for application, a place for washing and loading the products	20	

Source: Adapted Tommasino et al. (2012)

CHAPTER 6. CONCLUSION

Departing from the results of the application of the multi-methodology and key methods, outlined in the previous chapter, this final chapter comments on the most important considerations of the research and the key findings. In addition, a discussion about the contribution to knowledge and the limitations of the investigation are mentioned. Finally, further studies are suggested for the field to generate an improvement in the results.

6.1. Contribution to knowledge

This thesis aimed to analyze the impacts of climate change and its variability on the Uruguayan dairy sector by 2050. This was achieved by understanding the impacts of the projected climate on some of the main pastures used for dairy production in this country– Lucene and Ryegrass. It was concluded that the rise in temperature and modifications in precipitations' patterns projected by 2050 would affect the suitability of pastures across the country. The suitability of the land to grow Lucerne is expected to decrease in the north of the country but rise slightly in the south. On the other hand, Ryegrass is likely to increase its suitability for the majority of the country. These effects respond to an increase in the annual mean temperature and modifications in precipitation patterns, affecting the water balance. Land Suitability Analysis (LSA) modeling was useful to explore potential areas for the dairy sector to increase production or expand into, thus contributing to the sustainable development of the sector. The methodology developed in this thesis can be utilized for other commodities or regions as more studies are required in this field, such as the impact of climate change on other pastures or crops. Nevertheless, this is the first approach to a very complex problem, which however highlights the necessary collaboration between dairy farmers and public institutions in making decisions towards the sustainable intensification of the dairy sector.

The application of CSA policies, based on the expected suitability of Lucerne and Ryegrass via LSA modeling, can be a very good measure for adaptation to climate change. Still, to achieve a sustainable and more resilient dairy sector by 2050, more actions are required.

Both leading practitioners and theorists working on sustainability matters are stressing that agriculture is not only important for producing food and fiber, but also in generating jobs in rural areas, protecting landscapes and the environment, creating more recreational spaces, and mitigating the impacts of climate change. For these objectives to be achieved, it is considered that investment in agriculture and the promotion of CSA practices are essential. The impacts of climate change and its variability are only one driver of change among a multitude of others, such as a growing population, scarcity and pollution of natural resources, and the rise of the sea level.

Uruguay undoubtedly needs a concerted national response and strong policies to tackle these complex problems. Moreover, further understanding and constant assessment of the drivers of change will be required using sustainability indicators. In this sense, the proposed Sustainability Global Index has the potential of comparing the outcomes of different adaptation and mitigation policies.

6.2. Research limitations

Lack of, or poor, data sources caused some limitations to this research. For instance, the projected climate conditions used for Uruguay were derived from the general projections on the Worldclim´s website. Further investigation using different RCP models and local climate projections should be developed.

The quality of the data available for this research was another limitation. In particular, the LSA models used for this research were applied using soil data from FAO (see appendix VII) instead of locally CONEAT data. Consequently, the resolution of the results was lesser due to the low resolution of the inputs. Therefore, it would be of great value that this line of investigation is continued by other researchers generating more local data.

Due to time limitations, the LSA models for both pastures – Lucerne and Ryegrass- were adaptations of Australian models and sensitivity analyses were not conducted for them. Moreover, the LSA models have not taken into consideration management practices that could change the potential of growing Lucerne or Ryegrass, such as fertilization or pH control. Locally developed models addressing these limitations will henceforth be necessary to improve the precision of the results.

6.3. Methodological considerations

The *Rational Holistic Planning and Decision Making Model* methodology developed and applied in this thesis has an excellent capability for generating valuable information concerning the challenges facing agriculture, particularly it's dairy sector. Spatial analysis tools, such as GIS and various software (e.g., ArcInfo), provide helpful information and generate data that can be easily interpreted by farmers. Nonetheless, for farmers to adopt these tools, including them at the beginning of the research is central. This would increase both their understanding of the tools and their commitment to the results leading, in turn, to taking actions for improvement. The use of appropriate technology is essential to cope with climate change, increase farmers´ profits, and generate relevant adaptation and mitigation policies. A sensitivity analysis was not conducted because the model used an Analytical Hierarchy Process.

6.4. Further Recommendations

Based on the results, this thesis's research could be critical for understanding the impacts of climate change on the Uruguayan dairy sector. The results thus far obtained contribute to the decision-making process of dairy farmers and the related institutions. This could be, however, the first of a series of investigations in this field. Further studies on the impacts of climate change, using improved local data, are clearly required. The implementation of adaptation and mitigation policies and their outcomes have to be measured.

If the sustainable intensification of the Uruguayan dairy sector in the short-to-medium term is to be achieved, the adoption of new technologies and innovation in research and development will be required. For instance, the reduction of GHG emissions from the agriculture sector, especially from the enteric fermentation of cows, is imperative. Incorporating anti-methanogenic pastures such as *Biserrula sp.* or including other feed additives currently under development (for example, seaweed) would be very interesting.

Finally, an articulated and organized sector with strong institutions and private sector organizations and coordination among them is critical for these objectives to be achieved.

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APPENDIX I - Milk exports by country

World total milk exports (thousand tonnes milk equivalents)			
	2017	2018	Change 2018 over 2017 (%)
World	**72 667**	**74 781**	**2.9**
EU 28	20 395	20 504	0.5
New Zealand	18 666	18 748	0.4
United States	10 724	11 778	9.8
Belarus	3 714	3 789	2.0
Australia	3 015	3 055	1.3
Argentina	1 341	1 996	48.8
Uruguay	1 259	1 556	23.6

Source: FAO, 2019

APPENDIX II - Experts communication

Personal communication with Otero & Castro, authors of Otero, A & Castro, M 2018, ´Variability of Alfalfa (Medicago sativa L.) Seasonal Forage Production in the Southwest of Uruguay´, Agrociencia Uruguay 2019 23(1):1-11, DOI: 10.31285/AGRO.23.1.9

Hello Pablo, we were talking with Alvaro Otero about your query.

Some comments

For the UY model to be of any use, the two most important factors should be taken into account in alfalfa: temperature and then water stress (excesses and deficits).

Working according to the time of year, our biggest deficits and excesses occur in spring and summer.

To estimate excesses and deficits in the soil, it is essential to have good data on spatial variability of soil characteristics. You should work at the CONEAT scale (dominant soils) 1: 25000 or smaller scales if you have the data.

A good technology package should be included: fertilization.

Use effective precipitation instead of gross precipitation

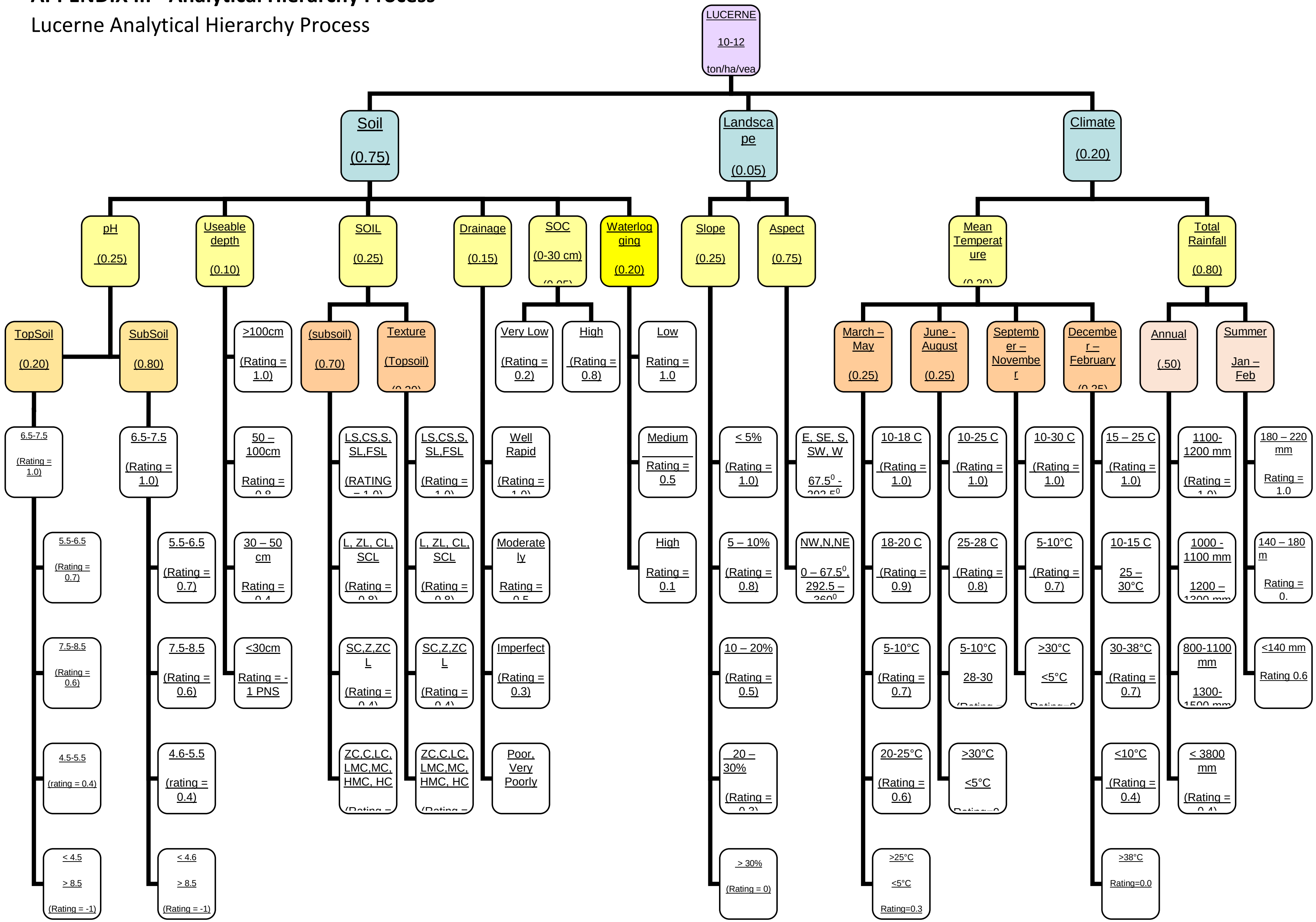
This is what we come up with.

