Supporting traditionally excluded stakeholders to design small-scale tropical agricultural systems and compare their sustainability.

Roberto Carlos Forte Taylor

Department of Bioresource Engineering
McGill University
Montreal, Canada

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ABSTRACT

It is estimated that the number of farms globally reaches 570 million, and family farms occupy 98% of the total farms worldwide (Graeub et al., 2016). There is an ongoing debate about the contribution of small-scale agriculture to world food production. Some experts claim that small-scale agricultural systems' contribution can reach 53% (Graeub et al., 2016) of the world's food production, while other studies estimate up to 70% (ETC Group, 2017). Regardless of the opinions of these experts, the relevance of small-scale agricultural systems' contribution to world food production is undeniable. Small-scale systems tend to be highly complex and diverse, thus contributing to the diversity of crops required by the market while safeguarding the genetic material of crop seeds crucial to the livelihoods of surrounding communities and our civilization.

Some experts argued that the complexity and diversity of these farms could considerably influence their performance and sustainability over time. Despite their critical role in world food production and surrounding communities, farmers in these smallholder farmers (particularly in the early stages of their development) face challenging environmental and climatic barriers. Conditions faced by smallholder farmers and motivators to undertake this activity differ from region to region. In Panama, there have been few attempts to provide technical and financial support to the smallholder farming sector, even though it is critical to the country's food sovereignty. Moreover, its importance was widely reaffirmed during the pandemic. Some of these attempts include the approval of Law No. 127 on Tuesday, March 3, 2020, "By which measures are issued for the development of family farming in Panama." It was published on Wednesday, March 4, 2020 in the Official Gazette. Subsequently, the law was regulated on July 9, 2021, by Executive Decree 112. However, only some programs have been developed. For instance, the Agroecological Family Orchards program (Huertas agroecológicas familiares) lacks a tool to guide and transmit the principles and fundamentals to smallholder farmers on developing sustainable systems. The sector needs more tools to help smallholders' farmers understand their agricultural systems' complexity, their main components, and the interactions between their elements and identify the variables that most influence their sustainability. In addition, the smallholder sector lacks a tool that would allow them to compare the ecological sustainability of small-scale systems under different climatic, environmental, and production conditions over time.

This thesis proposes to combine qualitative (stakeholder analysis and participatory process) and quantitative (stock and flow models) systems. System dynamic modeling (SDM) facilitates the representation of nonlinear, complex, multi-feedback, and unstable problems in small-scale agricultural systems. The result of this research indicates that implementing participatory methodologies for identifying elements, components, and feedback in small-scale systems has great potential. The participatory methodology successfully identified those indicators of importance in the local context when comparing the sustainability of these agricultural systems. Finally, this research work encourages the discussion on the integration of stock and flow models with more technical process-based models to develop tailor-made tools that facilitate the decision-making of farmers and stakeholders in developing this type of system. In the same way, integrating these models will help make these tools more user-friendly without losing the precision and robustness required for decision-making in these small but complex agricultural systems.

RÉSUMÉ

Il existe environ 570 millions d'exploitations agricoles dans le monde, et l'on estime que les exploitations familiales représentent 98 % du total de ces exploitations au niveau mondial (Graeub et al., 2016). Cependant, la contribution de l'agriculture à petite échelle à la production alimentaire mondiale fait l'objet d'un débat permanent. Certains experts affirment que la contribution des systèmes agricoles à petite échelle peut atteindre 53 % (Graeub et al., 2016) de la production alimentaire mondiale, tandis que d'autres études estiment jusqu'à 70 % (ETC Group, 2017). Indépendamment des opinions de ces experts, la pertinence de la contribution des systèmes agricoles à petite échelle à la production alimentaire mondiale est indéniable. Les systèmes à petite échelle ont tendance à être très complexes et diversifiés, contribuant ainsi à la diversité des cultures requises par le marché tout en sauvegardant le matériel génétique des semences de cultures cruciales pour les moyens de subsistance des communautés environnantes de même que de notre civilisation elle-même.

Certains experts proposent que la complexité et la diversité de ces exploitations pourraient considérablement influencer leurs performances et leur durabilité à travers le temps. Malgré leur rôle essentiel dans la production alimentaire mondiale et pour les communautés environnantes, les agriculteurs de ces petites exploitations (en particulier dans les premiers stades de leur développement) sont confrontés à des obstacles environnementaux et climatiques difficiles à surmonter. Les conditions auxquelles sont confrontés les petits exploitants agricoles, de même que leurs motivations d'entreprendre une telle activité, diffèrent d'une région à l'autre. Au Panama, peu de tentatives ont été faites pour soutenir ce secteur sur le plan technique et financier alors qu'il s'agit d'un secteur essentiel pour la souveraineté alimentaire du pays, importance qui fut largement réaffirmée lors de la pandémie. Parmi ces tentatives, cits l'approbation de la loi n° 127 le mardi 3 mars 2020, « Par laquelle sont émises des mesures pour le développement de l'agriculture familiale au Panama. » Elle fut publiée le mercredi 4 mars 2020 au Journal officiel. Par la suite, la loi fut activée le 9 juillet 2021 par le décret exécutif 112. Cependant, seuls quelques programmes furent développés par la suite. À titre d'exemple, le programme de vergers familiaux agroécologiques (Huertas agroecológicas familiares) manque d'un outil pour guider et transmettre aux petits exploitants agricoles les principes et les bases du développement de systèmes durables. Le secteur manque d'outils qui pourraient aider les petits exploitants agricoles à comprendre la complexité de

leurs systèmes, leurs principales composantes, les interactions entre ces composantes et la détermination des variables les plus influentes pour leur durabilité. Étant donné ces lacunes, nous sommes encore loin du développement d'un outil qui permettrait de comparer la durabilité écologique et la production des systèmes à petite échelle dans différentes conditions climatiques et environnementales au fil du temps.

Cette thèse propose de combiner des systèmes qualitatifs (analyse des parties prenantes et processus participatif) et quantitatifs (modèles de niveaux et de flux). La modélisation des dynamiques des systèmes (MDS) facilite la représentation des problèmes non linéaires, complexes, instables et avec de multiples rétroactions dans les systèmes agricoles à petite échelle. Le résultat de cette recherche indique le grand potentiel de la mise en œuvre de méthodologies participatives pour identifier les éléments, les composantes et les rétroactions dans les systèmes agricoles à petite échelle. La méthodologie participative a également permis d'identifier les indicateurs importants dans le contexte local lors de la comparaison de la durabilité de ces systèmes agricoles. Enfin, ce travail de recherche encourage la discussion sur l'intégration des modèles de niveaux et de flux avec des modèles plus techniques basés sur les processus afin de développer des outils sur mesure qui facilitent la prise de décision des agriculteurs et des parties prenantes dans le développement de ce type de système. De même, l'intégration de ces modèles permettra de rendre ces outils plus faciles à utiliser sans perdre la précision nécessaire à la prise de décision.

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ORIGINAL CONTRIBUTIONS TO KNOWLEDGE

This research presented here used participatory methods to better understand the climate resilience of small-scale farming systems, and to develop meaningful computational tools for this purpose that are appropriate for the needs of local stakeholders. The research was applied a novel combination of participatory processes, computer-assisted qualitative data analysis software, causal loop diagrams, and system dynamics modeling tools in the context of small-scale tropical agriculture. Amid extreme mobility constraints caused by the COVID pandemic, semi-structured interviews and the use of computer-assisted qualitative data analysis software proved to be highly effective. This work maps the development of customized dynamic system models built on stakeholder knowledge and integrated with process-based models, to increase end-users' understanding of ecological processes and help design small-scale agricultural systems that are resilient to climate change.

This work has made the following specific contributions.

1. Terms pertinent to the discussion of small-scale farming practices and systems were examined, compared, and clarified.
2. Tools such as bibliometrics, content analysis, H-indexes, and citation counts were applied for the first time to examine the evolution of the concept of permaculture over time and its acceptance by scientists.
3. A framework for stakeholder involvement was developed that incorporates rigorous, robust, and reliable qualitative and quantitative research methodologies. It helps promote the idea of ecologically sustainable, small-scale farming to academics, professionals, and the broader community.
4. The framework was employed to help traditionally marginalized stakeholders (community leaders, landowners, smallholder farmers, and extension agents):
   a) Conceptualize small-scale farming systems compatible with the local agricultural context;
   b) Identify drivers and barriers to their implementation;
   c) Identify elements that influence their ecological sustainability;
   d) Compare their sustainability at a conceptual level, based on indicators such as yield and soil health;

    e) Provide information to guide the development of computational models of small-scale agricultural systems.

5. Computational models of small-scale agricultural systems were created incorporating the knowledge of the stakeholders.
6. An approach was proposed to combine the stakeholder-based models with process-based models commonly used for analysis of large-scale agricultural production systems.

CONTRIBUTIONS OF AUTHORS

Chapter 1 and 2 – Roberto Forte wrote the two chapters completely, with Dr. Grant Clark reviewing and editing them.

Chapter 3 – The entire manuscript was written by Roberto Forte, who acquired funding, collected data (in English and Spanish), conducted the data analysis, and created all figures and tables. Dr. Julian Malard collected the data (in French) and reviewed and edited the manuscript. The manuscript was also reviewed and edited by Dr. Grant Clark, who provided funding, supervised the conceptualization and execution of the literature review.

Chapter 4 – Roberto Forte drafted the entire manuscript, conducted the participatory field process, analyzed the data, and created all figures and tables. The manuscript was reviewed and edited by Dr. Julian Malard. Dr. Grant Clark also reviewed and edited the manuscript and supervised the conceptualization and execution of the research.

Chapter 5 – Roberto Forte drafted the entire manuscript, created all the figures and tables, built the model, performed the model sensitivity analyses and model stability tests, and analyzed the results. Dr. Grant Clark reviewed and edited the manuscript, as well as supervised the conceptualization and execution of the model and methodology.

Chapter 6, 7 and 8 – Roberto Forte wrote the two chapters completely, with Dr. Grant Clark reviewing and editing them.

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LIST OF ABBREVIATIONS

CLDs	Causal loop diagrams
DNDC	DeNitrification-DeComposition model
NGOs	Non-Governmental organization
PSDM	Participatory system dynamics model
RPR	Residue to product ratio
SDM	System dynamics model
SF	Stock and flow model
SOM	Soil organic matter

CHAPTER I: **Introduction**

The world is losing its fertile soil at a rate of 24 billion t per year according to a recent report by the Secretariat of the United Nations Convention to Combat Desertification (UNCCD). The report also alleges that at least 1.3 billion people, mostly located in developing countries, are trapped in degrading lands and thus excluded from the right to economic development (UN, 2017). Moreover, the Science and Policy for People and Nature (IPBES) Secretariat asserted that the well-being of at least 3.2 billion people on the planet had been negatively impacted by the degradation of the Earth's surface (Science and Policy for People and Nature 2018). IPBES also warned that the constant pressure exerted by anthropogenic activities are driving the Earth towards its sixth mass species extinction.

I.1 Background

I.1.1 Population growth

The world population continues to increase, however at a slower rate than at any time between 1950 and now. This is due to reduced fertility levels in some regions of the world. According to the United Nations (UN, 2019) it is estimated that there were 7.7 billion people worldwide in 2019 and it is projected based on a medium variant scenario that the world population could grow to 8.5 billion by 2030, 9.7 billion by 2050, and 10.9 billion by 2100.

Population in 55 countries could decrease by 1% or more between 2019 and 2050 due to the constant low fertility and high emigration rates. Furthermore, in countries such as Bulgaria, Latvia, Lithuania, Ukraine and Wallis and the Futuna Islands, population reductions of 20% or more are projected. On the other hand, half of the world population will be concentrated in countries such as the Democratic Republic of the Congo, Egypt, Ethiopia, India, Indonesia, Nigeria, Pakistan, the United Republic of Tanzania, and the United States of America by 2050. The growth rate between China and India is projected to reverse, and thus India will overtake China as the most populous country in the world by 2027 (UN, 2019).

According to the UN, there are countries with the highest growth among the 47 least developed countries in the world. Hence, it is expected that many of these countries will double their population between 2019 and 2050. This rapid and continuous population growth will generate enormous pressure on the already depleted natural resources and on the policies and strategies that aim to achieve the 17 goals of sustainable development. For many countries, including some small developing islands, the challenges are even more significant as they are compounded by their vulnerability to climate change and sea-level rise. There is no doubt that this rapid and continuous growth of the population presents challenges for the sustainable development of future generations (UN, 2019). Besides, this rapid rate of change in population will bring significant economic and social challenges. Ecological Engineering design will supply meaningful answers and solutions to the complex problems facing by the next generations. These responses include the design of more resilient agricultural systems, converting urban areas back into forests and create affordable, prosperous and sustainable communities in an ageing population (Matlock and Morgan 2011).