Greetings,

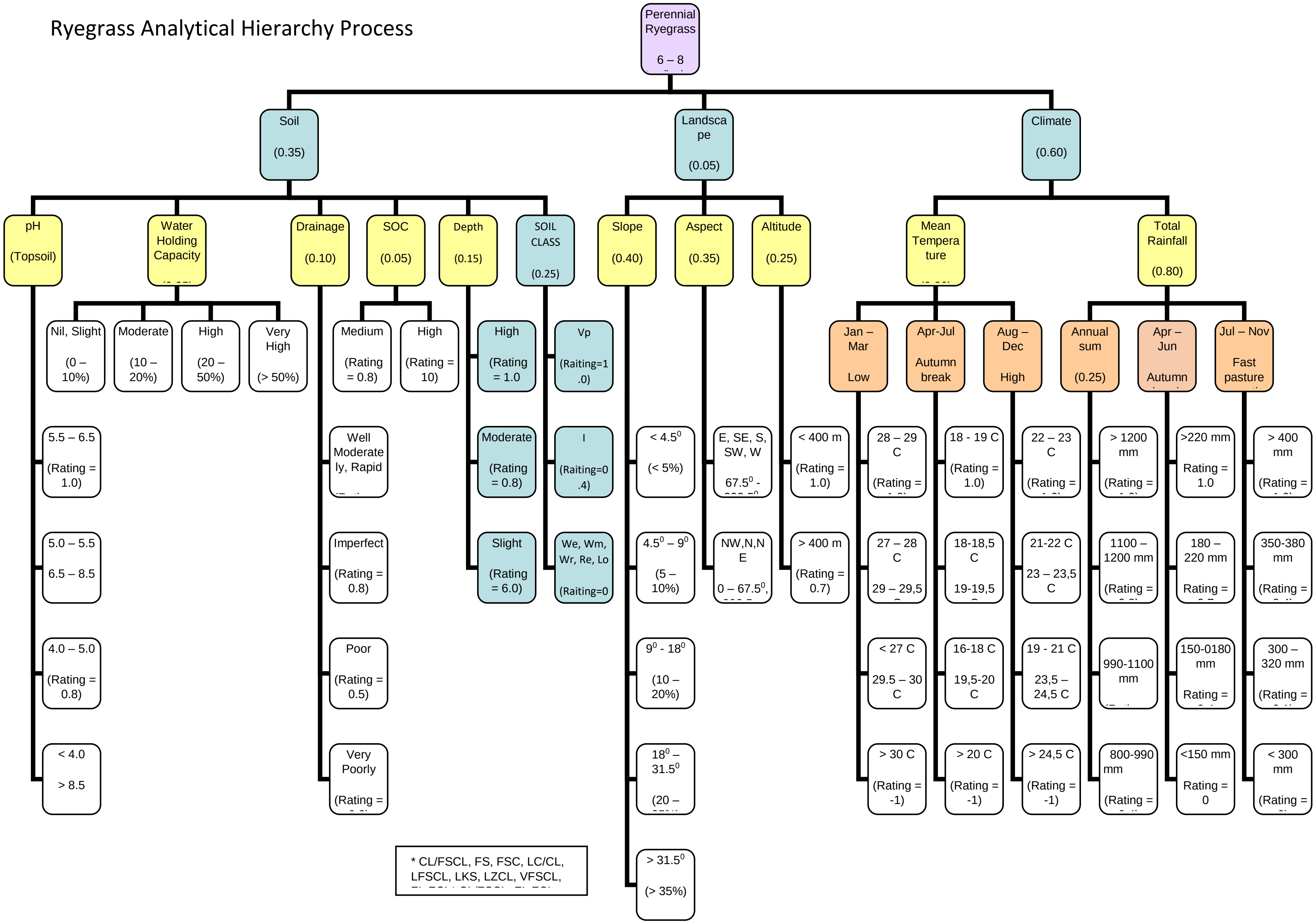
Marina and Alvaro

APPENDIX III - Analytical Hierarchy Process

Lucerne Analytical Hierarchy Process

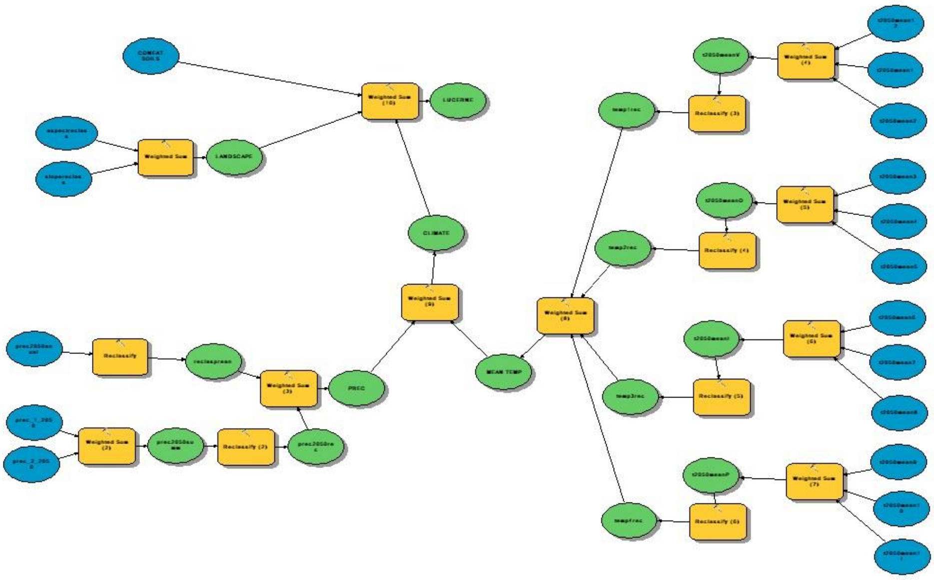


Ryegrass Analytical Hierarchy Process

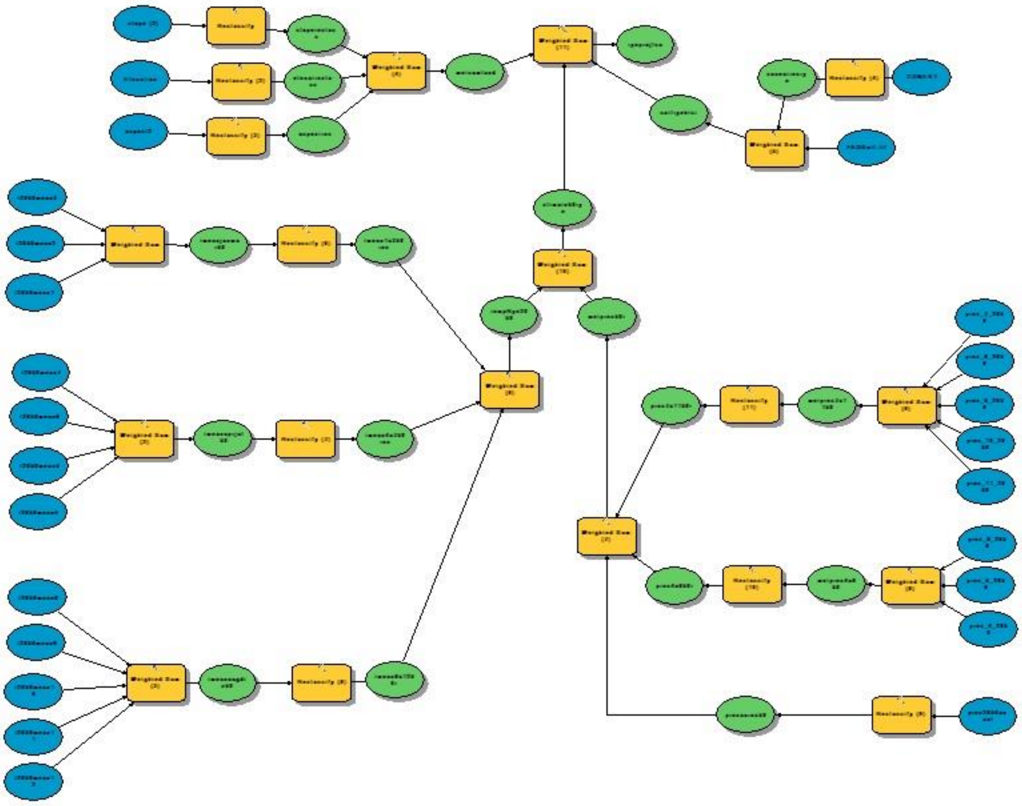


APPENDIX IV - Pastures Models

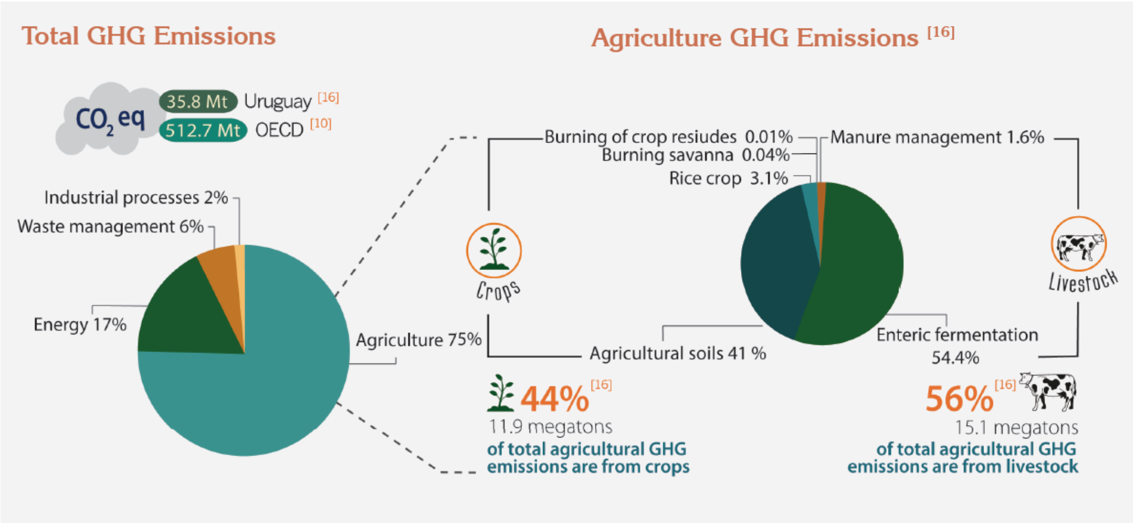
Lucerne Model



Ryegrass Model



APPENDIX V - Uruguay GHGs emissions



Source: World Bank, 2015

APPENDIX VI - CONEAT Reclassification based on experts

PH 0 _ 30 cm	value	reclass
0_2	5.5_6.5	7
2_3	6.5_7.5	10
3_7	5_8.5	6

PH 30_ 100 cm	value	reclass
0_2	5.5_6.5	7
2_3	6.5_7.5	10
3_7	5_8.5	6

SOIL DEPTH	value	reclass
3	80-110	4
4	110-140	10
7	50-140	8

SOIL	value	reclass
Ao		3
Gm		2
Hi		9
I		2
Lo		5
Rd		8
Re		2
Vp		10
WR		2
We		1
Wm		2