I.1.2 Human demand for ecosystem services

The demands for food, feed, fibre and fuel will increase considerably, possibly creating resource shortages and complications in the supply chain. According to Matlock & Morgan (2011), food production will have to raise at least 50 percent in the next 40 years to satisfy the imminent demand. However, food production that meets future needs must face significant challenges such as competition between food and biofuels for land and water, as well as the harmful effects of climate change (Matlock et al. 2011). In addition to this, the world is losing its fertile soil. It is estimated that more than 1500 million hectares of natural ecosystems have been transformed into farmland (Science and Policy for People and Nature 2018). The land used for food production (crops, grasslands, and pastures) occupies approximately 40% of the entire unfrozen surface of the Earth (Matlock et al. 2011). More than 75% of the earth's surface has suffered substantial impacts from anthropogenic activities, and IPBES estimates that by 2050 these surfaces will expand to more than 90% of the earth's total surface (Science and Policy for People and Nature 2018). As a result of the constant pressures of anthropogenic activities, ecosystem services (water, food, sediment control, fresh air, medicine, among many others) have been considerably reduced.

On the contrary, the demand for these services continues to increase as the world population increases. We all depend on nature and the services provided by ecosystems to provide the conditions for a healthy and safe life (Watson 2005). The loss of ecosystem services adds to the barriers that make it challenging to meet sustainable development goals such as reducing poverty, hunger and disease. Strategies, measures and efforts for the restoration of ecosystem services must include and empower local communities; implement mainly natural and human technology complementary; and will require close coordination between governments (national/local), public and private sectors (Watson 2005). Finally, the productivity of ecosystems will require an in-depth review of the conventional options of policies, investments, subsidies, taxes and regulations (Watson 2005).

I.1.3 Climate change

The Intergovernmental Panel on Climate Change (IPCC) is 95% confident that humans are the leading cause of global warming (Intergovernmental Panel on Climate Change 2018). Anthropogenic activities are estimated to have caused approximately 1.0°C of global warming above pre-industrial levels, and it is expected that global warming will reach 1.5°C between 2030 and 2052 if it continues to increase at the current rate (Intergovernmental Panel on Climate Change 2018). According to the IPCC, the more that anthropogenic activities disrupt Earth's climate, the higher the risks of extreme, permeating, and irreversible impacts for humans and ecosystems (Intergovernmental Panel on Climate Change 2014). Besides, IPCC estimated that “agriculture, forestry, and other land use” (AFOLU) account for 24% of global greenhouse gas emissions (Intergovernmental Panel on Climate Change 2014). These greenhouse gas emissions come mostly from agriculture practices such as crop cultivation, livestock, and the deforestation that historically precedes them. Vulnerable populations, indigenous peoples, and local communities dependent on agriculture are in a higher risk of severe consequences with global warming of 1.5°C (Intergovernmental Panel on Climate Change 2018). Even though there are few studies on the impacts to which Central America and the Caribbean may be exposed under a 1.5°C scenario, small islands, and coastal communities are projected to be exposed to more intense tropical cyclones (Intergovernmental Panel on Climate Change 2018). Evidence of this undeniable claim by IPCC includes Hurricane Dorian's devastation, which lands on Great Abaco Island, Bahamas, on September 1, 2019. By the time it reaches Grand Abaco Island (17,224 inhabitants), Hurricane Dorian was a category 5. Coincidentally Hurricane Dorian matched the hurricane known as the "Labor Day" of 1935 as the strongest hurricane recorded in the Atlantic with maximum sustained winds of up to 185 miles / h. On September 2, Dorian, still a category 5 hurricane, made landfall on Grand Bahama, where it stalled for approximately 24 h before moving up the east coast of North America. Reports have identified over 60 hurricane-related fatalities; official damage was estimated at US $7 billion; hundreds of people are still reported as missing (Bouland, Selzer et al.).

It is estimated that 75% of the world's poor (up to 800 million) live in rural areas, and primarily rely on agriculture (farming, livestock, and aquaculture) which is their most important income source (World Bank Group, 2013). Hence, agricultural productivity and efficiency must be increased, especially in the smallholder sector, to reduce poverty and to achieve food security in rural areas.

However, global warming and the harmful effect of climate change are already hindering agricultural growth. Climate change is affecting crop production, especially in rural areas, which are expected to substantially impact water availability and supply, agricultural incomes, and food security (Intergovernmental Panel on Climate Change 2014). Frequency and intensity of extreme events such as flooding, heavy rainfall, and drought are expected to accelerate in many regions. Recently the Food and Agriculture Organization (FAO) and the World Meteorological Organization signed a memorandum of understanding to deepen their cooperation in response to climate variability and climate change, which, according to the agreement, "represents an urgent and potentially irreversible threat to human societies, natural ecosystems, and food security" (Food and Agriculture Organization 2017).

Climate change has already reduced global yields of maize and wheat by 3.8% and 5.5% respectively (Lobell, Schlenker et al. 2011), several studies have warned of precipitous declines in crop productivity due to higher temperatures from global warming (Peng, Huang et al. 2004; Schlenker and Roberts 2009). Increased climate variability intensifies production risks and challenges to smallholder farmers. Recently, a team of researchers from the University of Minnesota's Institute on the Environment dedicated four years to collect data on crop productivity and weather from around the world. The study focused on analysing if whether climate change was affecting crop productivity and global food security. The team focused on the top 10 global crops that compile most consumable food calories, which include: maize, rice, wheat, soybeans, oil palm, sugar cane, barley, canola, cassava, and sorghum. The study concluded that climate change had affected yields in many places, including Central America and specifically Panama, where consumable food calories have decreased. Moreover, the study stated that overall, climate change is reducing the global production of staples such as rice and wheat (Ray, West et al. 2019). "When we translated crop yields into consumable calories — the actual food on people's plates — we found that climate change is already shrinking food supplies, particularly in food-insecure developing countries" (Ray et al. 2019). Henceforth, climate change poses a threat to food access for rural communities by decreasing crop production and incomes, and disrupting markets (Lipper, Thornton et al. 2014).

I.1.4 Panama: From jungles to pastures

Figure 1.1. Study area in Mariato district, Panama.

Panama is located in the intertropical zone close to the equator, and it is an isthmus oriented from East to West, limited in its coasts by the Caribbean Sea and the Pacific Ocean. These oceanic masses are the primary sources of high moisture content in the environment. The oceans highly influence the climate in Panama due to the narrowness of the isthmus (Empresa de Transmisión Eléctrica S.A., 2009). Mariato is a coastal district in the southern part of Panama in the Azuero Peninsula. The economy in Mariato is mainly based on livestock, monocultural agriculture, shrimp farming, and, recently, tourism. Fig. 1.1 illustrates satellite images of Panama and the Mariato District, where this research was conducted.

The first zoological expedition reported in the Azuero Peninsula in Panama was carried out by Rex Benson in 1925 for the American Museum of Natural History. During this expedition, Benson spent a summer in Punta Mala in which he managed to catalog 160 bird specimens. Benson described the Azuero Peninsula at that time as a mountainous region covered in heavy forests (Aldrich and Bole 1937). Later, between February 2 and April 4, 1932, two zoologists from the Museum of Natural History of Cleveland, John Aldrich and Benjamin Bole, carried out an expedition to the Azuero Peninsula. The Cleveland Museum in 1937 later published the results of this expedition as "The Birds and Mammals of the Western Slope of the Azuero Peninsula". During the expedition, Bole and Aldrich described the topography and climate of the peninsula. They observed pebble beaches, mangrove-lined estuaries and stream outlets with extensive mud plains exposed at low tide. Half a mile from the bay they identified a low flat plain with interspersed lagoons, mangroves, and bottomland forests. It was evident to Bole and Aldrich that this land had risen above sea level in a relatively recent geological time. In addition, they catalogued the area as a semi-deciduous forest characteristic of the arid division of the Lower Tropical Zone. According to Aldrich and Bole, the semi-deciduous nature of the forest disappeared very quickly as they advanced on their way from the low coastal plain to the mountains. Bole and Aldrich reported that one of the sample collection stations (birds and mammals) was located in Mariato. Specimen's collection was carried out in " heavy semi-deciduous forest 10 miles inland from Montijo Bay along the banks of the Mariato River" (Aldrich et al. 1937) They also described that these dense semi-deciduous forests appeared from the slopes of the lower mountains. At 1000 feet above sea level, Aldrich and Bole described the area as "the humid division of the Tropical Zone, where the trees retain most of their leaves throughout the dry season."

The findings outlined by Benson, Aldrich, and Bole contrast radically with those reported by the anthropologist and sociologist Stanley Heckadon-Moreno in his book "De Selvas a Potreros" published in 2009, which highlights that men destroyed the forests to establish subsistence crops and later turned them into extensive pastures. By 1947 there were only 15% (200 km^2) and 30% (1100 km^2) forest areas left in the two main provinces of the Azuero Peninsula, Herrera and Los Santos, respectively. According to Heckadon-Moreno, the cause of the massive deforestation of at least 50,000 hectares of productive land by 1973, was the annual cultivation practice of slash-and-burn and extensive livestock. These agricultural practices accelerated environmental degradation and soil impoverishment. The deforestation altered the hydrology of the rivers, reduced the volume of rainfall and increased soil erosion and sedimentation that resulted in constant flooding of the lowlands in the rainy season, causing considerable losses in crops and livestock (Heckadon-Moreno 2009).

The Azuero Peninsula belongs to the area called the Dry Arch of Panama. According to data from the Electric Transmission Company S.A. (ETESA) temperatures in the region can reach up to 38 ^{o}C during the hottest months (April, May, and June). In the District of Mariato the annual average temperature is 23.8 ^{o}C, nevertheless high and low temperatures of 34 ^{o}C and 14 ^{o}C respectively have been recorded (44 years of data collection). In general, the dry season lasts about four months (December to April), and the rainy season lasts about eight months (April to December). In the dry season, the region is swept by the trade winds of the north, which together with low rainfall, low humidity, and high solar radiation intensify the effects of desiccation. During the rainy season, the majority of precipitation occurs between September and November. A phenomenon known as the “Veranillo de San Juan” often interrupts the continuity of the rains during the first three months of this season (Heckadon-Moreno 2009).

It is the forests that article 123 of the constitution identifies as uncultivated, unproductive, or idle land. A goal of the public and private sector of the country has been to integrate the remaining forest areas of the country into the national economy (Heckadon-Moreno 2009). The most ecologically severe problem facing the country is the vast destruction of remaining forests due to a process of uncontrolled colonization based on extensive livestock and timber extraction. The causes of the emigration of the peasants to the jungles and cities are very complex. One of the hypotheses is that the construction of the Panama Canal generated profound transformations in rural society that resulted in the current process of urbanization and the creation of the beef market. Another motivator of the massive deforestation and immigration of the peasants to the cities was the demographic growth provoked by public health improvement, which ultimately led to doubling of the rural population every three decades. In order to feed this population, pressures on natural resources (i.e. Darien province jungle colonization) were accentuated, expanding slash-and-burn crops and livestock production (Heckadon-Moreno 2009). According to the anthropologist Gloria Rudolf (2003), by 1903 (year of the foundation of the Republic of Panama), the majority of the population lived in the countryside, earning a living as subsistence farmers, fishers, and hunters. However, almost 100 years later (2000), only 38% of the population remained rural. Of the remaining 62% of the country's population, 68% were concentrated in the two most significant districts of the capital (Panama and San Miguelito) and cities near the capital (Arraijan and Chorrera) (Rudolf 2003). According to Rudolf (2003), the massive rural-urban migrations from World War II were motivated because the countryside had become a place of subsistence crisis. Even when the specific causes of these migrations depend on place and time, Rudolf (2003) adjudicated them to two significant generic facts. The first that people who lived in rural areas were losing access to enough fertile land for their livelihood. Heckadon-Moreno (2009) claimed that the deterioration of the soils was directly related to the indiscriminate practices of extensive livestock and timber extraction. For Rudolf (2003), based on his extensive research of the rural town Loma Bonita, in the province of Cocle, another possible cause was the motivation of farmers in the 1920s to plant coffee monocultures for commercial purposes. Rudolf (2003) didn't explain what encourages Loma Bonita farmers to leave their traditional farming practices (based on slash) and instead only plant coffee monocultures. Rudolf (2003) stated that in a short time, whole families generated large debts with coffee merchants that generated a more insecure economic situation for them. For Rudolf (2003), "commercial agriculture generated within Loma Bonita a growing inequality between domestic groups - and between men and women - in their access to land." The second cause of the massive immigration to the cities is that by not having their land to work on, people were adrift in a minimal and insufficient labour market that did not allow them to cover their basic needs neither to stay in the countryside.