CONEAT	count
22	57
50	97
23	390
41	291
40	554
33	86
35	246
32	422
70	33
1	256
2	59
6	98
34	86
69	190
39	103
79	3
107	68
72	3805
99	375
82	983
113	35
75	292
65	904
109	160
59	182
142	280
180	27

CONEAT SC	RYEGRASS reclass	LUCERNE reclass
03.10	1	1
03.11	1	1
03.2	1	2
03.3	1	1
03.40	3	1
03.41	2	3
03.51	3	4
03.52	2	2
03.6	2	1
07.1	1	1
07.2	1	1
09.1	4	4
09.2	3	2
09.3	4	4
09.4	7	3
09.5	5	4
1.10a	2	2
1.10b	1	1
1.11a	3	2
1.11b	2	1
1.12	2	2
1.20	2	1
1.21	5	3
1.22	4	3
1.23	4	3
1.24	3	1
1.25	4	2

SOC 0_30	value	reclass
2	0.5_1	2
2_3	1_3	8

FAO drainage	value	reclass
2		-1
2_3		2
3_4		6
4_7		8
7_8		10

62	393
27	6
17	85
51	534
85	127
55	4
53	263
84	157
57	403
38	948
52	167
16	149
25	173
15	83
9	635
29	718
37	703
141	10
100	44
18	18
64	305
134	153
91	168
80	328
71	199
73	212
83	22
43	102
118	151
74	796

10.1	8	5
10.10	7	7
10.11	8	7
10.12	10	9
10.13	8	7
10.14	8	6
10.15	8	8
10.16	9	8
10.2	9	7
10.3	9	8
10.4	8	5
10.5	8	7
10.6a	8	7
10.6b	8	6
10.7	6	6
10.8a	8	8
10.8b	10	9
10.9	9	8
11.1	8	5
11.10	9	8
11.2	9	6
11.3	8	6
11.4	9	6
11.5	9	7
11.6	9	7
11.7	9	7
11.8	9	7
11.9	10	9
12.10	8	7
12.11	8	6

77	89
61	480
108	62
106	774
81	962
150	74
157	57
152	73
143	151
146	238
156	7
8	296
24	1971
12	809
7	1793
31	227
89	495
86	440
3	1145
63	24
14	12
56	30
5	30
28	75
67	142
4	187
30	213
26	95
20	479
88	82

12.12	8	6
12.13	7	6
12.20	8	5
12.21	7	5
12.22	7	5
13.1	6	5
13.2	8	6
13.31	7	5
13.32	7	4
13.4	9	7
13.5	8	5
2.10	1	1
2.11a	2	2
2.11b	2	1
2.12	3	3
2.13	3	3
2.14	3	2
2.20	3	3
2.21	4	3
2.22	7	4
3.10	1	1
3.11	1	1
3.12	1	1
3.13	1	1
3.14	1	1
3.15	1	1
3.2	1	1
3.30	1	1
3.31	1	1
3.40	2	2

10	236
87	3
42	347
47	579
36	211
11	335
93	289
13	248
45	19
60	79
68	46
92	113
19	2782
54	70
21	376
66	32
170	57
166	104
162	54
171	48
174	14
176	4
148	19
168	199
138	45
116	62
147	108
172	7
177	4
158	102

3.41	3	2
3.50	3	2
3.51	2	1
3.52	2	1
3.53	2	1
3.54	3	2
4.1	4	3
4.2	5	3
5.01a	2	1
5.01b	2	1
5.01c	2	2
5.02a	2	2
5.02b	8	5
5.3	7	5
5.4	7	5
5.5	4	3
6.1/1	2	3
6.1/2	4	4
6.1/3	5	4
6.10a	7	5
6.10b	8	5
6.11	5	4
6.12	5	4
6.13	6	4
6.14	2	2
6.15	5	4
6.16	8	4
6.17	7	4
6.2	2	3
6.3	8	4

48	118
181	14
173	17
160	12
151	227
175	1
115	93
164	348
159	233
163	299
161	95
169	118
149	99
94	110
102	7
129	38
167	19
153	46
123	44
130	38
137	63
101	83
140	15
125	144
126	143
95	212
120	64
96	46
111	194
154	45

6.4	8	4
6.5	5	3
6.6	6	5
6.7	6	5
6.8	7	5
6.9	8	5
7.1	2	2
7.2	3	2
7.31	4	4
7.32	4	4
7.33	7	6
7.41	5	4
7.42	4	4
8.02a	3	3
8.02b	3	2
8.1	2	3
8.10	5	4
8.11	4	3
8.12	4	3
8.13	5	4
8.14	6	4
8.15	4	3
8.16	3	3
8.3	2	2
8.4	3	3
8.5	5	4
8.6	6	4
8.7	6	4
8.8	5	3
8.9	4	4

76	954
90	221
58	405
49	9
44	32
78	155
132	341
103	2
46	30
105	73
122	386
97	85
104	22
98	40
127	78
121	827
110	815
117	453
144	128
155	16
135	20
131	65
139	15
145	7
136	34
119	92
124	55
128	67
165	10
133	15

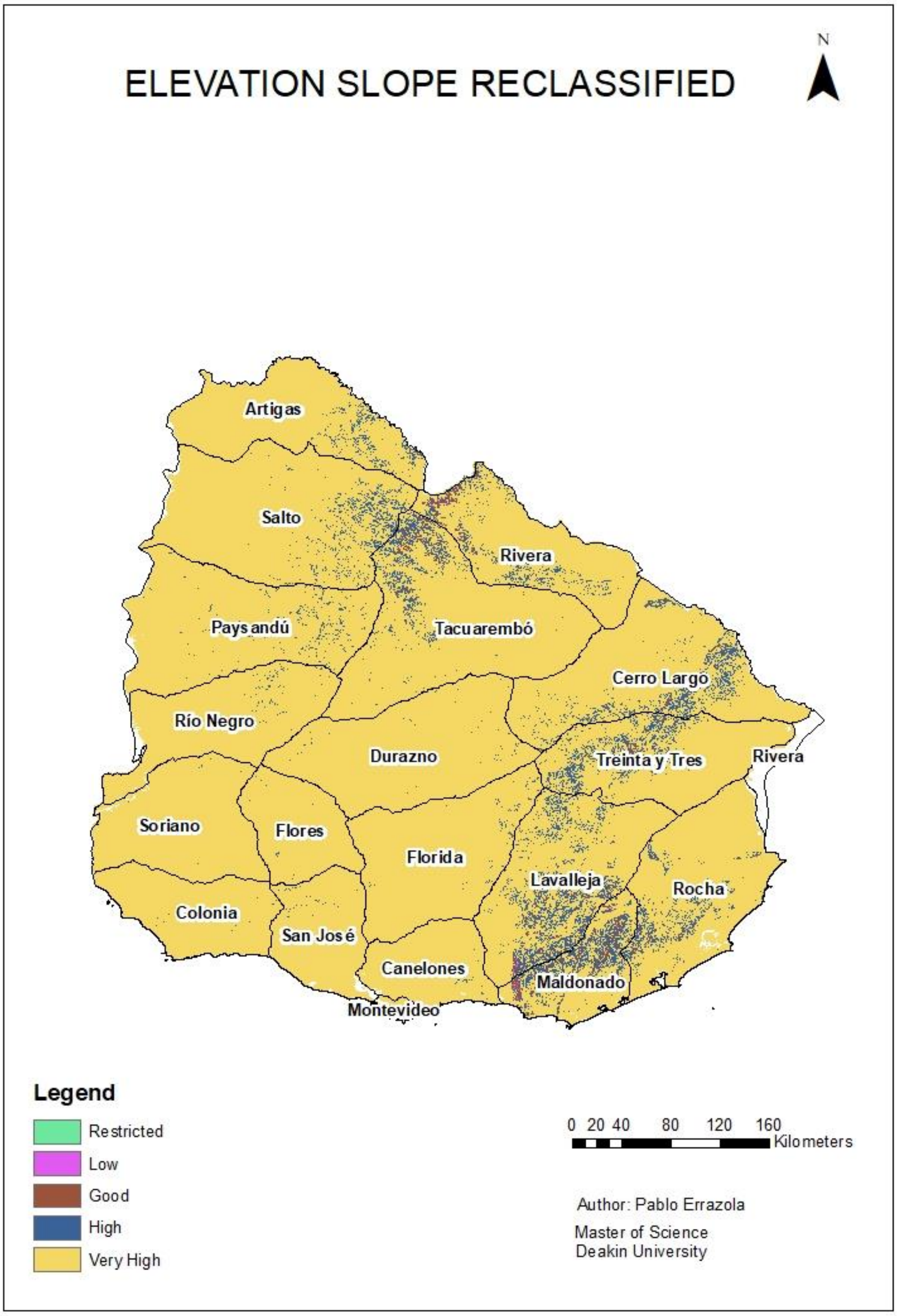
9.1	6	4
9.2	7	5
9.3	6	4
9.41	7	5
9.42	5	4
9.5	7	4
9.6	8	5
9.7	5	4
9.8	4	4
9.9	4	4
B03.1	4	2
D10.1	9	7
D10.2	9	6
D10.3	8	6
G03.10	1	1
G03.11	1	1
G03.21	1	1
G03.22	1	1
G03.3	1	2
G10.1	6	4
G10.10	8	4
G10.2	8	7
G10.3	8	7
G10.4	8	6
G10.5	7	5
G10.6a	6	4
G10.6b	6	5
G10.7	6	5
G10.8	7	5
G10.9	6	5