Millions of people migrate to large cities every year, leaving behind the lands that have belonged to their families for generations. Their descendants grow up with the idea that agriculture naturally leads to the degradation of the soil and its nutrients (United Nations Convention to Combat Desertification 2017). All this is amplified by a generalized perception that farming is for uneducated people and barely feasible. In turn, society loses valuable traditional agricultural knowledge transferred from generation to generation for hundreds of years and often, along with this knowledge, the cultural identity of its rural areas. The industrialized agricultural sector has shown considerable improvements in technology, yield and production in the last 60 years.

However, some experts (Filson 2004; Horrigan et al., 2002) adduced that conventional agriculture is also causing environmental and land degradation, among other problems.

Small-scale agricultural systems have been proposed internationally as alternative agriculture options, for the smallholder sector. Experts and practitioners of these systems claim that they generate less CO_2 emissions (Akhtar et al., 2016; Altieri and Norgaard 1987; White 2020) and even have the capacity to sequester carbon from the atmosphere (Badgley, Moghtader et al. 2007; Reganold and Wachter 2016). Furthermore, these systems are perceived sustainable since they are less energy-intensive, promote a closed cycle of inputs and considerably reduce the use of pesticides and fossil fuel-based fertilizers (Toensmeier 2016).

I.2 Research Questions

How does the sustainability of different agricultural production systems in Panama compare with each other and against conventional monoculture systems, using production, and soil quality indicators as a basis for comparison?

We acknowledge various definitions of sustainability (financial, ecological, and social). For this research work, ecologically sustainable systems are those that are not highly mechanized and therefore operate with little or no use of fossil fuels or external inputs (synthetic fertilizers, herbicides, and pesticides), and can remain productive over time compared to the baseline (conventional monoculture) while maintaining soil quality.

To test this research question, we propose a series of objectives listed as follows:

I.3 Research Objectives

I.3.1 General

The overall objective is to develop a methodology combining qualitative (stakeholder analysis and participatory process) and quantitative (stock and flow models) methods to evaluate the ecological sustainability of small-scale agricultural systems in rural areas of Panama.

I.3.2 Specific objectives

1. Review the current state-of-the-art in small-scale agricultural systems. Analyze the body of scientific literature about permaculture, focusing on the evolution of the concept over time and its acceptance in the scientific community.
2. Implement a farmer-oriented participatory process in Mariato, Panama, to:
    a) Understand the agricultural context of the region;
    b) Identify problems that limit the implementation of small-scale agroecological systems;
    c) Use tools such as Causal Loop Diagrams (CLDs) and Loop Polarity Analysis to compare stakeholders' understanding of small-scale farming systems and their ecological performance.
3. Use participatory System Dynamic Modeling (SDM) methods to analyze concepts about the ecological sustainability of small-scale agriculture systems:
    a) Create stock-and-flow models to visualize the key components of small-scale agricultural systems as conceived by the stakeholders;
    b) Use the stock-and-flow models to compare the ecological performance of small-scale agricultural systems, based on productivity and soil health indicators.
4. Propose a more sophisticated modeling approach to compare the sustainability of small-scale agricultural systems:
    a) Consider the integration of stock-and-flow and process-based models, such as the DeNitrification-DeComposition (DNDC) model;
    b) Develop an interface for the models using Stella architect, Vensim, or similar user-friendly software, to improve accessibility for stakeholders with different technical and educational backgrounds, such as community leaders, farmers, and extension workers.

I.4 Structure of the Thesis

Chapter 1 summarizes the state of knowledge on regenerative agriculture, family farming, and small-scale agriculture from an ecological and social perspective. Each of the following chapters is derived from a different scientific publication of the author of this thesis. Chapter 2 presents a systematic review of literature in three different languages (English, French, and Spanish) about the term permaculture and its evolution through time. Chapter 3 presents the methodology and results of the inclusive, participatory study of stakeholder knowledge. The resulting information was then used to develop system dynamic models of small agricultural systems in the study region. Chapter 4 maps out the development of a process-based model for small-scale farming systems, from establishing its scope to building confidence in the model. Chapter 5, in conclusion, reiterates the original contributions of this work and offers recommendations for further research on these topics. Chapter 6 contains general references from those chapters that were not written as manuscripts for publication.

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CHAPTER II: **Literature review**

The agricultural sector underwent unprecedented transformations in the 50s, from the manual cultivation of grains to the mechanization of the agricultural sector (60 to 70). For example, the area of land per worker increased from 1 to more than 200 hectares. Moreover, the average grain (barley, spelt, emmer wheat, etc.) yield, which in the 1970s was of the order of 1000 kg per hectare (traditional agriculture without fertilizer application), is increased to more than 5000 kg per hectare in industrialized agriculture (chemical fertilizer application) (Mazoyer and Roudart 2006). Milk production is an excellent example of how industrialized agriculture significantly increased (1940s – 1970s) work pride compared to traditional agriculture of the time. While a farmer milked a dozen cows by hand twice a day, with the progress of mechanization, the same farmer milked fifty of them in a herringbone shed, and one hundred with a rotating milking stand (rotolactor) (Mazoyer et al. 2006).

According to Vereijken (2003), in Europe, agricultural research, education and extension contributed significantly to increased productivity and efficiency in the use of labour. The success of agriculture in Europe (1950-2000) prompted the reestablishment of goals and targets on land use and agricultural production. In principle, the agrarian sector had as its main functions the production of food for the urban and rural population, in addition to providing work and income to the rural population. After World War II, the region lacked food production and income to meet the needs of the population, especially in rural areas. Therefore, the region decided to implement a combination of policies and subsidies that included, guaranteed prices and protection against food imports. These set of policies also encouraged improvements in the efficiency of production processes, turning food shortages into excess food, coupled with a reduction in jobs. As a result, employment rates fell sharply, and poverty levels increased in many rural regions (Vereijken 2003).

However, the industrialization of agriculture has contributed in large part to numerous forms of environmental and health degradation, such as loss of biodiversity, soil degradation, air and water pollution and greenhouse gas emissions (Altieri 1998; Horrigan, Lawrence et al. 2002; Kimbrell 2002). Agroecology, born as a scientific discipline, to later become an agricultural practice arises in response to the challenges that emerged with industrialized agriculture and intended to promote more sustainable agriculture (Krebs and Bach 2018). There are many variants of agroecological systems, among which are organic agriculture, permaculture, bio-intensive, biodynamic, and natural farming.