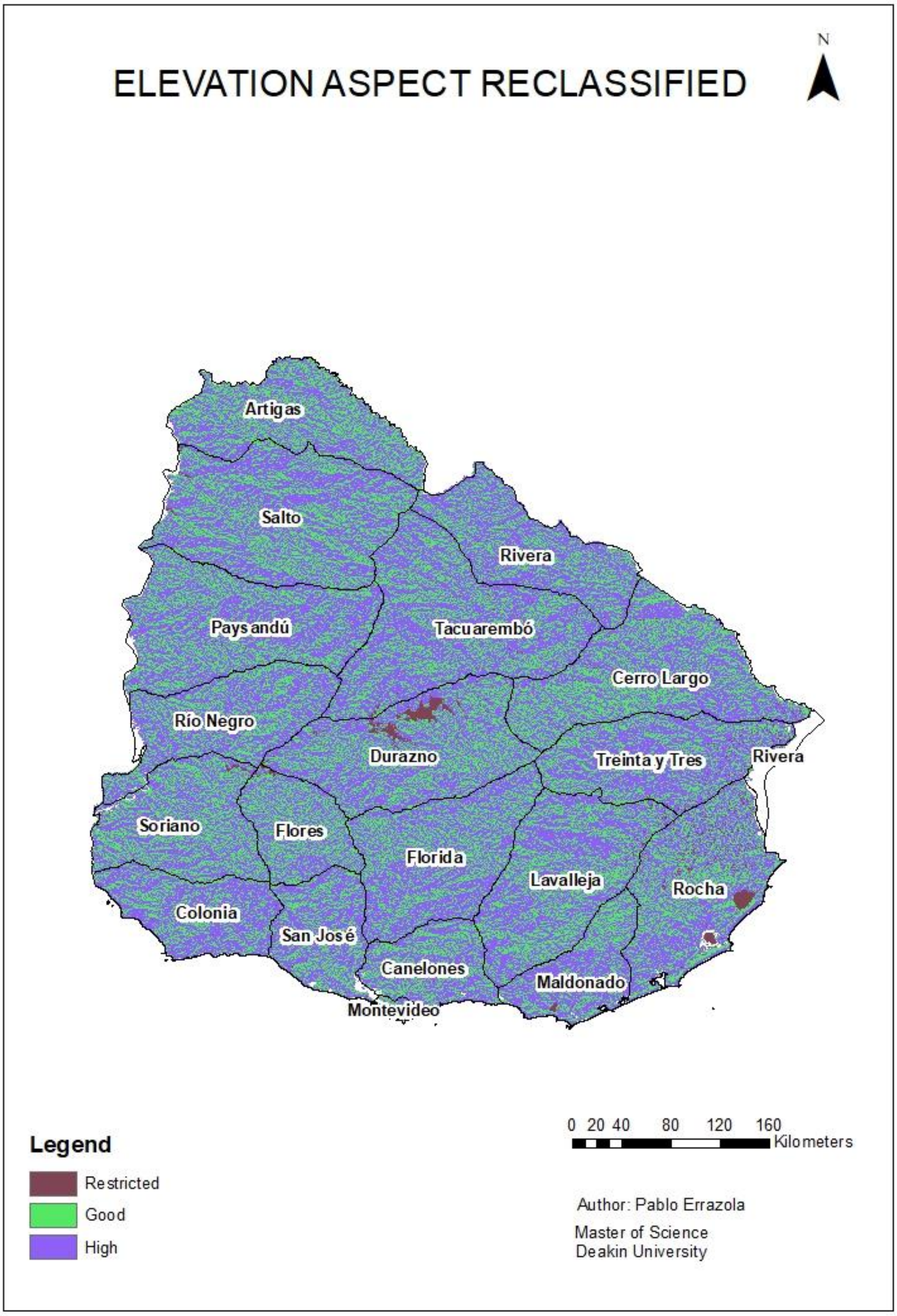
179	45
184	64
114	64
183	50
185	40
187	11
188	6
186	46
178	12
112	54
182	70

S09.10	5	3
S09.11	4	2
S09.20	4	3
S09.21	3	3
S09.22	4	4
S10.10	8	7
S10.11	5	3
S10.12	8	7
S10.13	7	6
S10.20	7	5
S10.21	7	7

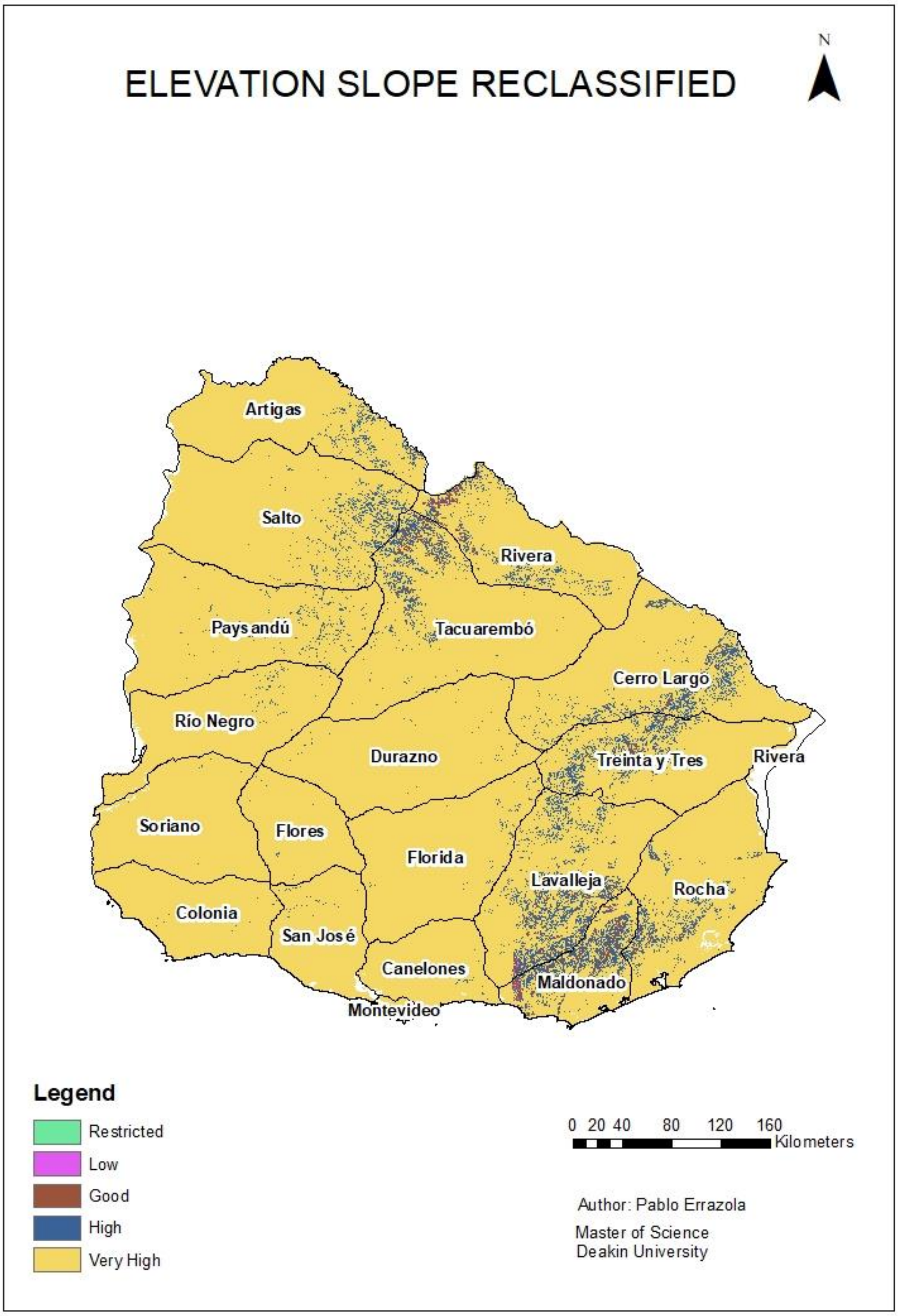
APPENDIX VII - Elevation slope and aspect reclassified

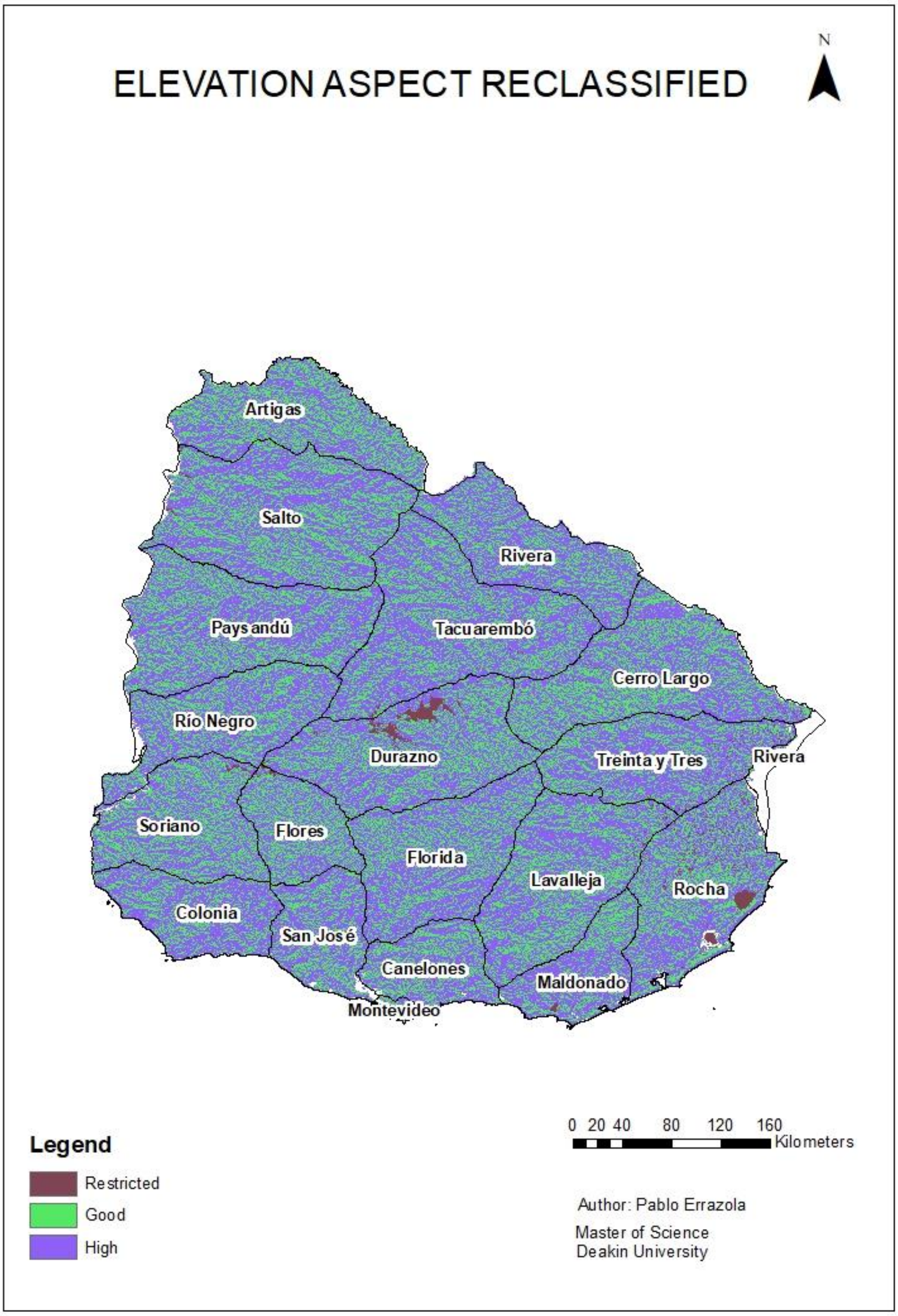
Ryegrass elevation slope and aspect reclassified