II.1 Agroecology

The term "agroecology" dates back to 1928, and it was first used by Bensin (1928; 1930). In its beginnings, agroecology was considered only a scientific discipline. It was not until the 60s that the term agroecology was conceived as describing a movement. In that period, a more significant global awareness towards the care and protection of the environment began to emerge, due to the impact of industrialized agricultural evolution(Wezel, Bellon et al. 2009). Furthermore, Agroecology emerged as an initiative to try to understand the complexity of traditional agricultural ecosystems better and thus respond to the growing concerns of its impacts (pollution, deforestation, cancer, among others) resulting from an agri-food system focused on industrialization and globalization (Altieri and Norgaard 1987; Méndez, Bacon et al. 2013). In its early stages, agroecology focused on the application of ecological principles and strategies for the design of more sustainable agricultural systems (Altieri et al. 1987; Gliessman, Garcia et al. 1981). Later, agroecology was integrated with social science concepts and methods that helped to understand the complexity of traditional agricultural systems (Méndez et al. 2013). Currently, the term agroecology represents a scientific discipline, an agricultural practice, and a political or social movement (Wezel et al. 2009).

II.2 Smallholder

The concept of family farming is widely used in the literature, and its contributions to the agricultural and food production sectors are widely recognized throughout the world (Food and Agriculture Organization 2017; Samberg et al., 2016; Lowder et al., 2016). A recent study (2014) from Food and Agriculture Organization of the United Nations (FAO) showed that family farms comprise a large part of the world's agricultural land. The study estimates that agricultural families produce 80% of the world's food. The Action Group on Erosion, Technology and Concentration (ETC) carried out a study in 2009 that was lately updated in 2014 and 2017 which estimated that 4.5-5.5 billion (70% of the world's population) people depends on the small family farmers web.

Moreover, ETC (2017) claimed that the small family farmers web produces approximately 70% of the world's available food, in calories and weight. According to ETC developing countries harvest "53% of the world's crop calories consumed by humans (e.g. 80% of rice and 75% of groundnuts)". In Latin America, the literature shows that the contribution of small family farms averaged 40% in crops and livestock. The study estimated the contribution of the sector to be 60%, 52% and 43% in Honduras, El Salvador and Brazil respectively (Altieri & Hecht, 1990). Likewise, the literature also suggests that small farms contribute to the conservation of crop diversity and tend to achieve higher yields than larger farms (Altiere, 2008).

However, in recent years some experts have considered that one of the most critical barriers that prevent the generation of productive policy dialogue in the agricultural sector, is the lack of clarity, and adequate terminology (Lowder et al., 2016). Garner & Campos (2014) concluded that considering the diversity of definitions that already existed on the term family farming, it made more sense to propose a concept that would highlight the main characteristics of this term instead of adding another definition to the large stack. Through an exhaustive review of 36 different definitions of the term worldwide, Garner & Campos (2014) proposed six common aspects that define a family farm: labour, management, size, family inter-generational considerations, social and family ties and subsistence or profitable business. According to Garner & Campos (2014) "Family Farming (also Family Agriculture) is a means of organizing agricultural, forestry, fisheries, pastoral and aquaculture production which is managed and operated by a family and predominantly reliant on family labour, both women's and men's. The family and the farm are linked, coevolve and combine economic, environmental, reproductive, social and cultural functions". Meanwhile, the Committee on World Food Security's (CFS) High Level Panel of Experts (HLPE) in 2013 defined smallholder agriculture as "…families (including one or more households) using only or mostly family labour and deriving from that work a large but variable share of their income, in kind or in cash. Agriculture includes crop raising, animal husbandry, forestry and artisanal fisheries…" (Bosc, Berdegué et al. 2013). In both definition workforce, operation and management of the farm are carried out mostly by a family; Moreover, both infer that the concept family farming and smallholders are not exclusively defined by the size of landholdings. However, the terms family farming and smallholder continues to be used interchangeably in the literature.

Some studies use the term ‘smallholder farmer’ to refer to those that are capable to produce within 1 to 10 hectares (Dixon et al., 2004). Some authors differentiate smallholder farm from family farm by establishing a site limit of less than 2 hectares (Thapa 2014) while others found that this limit may be applicable to some regions but not all (Berdegué and Fuentealba 2011). Some experts consider that many of the claims about the impact of family farms on feeding the world lack of the relevant documentation that supports them, obsolete information, or the estimates are not based on comprehensive global comparisons. Nevertheless, some of the conclusions reached by these experts coincide in some of the claims made by FAO (2014) and ETC (2017) regarding the impact of family farms on the world production of food. Such is the case of the percentage represented by family farms and how many smallholders. For the purpose of this research work family farms are all those farms where labour is mostly carried out by family members while smallholder farmers are a subgroup of family farmers that manage land area not exceeding 2 hectares. According to Lowder (2016), approximately 570 million farms exist in the world, of which 72% (410 million) occupy land areas of less than 1 hectare, and 84% (475 million) occupy less than 2 hectares of land. In terms of size and distribution, The State of Food and Agriculture - SOFA (2014) claims that the vast majority of farms in the world are small or very small. They also assure that even in countries of low income the sizes of the farms are reduced more and more. According to SOFA (2014), farms under 1 hectare of land account for 72% of all farms in the world. Moreover, the farms between 1 and 2 hectares of land account for 12% of all the farms in the world. On the contrary, farms of more than 50 hectares only account 1% of the total farms in the world; however, they control 65% of the world's agricultural land.

Graeub et al (2016), agrees that the number of farms in the world reaches 570 million and add that family farms occupy 98% of the total farms worldwide. However, using a more extensive and updated data set (census data from 105 units-98 countries and seven territories) than the one used by SOFA 2014, they concluded that family farms produce at least 53% of the food of the world. Besides, family farms cover 53% of all agricultural land in the world. These conclusions considerably differ from what SOFA 2014 established regarding the land tenure of family farms (75%) and also the percentage of the contribution of family farms to the world's agricultural production (80%). More studies will be required in the future to finally reach an agreement on the number, production, and dimensions of the different subgroups within family farms. However, the critical role of the smallholder sector in the current food production and the long-term fulfilment of the second goal of sustainable development (Zero Hunger) is undeniable (Lowder, 2016). Recently, the international agricultural sector has turned its attention to smallholders. More and more research keeps piling up to support the impact of these family farms on feeding our planet, in addition to the potential impact they have (when applying good practices such as agroforestry, silvopastoral, and permaculture) in increasing biodiversity, reducing poverty and CO_2 emissions. The potential of these smallholders is very well aligned with the Sustainable Development Goals (SDGs), mainly because experts have recognized that a more sustainable agricultural sector is essential for reducing poverty, hunger and CO_2 emissions (Samberg et al., 2016).