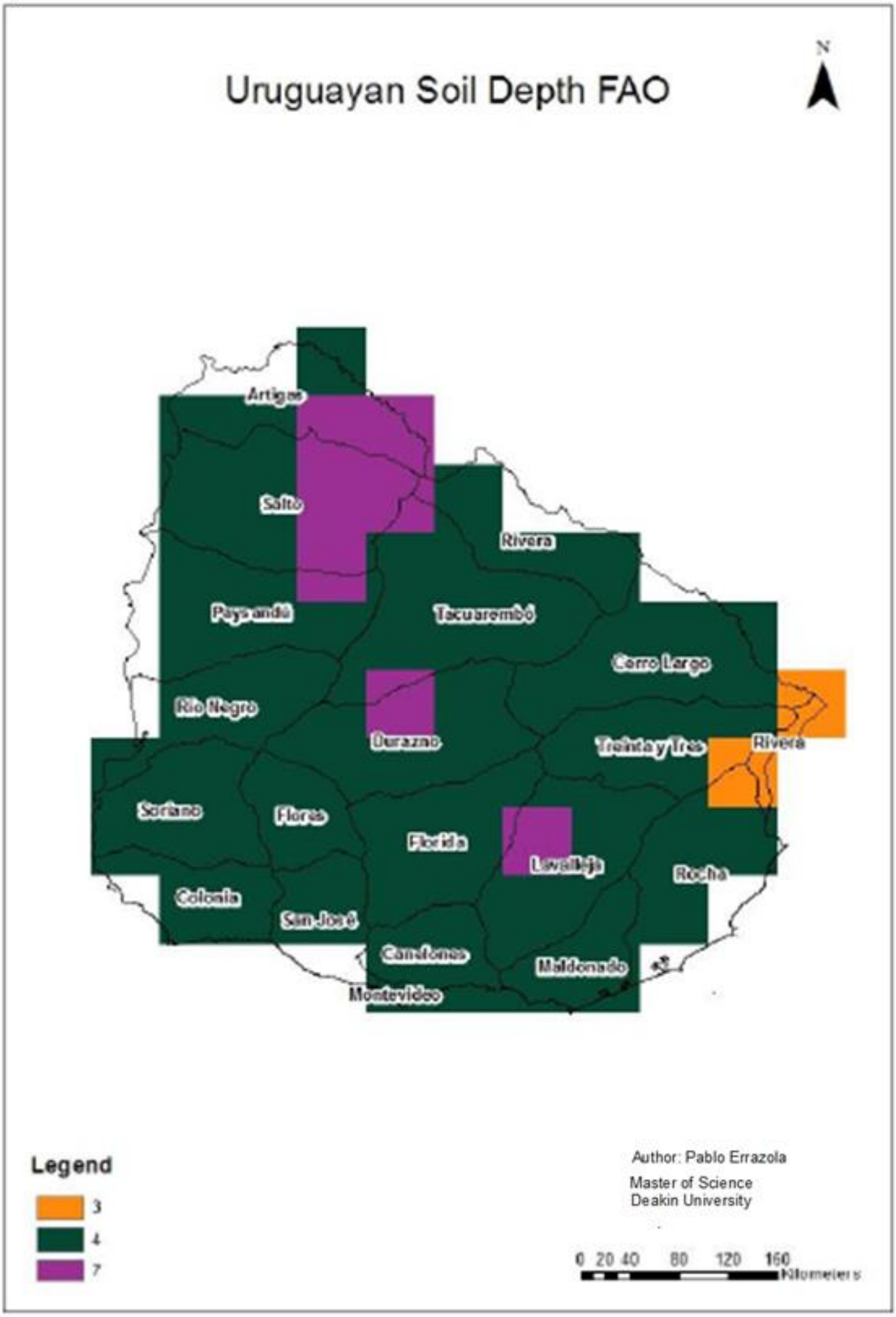

ELEVATION ASPECT RECLASSIFIED
N
Artigas
Salto
Rivera
Paysandú
Tacuarembó
Cerro Largo
Río Negro
Durazno
Treinta y Tres
Rivera
Soriano
Flores
Florida
Lavalleja
Rocha
Colonia
San José
Canelones
Maldonado
Montevideo
0 20 40 80 120 160
Kilometers
Legend
Restricted
Good
High
Author: Pablo Errazola
Master of Science
Deakin University

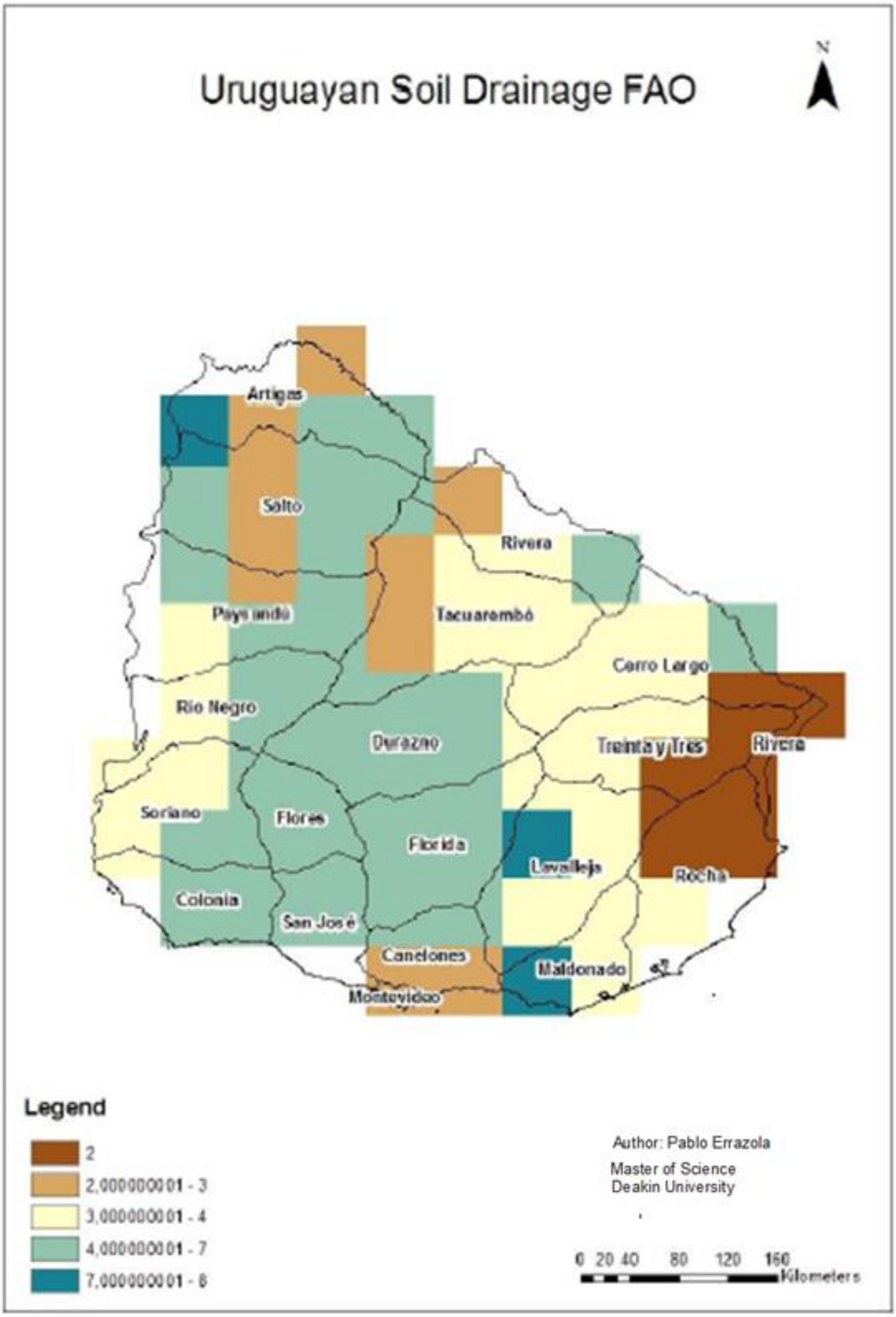
Lucerne elevation slope and aspect reclassified

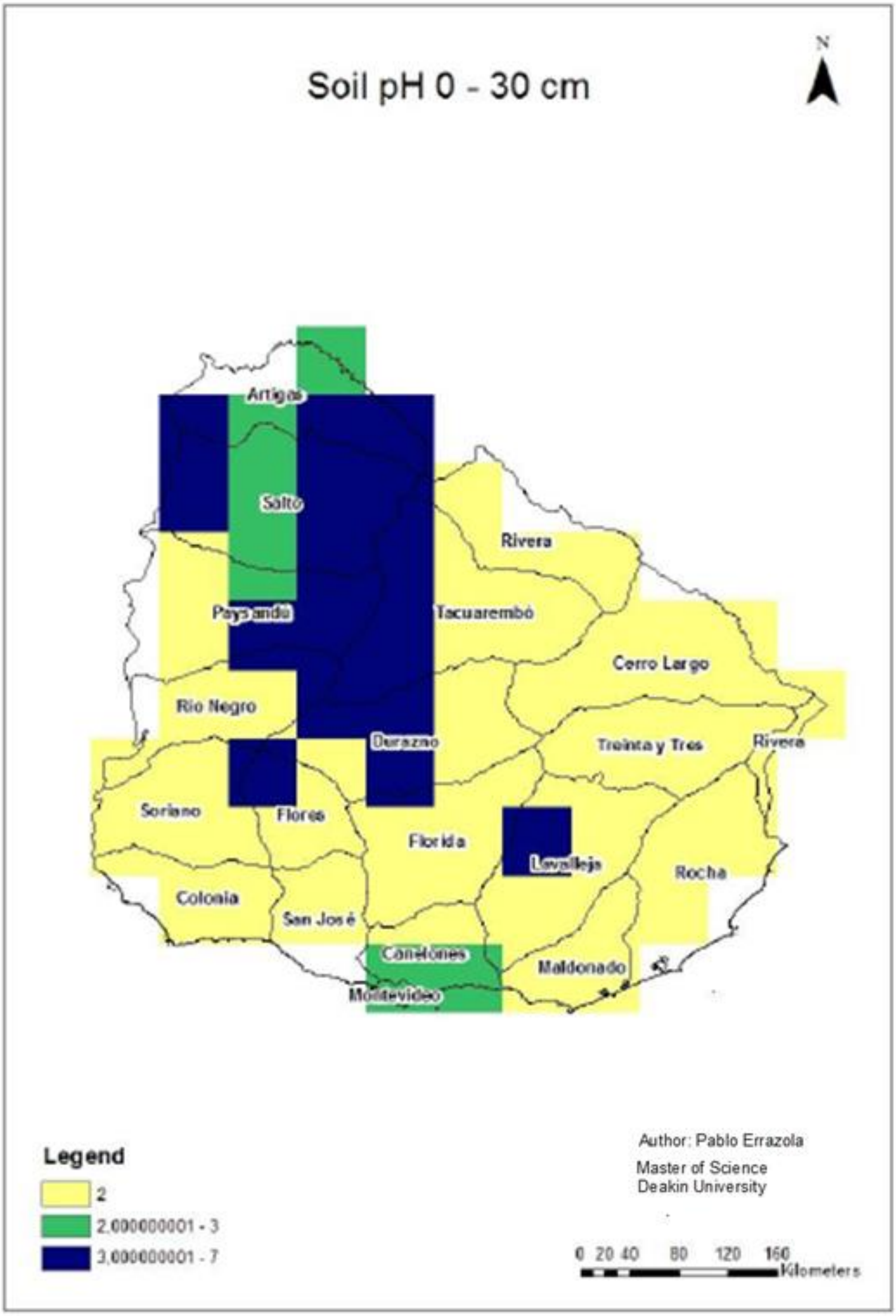



ELEVATION ASPECT RECLASSIFIED
N
Artigas
Salto
Rivera
Paysandú
Tacuarembó
Cerro Largo
Río Negro
Durazno
Treinta y Tres
Rivera
Soriano
Flores
Florida
Lavalleja
Rocha
Colonia
San José
Canelones
Maldonado
Montevideo
Legend
Restricted
Good
High
0 20 40 80 120 160
Kilometers
Author: Pablo Errazola
Master of Science
Deakin University

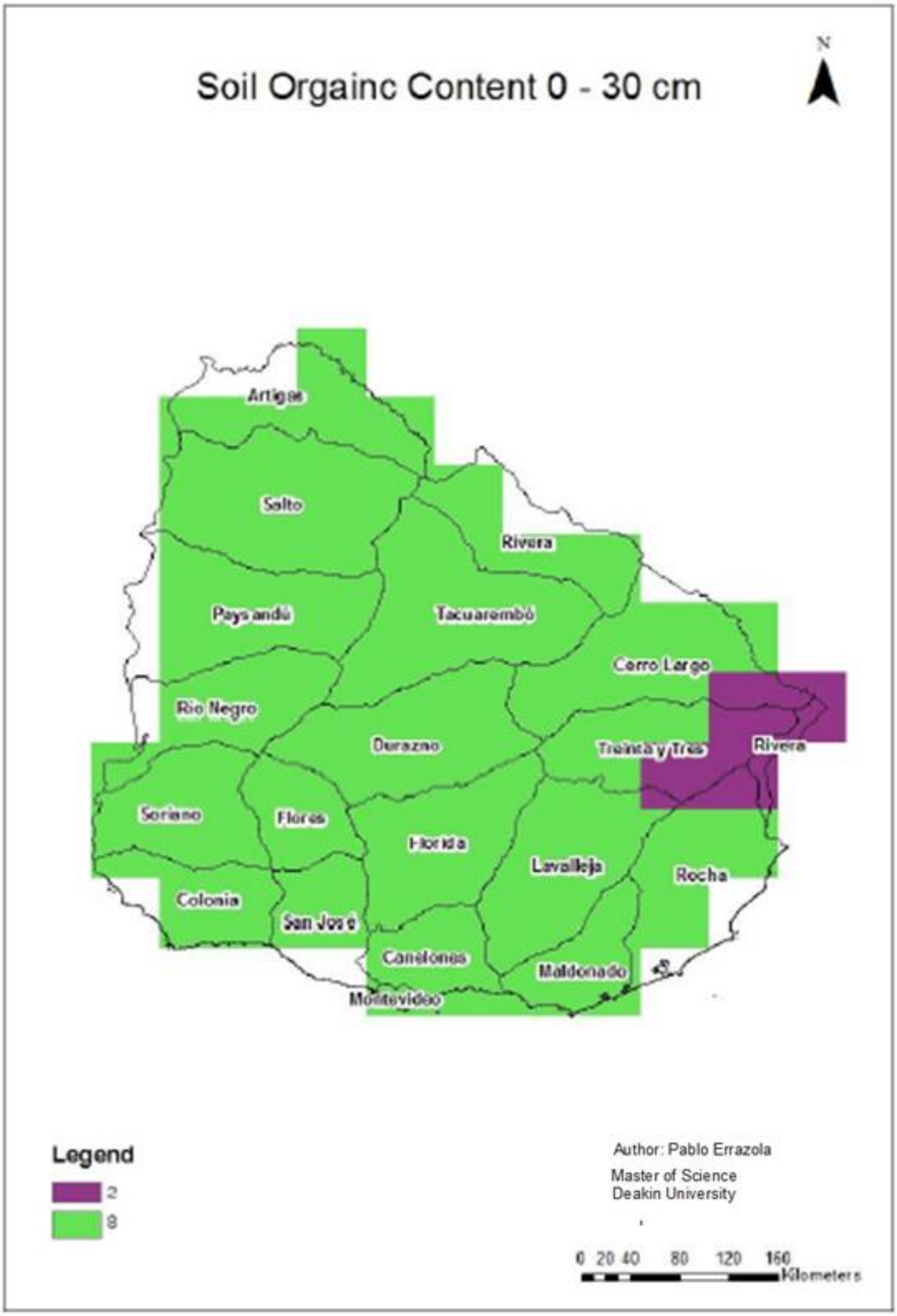
APPENDIX VIII - Previous model´s results based on FAO soil data