II.3 Regenerative Agriculture

According to O'Donoghue et al. (2015), the idea of sustainable agriculture had been discussed since the 50s and 60s and played a vital role during the United Nations (UN)-backed Brundtland Commission (1983–1987). However, the concept of regenerative agriculture dates back to the 80s, when some authors (Gabel 1979; Sampson 1982) emphasized that the restoration of crucial resources (whose degradation was caused by the practices implemented by conventional agriculture) was required to achieve sustainable food production O'Donoghue et al., O'Donoghue, Minasny et al. (2022). Other authors (Colley et al., 2020) argue that the term regenerative agriculture tends to be used interchangeably with other terms such as agroecology, ecological agriculture, conservation agriculture, and holistic farm management. Regenerative agriculture is a set of practices that seek to restore the health and fertility of the soil, and promote the protection of biodiversity and watersheds, thus improving ecological conservation and economic resilience (White 2020). The scope of regenerative agriculture includes improving living conditions above and below the surface. Furthermore, this is achieved by implementing good practices, especially in degraded areas, which facilitate and accelerate soil recarbonization through photosynthesis and biology. Regenerative agriculture is therefore considered to have great potential to sequester increasing amounts of atmospheric carbon (CO2) underground at low cost. In addition, it is proposed as an agricultural system capable of producing healthy and highly nutritious food (White 2020).

II.4 Alternative Agriculture Critics

Clark and Tilman (2017) carried out a study in which they analyzed 164 publications on food life cycle assessment (LCA) published before July 2015. These publications, in total, comprise 742 unique food production systems. Clark and Tilman (2017) established five indicators (greenhouse gas emissions, land use, energy use, acidification potential, and eutrophication load) to compare the sustainability of organic vs. conventional systems. Their analysis includes pre-farm and on-farm activities such as fertilizer production and application, agricultural energy use, feed, and seed production. Clark and Tilman (2017) report that 86% of LCAs were carried out in Europe, North America, Australia, and New Zealand, while the rest occurred in countries such as China, Japan (2%), and the African continent. Clark and Tilman (2017) conclude that organic systems require 25-110% more land use, require 15% less energy, and have a 37% higher eutrophication potential than conventional systems per unit of food. In their study, the generation of greenhouse gas emissions and the acidification potential do not differ significantly between both systems.

II.5 Common Small-Scale Agroecological Systems

Manifold studies are conclusive on the imminent need to implement significant changes to the global food system. Agriculture must face two main challenges: 1) The sector must feed a growing population, with an increasing demand for meat and high-calorie diets 2) on the other hand, the industry must minimize environmental impacts and the generation of CO_2 emissions globally (De Ponti et al., 2012; Sauer 1990; Seufert, Ramankutty et al. 2012; Thapa 2014). Alternative or agroecological systems are becoming increasingly popular, especially on a small scale. In countries like France, the so-called "microfarms" have aroused greater interest and increased their public profile (Morel and Léger 2016). Unlike conventional agriculture, whose primary focus is to maximize crop income and yield, agroecological systems tend to share some key characteristics (Fortier 2014; Hervé-Gruyer 2014):

1) Smaller commercial market gardens
2) Locally oriented marketing (community)
3) Sales and logistics through short chains implementing programs such as (CSA, farmer markets, community food cooperatives, amongst others)
4) A wide diversity of crops

5) Low level of mechanization and investment in equipment and technology
6) Enhance biodiversity, especially in previously degraded soils, improve the ecosystem's health and promote social well-being.
7) Implement a wide range of alternative strategies, practices, and philosophies such as biointensive agriculture (Ecology Action, 2015; Jeavons, 1982); natural farming (Fukuoka 1978); biodynamic (Steiner 2013; Turinek et al., 2009); permaculture (Ferguson and Lovell 2014; Holmgren 2013; Mollison and Slay 1988); among many others.

Based on a comprehensive literary review, some of the most applied and/or studied agroecological systems on a smallholder farm-scale include: permaculture systems, organic farming, and bio-intensive farming (Birovljev and Ćetković 2014; Ferguson and Lovell 2014; Fortier and Bilodeau 2014; Jansen 2000; Morel, Guégan et al. 2015; Morel et al. 2016; Morel, Leger et al. 2019; Morel 2018; Seufert and Ramankutty 2017; Seufert et al. 2012). International case studies, including many carried out in Quebec, Canada and France implement these systems either in combination or independently. From these three systems, the one that compiles the majority, scientific studies and publications is organic agriculture. From organic systems, one can find an extensive body of information which includes systematic literature reviews and meta-analyses (Seufert et al. 2017; Seufert et al. 2012).

II.6 Organic Agriculture

According to the International Federation of Organic Agriculture Movements (IFOAM) "Organic Agriculture is a production system that sustains the health of soils, ecosystems and people. It relies on ecological processes, biodiversity and cycles adapted to local conditions, rather than the use of inputs with adverse effects. Organic Agriculture combines tradition, innovation and science to benefit the shared environment and promote fair relationships and a good quality of life for all involved"(IFOAM 2005).

The Organic Agriculture Research Institute (FIBL), in cooperation with the International Federation of Organic Agriculture Movements (IFOAM), published in 2020 a compelling study on the status of organic agriculture worldwide (Willer et al., 2020). The survey collects data from more than 186 countries/territories. Willer et al (2020) estimated that the share of organically managed land attains 1.5% of the total agricultural land in the world. By 2018, the extent of organically managed land in the world was approximately 71.5 million hectares (Willer et al., 2020). Oceania is the region that tops the list on the amount of land under organic practices with 36 million hectares, which represents 50% of the total organically managed land in the world (Willer et al., 2020). Oceania also leads with the highest organic share of total agricultural land, by region (8.6 %) followed by Europe with 3.1 % and Latin America with 1.1 %. Europe also follows Oceania in the number of hectares managed organically with 15.6 million hectares, then Latin America (8 million hectares), Asia (6.5 million hectares), North America (3.3 million hectares) and Africa (2.0 million hectares) (Willer et al., 2020).