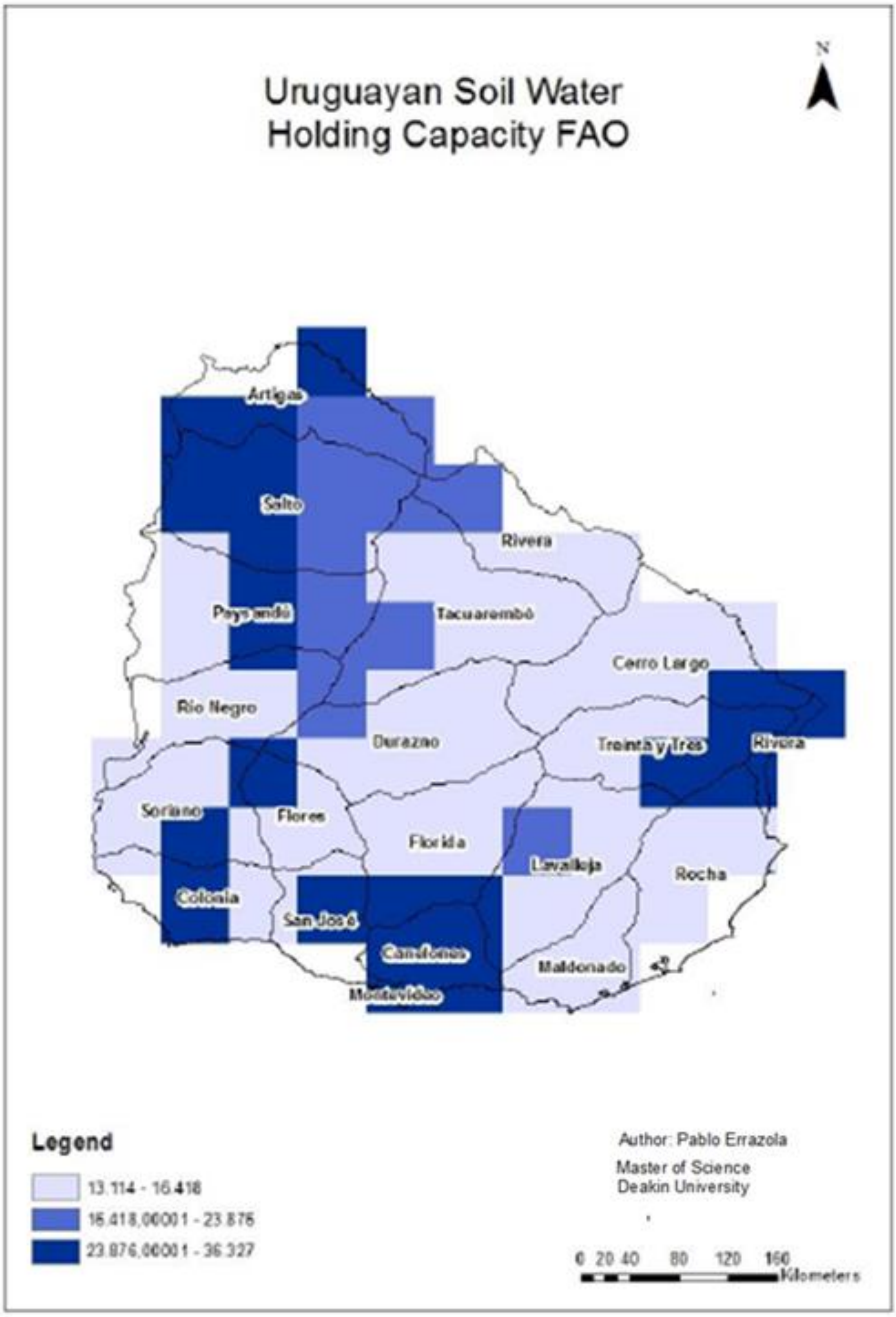



Uruguayan Soil Drainage FAO
N
Artigas
Salto
Rivera
Paysandú
Tacuarembó
Cerro Largo
Rio Negro
Durazno
Treinta y Tres
Rivera
Soriano
Flores
Florida
Lavalleja
Rocha
Colonia
San José
Canelones
Maldonado
Montevideo
Legend
2
2,000000001 - 3
3,000000001 - 4
4,000000001 - 7
7,000000001 - 8
Author: Pablo Errazola
Master of Science
Deakin University
0 20 40 80 120 160
Kilometers

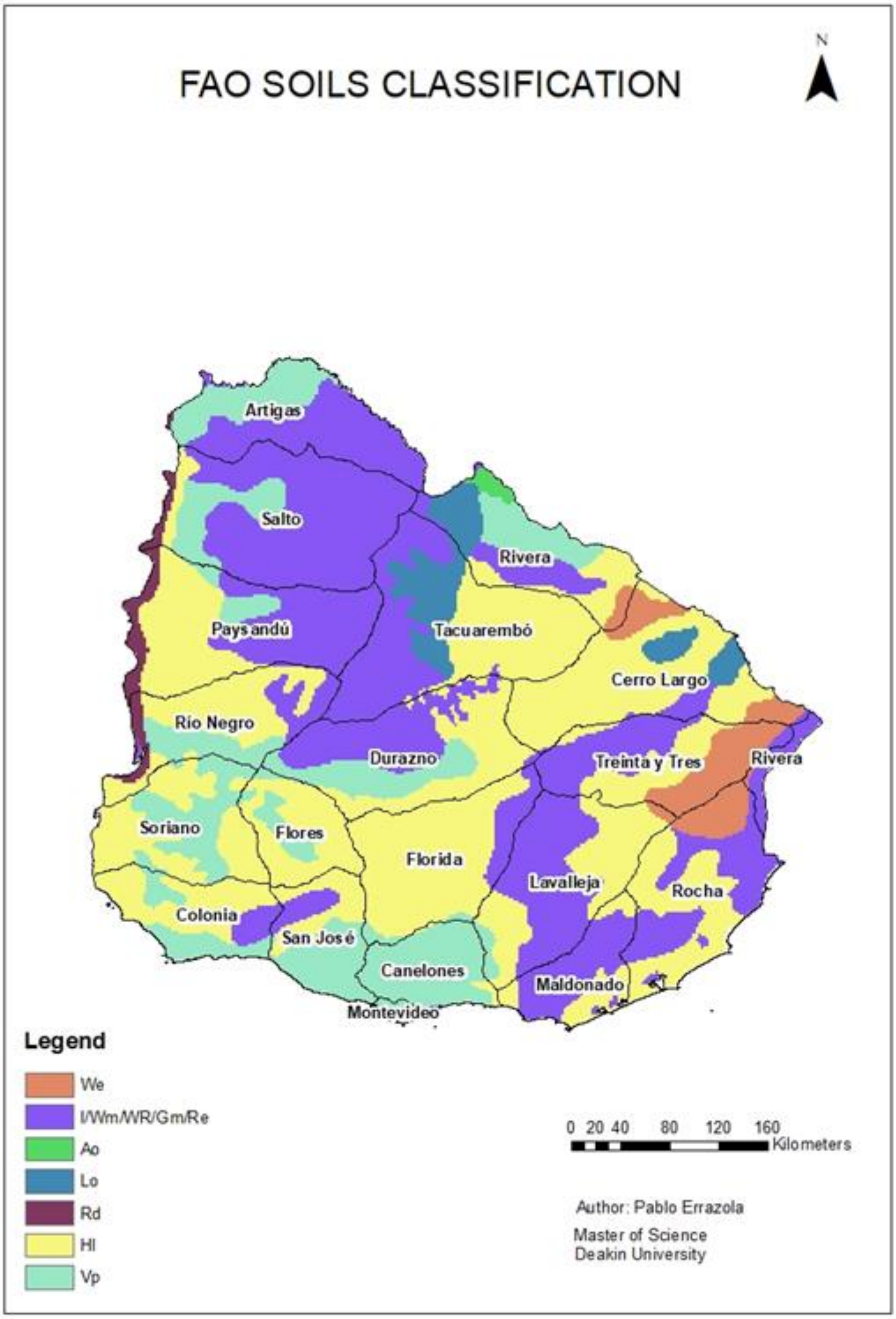


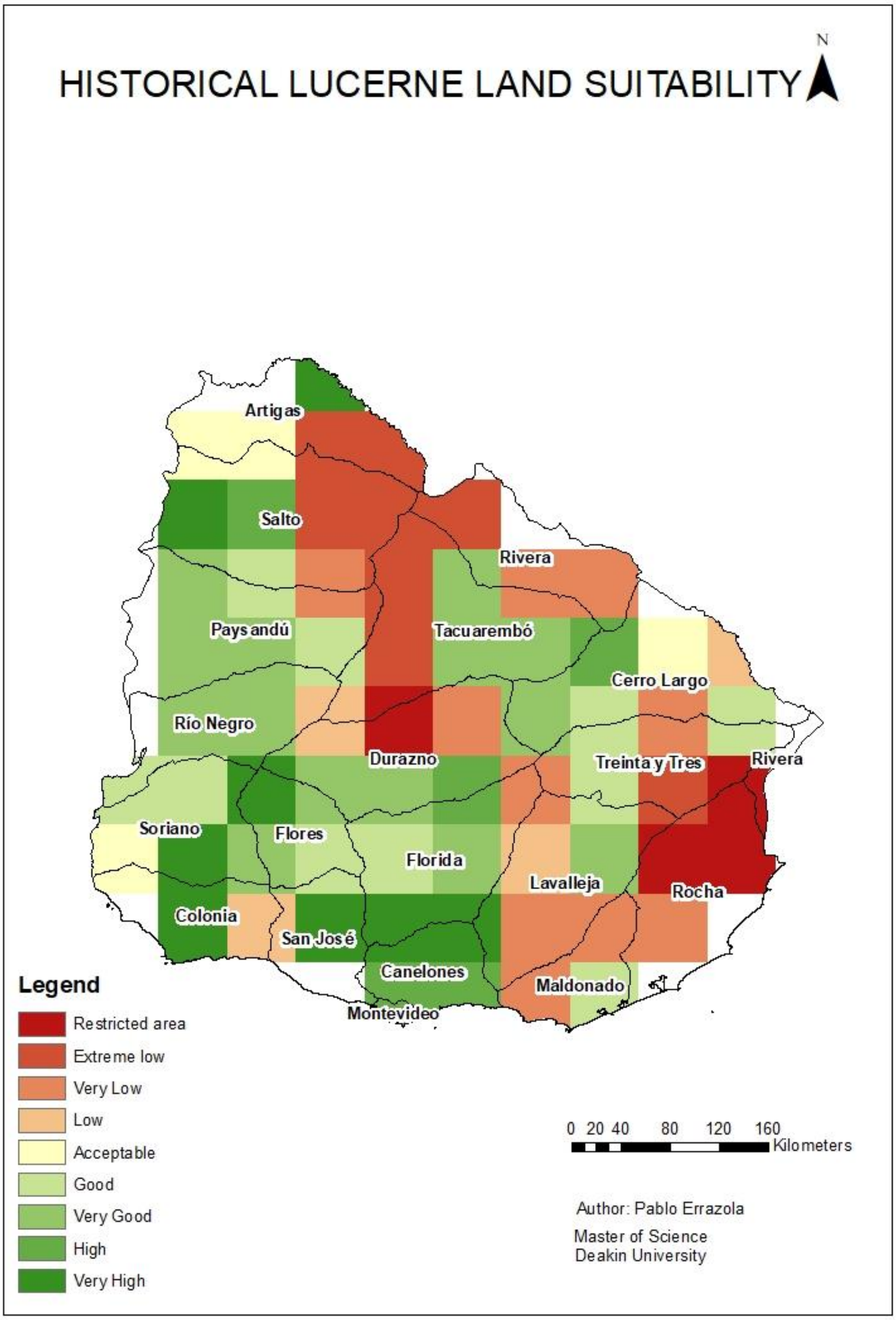
Soil pH 0 - 30 cm
N
Artigas
Salto
Rivera
Paysandú
Tacuarembó
Cerro Largo
Rio Negro
Durazno
Treinta y Tres
Rivera
Soriano
Flores
Florida
Lavalleja
Rocha
Colonia
San José
Canelones
Maldonado
Montevideo
Legend
2
2,000000001 - 3
3,000000001 - 7
Author: Pablo Errazola
Master of Science
Deakin University
0 20 40 80 120 160
Kilometers

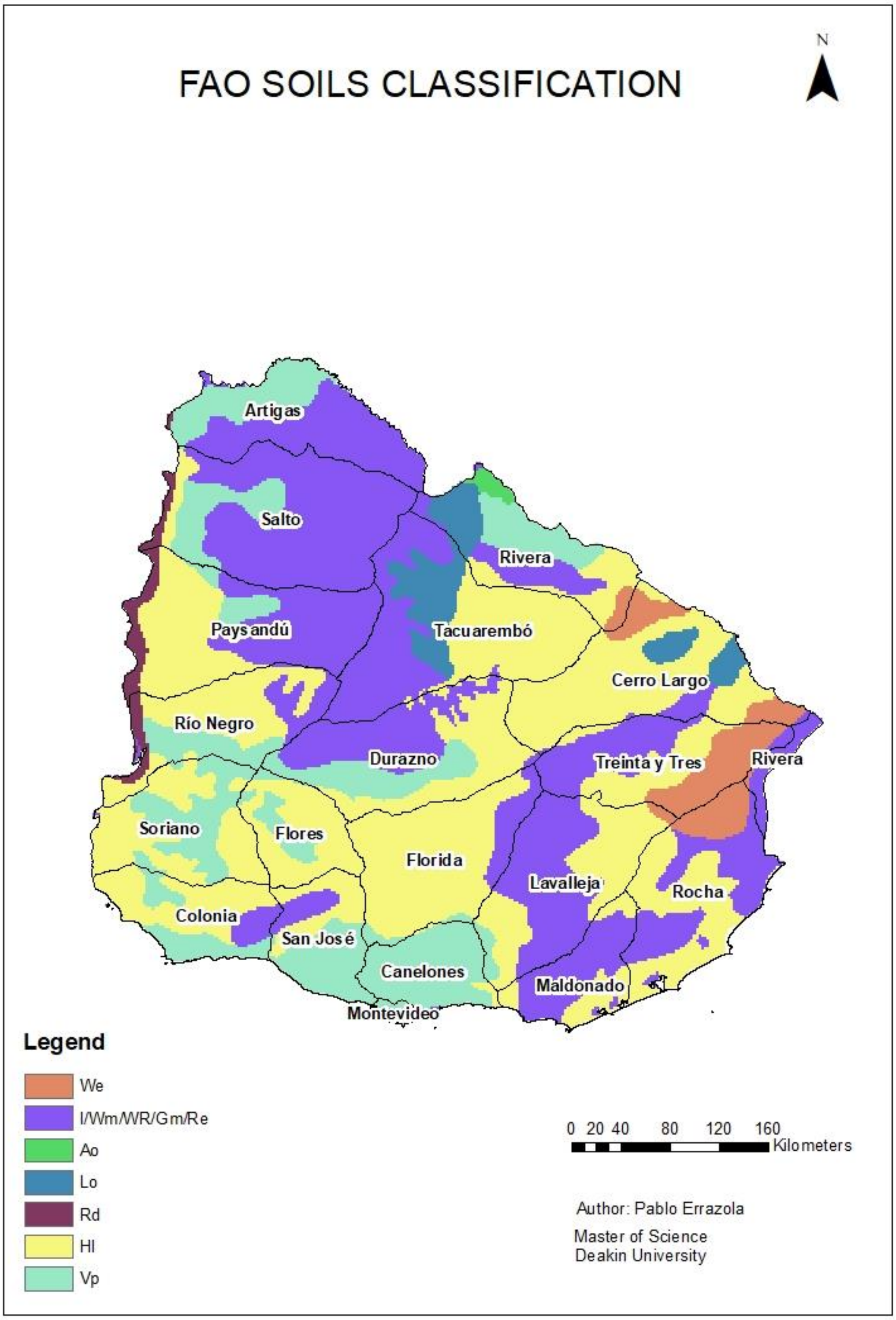

Soil Orgainc Content 0 - 30 cm
N
Artigas
Salto
Rivera
Paysandú
Tacuarembó
Cerro Largo
Rio Negro
Durazno
Treinta y Tres
Rivera
Soriano
Flores
Florida
Lavalleja
Rocha
Colonia
San José
Canelones
Maldonado
Montevideo
Legend
2
8
Author: Pablo Errazola
Master of Science
Deakin University
0 20 40 80 120 160
Kilometers

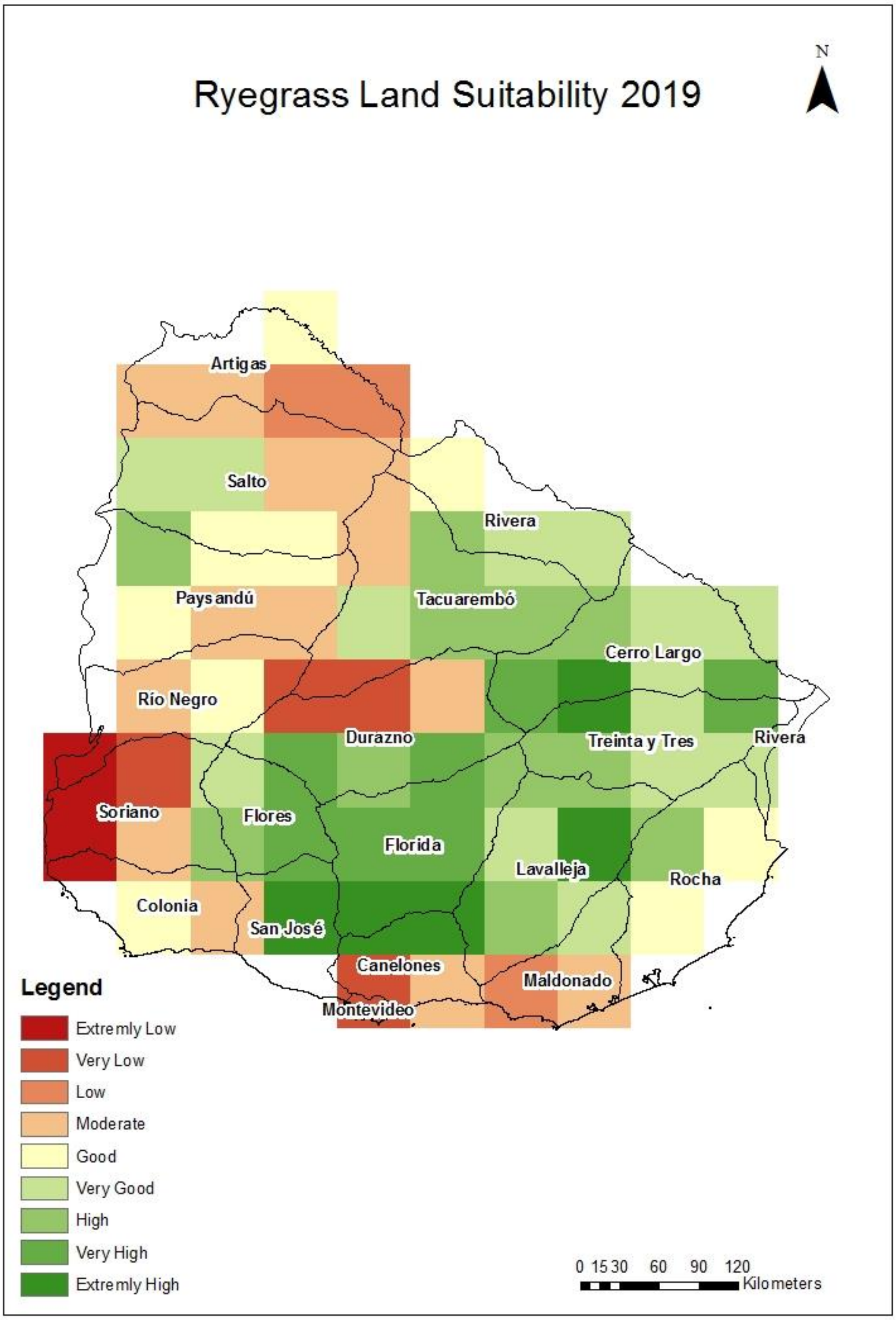


Uruguayan Soil Water Holding Capacity FAO
N
Artigas
Salto
Rivera
Paysandú
Tacuarembó
Cerro Largo
Rio Negro
Durazno
Treinta y Tres
Rivera
Soriano
Flores
Florida
Lavalleja
Rocha
Colonia
San José
Canelones
Maldonado
Montevideo
Legend
13.114 - 16.418
16.418,00001 - 23.876
23.876,00001 - 36.327
Author: Pablo Errazola
Master of Science
Deakin University
0 20 40 80 120 160
Kilometers


FAO SOILS CLASSIFICATION
N
Artigas
Salto
Rivera
Paysandú
Tacuarembó
Cerro Largo
Río Negro
Durazno
Treinta y Tres
Rivera
Soriano
Flores
Florida
Lavalleja
Rocha
Colonia
San José
Canelones
Maldonado
Montevideo
Legend
We
I/Wm/WR/Gm/Re
Ao
Lo
Rd
Hl
Vp
0 20 40 80 120 160
Kilometers
Author: Pablo Errazola
Master of Science
Deakin University


HISTORICAL LUCERNE LAND SUITABILITY
N
Artigas
Salto
Rivera
Paysandú
Tacuarembó
Cerro Largo
Río Negro
Durazno
Treinta y Tres
Rivera
Soriano
Flores
Florida
Lavalleja
Rocha
Colonia
San José
Canelones
Maldonado
Montevideo
Legend
Restricted area
Extreme low
Very Low
Low
Acceptable
Good
Very Good
High
Very High
0 20 40 80 120 160
Kilometers
Author: Pablo Errazola
Master of Science
Deakin University


FAO SOILS CLASSIFICATION
N
Artigas
Salto
Rivera
Paysandú
Tacuarembó
Cerro Largo
Río Negro
Durazno
Treinta y Tres
Rivera
Soriano
Flores
Florida
Lavalleja
Rocha
Colonia
San José
Canelones
Maldonado
Montevideo
Legend
We
I/Wm/WR/Gm/Re
Ao
Lo
Rd
Hl
Vp
0 20 40 80 120 160
Kilometers
Author: Pablo Errazola
Master of Science
Deakin University



Ryegrass Land Suitability 2019
N
Artigas
Salto
Rivera
Paysandú
Tacuarembó
Cerro Largo
Río Negro
Durazno
Treinta y Tres
Rivera
Soriano
Flores
Florida
Lavalleja
Rocha
Colonia
San José
Canelones
Maldonado
Montevideo
Legend
Extremly Low
Very Low
Low
Moderate
Good
Very Good
High
Very High
Extremly High
0 15 30 60 90 120
Kilometers