In the European Union, the proportion of organically managed land vs. the total agricultural area is 7.7% (Willer et al., 2020). In other regions, the organic land share is less than 1%. In 57% (100) of the countries included in the study, less than 1% of their agricultural land is organically managed (Willer et al., 2020). However, many other countries have a much higher organic share; for instance, in 16 of them, their percentage of the area managed under organic practices reaches or exceeds 10% of their total agricultural land. Some of these countries include Finland, French Guiana, the Czech Republic, Uruguay, Italy, Sweden, and Samoa (Willer et al., 2020).

II.6.1 Organic vs. conventional agriculture: An ongoing debate

Organic agriculture is proposed as a solution to the challenges faced by the agricultural sector and to the second goal of sustainable development (Zero Hunger). Nonetheless, organic agriculture only represents 1.5% of the share of total agricultural land in the world (Willer et al. 2020). Besides, organic agriculture only contributes approximately 1 to 8% of total food sales in most European and North American countries (Willer et al. 2020). Nevertheless, the "organic" label is highly recognized; it is well-positioned in food markets in North America and Europe; and is the fastest-growing food sector in both regions (Seufert et al. 2017). Organic agriculture is also one of the few alternative agricultural systems that have a legally regulated label at the local and international levels (Seufert et al. 2017). However, its global environmental and economic benefits are still widely debated.

For instance, Trewavas (2001), claimed that the widespread belief that organic agriculture can replace conventional agriculture by feeding almost 10 million people by 1950 is ideological rather than pragmatic. Besides, organic farming lacks sufficient scientific support for many of its claims (Trewavas 2001). While for Leifeld et al. (2013), the acclamations of some scientists (Gattinger, Muller et al. 2012) on the contribution organic agriculture may have in carbon sequestration, are misleading (Leifeld, Angers et al. 2013).

Furthermore, Stanhill (1989) carried out a study to compare the yields of organic and conventional agriculture systems. A total of 205 comparisons of yields of organic and conventional farming systems were carried out. The data was collected through comparative observations, four long-term replicated field plot experiments and whole-system experiments. Stanhill (1989) analyzed 26 crops and two types of animal products (milk and eggs) based on information collected from 15 sites, mostly in northern Europe and North America. The study concluded that there was no evidence supporting that the organic cultivation methods had any effect on year-to-year yield variability (Stanhill 1990). Moreover, there was no evidence of consistent change in yields between organic and conventional cultivation methods over periods up to 7 years preceding conversion initiation (Stanhill 1990).

Kirchmann (2019), claims that the term organic farming was based on philosophical ideas of nature rather than science. Moreover, that there is very little science that supports the abandonment of the conventional agricultural practice of using synthetic mineral fertilizers (Kirchmann 2019). Besides, lowest yields of organic farming systems vs conventional farming has been widely reported in recent literature (SBA 2016; Seufert et al. 2012). According to Kirchmann (2019), this gap in yields between the organic and conventional agricultural systems will require at least 50% more arable land (Connor 2018). An increase in the amount of arable land means significant land changes along with countless environmental impacts such as deforestation, erosion, and loss of ecosystem services (Kirchmann 2019).

For Ramankutty et al. (2019) organic agriculture has shown many potential benefits, including greater biodiversity, better soil and water quality per unit area, higher profitability and nutritional value). However, Ramankutty et al. (2019) argues that the organic systems' yield and variability increase uncertainty on their environmental performance. Organic systems have higher land use, eutrophication and acidification potential per unit of food produced (Clark and Tilman 2017). Moreover, they do not offer GHGs reduction (Clark et al. 2017). Ramankutty et al. (2019)

concluded that instead of concentrating the discussion on the comparison of one method or the other, efforts should be focused in parallel to identify ways that promote sustainability in both systems (conventional or alternative). In other words, to reform the elements of the conventional system that do not work integrally and correctly, and in turn, implement transitions to alternative methods where they have been shown to achieve higher returns (for example smallholder scale) (Ramankutty et al., 2019).

Other scientists (Akhtar et al., 2016; Badgley, Moghtader et al. 2007; Reganold and Wachter 2016) disagree with some of the claims of organic agriculture detractors (Kirchmann 2019; Leifeld et al. 2013; Stanhill 1990; Trewavas 2001). For Reganold & Wachter (2016) the benefits of organic farming systems outweigh those of conventional farming. Organic agriculture is more profitable, environmentally friendly and produces food with higher nutritional value (Reganold et al. 2016). Additionally, organic agriculture products are a rapidly growing market segment in the global food industry. Finally, organic farming systems generate more ecosystem services and benefits for communities. Reganold & Wachter (2016) took into consideration four critical sustainability metrics, which included productivity, environmental impact, economic viability and social well-being. For instance, the studies concluding that organic agriculture yields are lower (between 6% to 37%) than conventional systems, have been mostly estimated using meta-analysis. While it is true that this tool is very good at describing general patterns, it cannot be generalized that a single agricultural system is the best option everywhere. In certain conditions such as severe flooding as a result of climate change, organic methods have shown better performance over those conventional.

Besides, organic systems internationally (Germany, Italy, Sweden and Switzerland) are less energy-intensive than conventional agricultural methods. These systems have also been shown to contain high organic matter contents. Both characteristics make organic systems an ideal tool to combat climate change. Regarding the economic aspect, Reganold & Wachter (2016) claimed that it has been shown that even if the premiums of organic agriculture were reduced over time, it would still keep expanding. In the social aspect, organic agriculture offers an environment with low or no exposure to pesticides and other chemicals; promotes social interaction between farmers and consumers; increases employment for farm workers and cooperation among farmers (Reganold et al. 2016).

Gattinger et al. (2012) claimed that the performance of organic vs. conventional agriculture could not be judged based on the comparison of a single crop or a year. Organic agriculture generally works best when considering the total production of commercial crops by area (Gattinger et al. 2012). Extreme climatic fluctuations present an increasing threat to agriculture, and it is in these types of conditions (severe droughts and floods) that organic systems have proven to be more stable and resilient compared to their counterpart systems (Gattinger et al. 2012). The composition of the soil and its low compaction as a result of organic management practices, favour crop yields in extreme climatic conditions. For Gattinger et al. (2012) the most significant barriers faced by farmers interested in the transition to alternative systems include lack of knowledge of alternative methods, limited access to information and little technical support.

A recent study (Badgley et al. 2007) concluded that organic methods could produce enough food for the world's growing population, all without increasing the current agricultural land base. It also demonstrated that nitrogen fixation by legume cover crops in agroecosystems in the tropics could supply the current consumption of synthetic-based nitrogen fertilizers (Badgley et al. 2007). The results of this study indicated that organic agriculture has the potential to supply the required food globally while reducing the harmful environmental impacts of conventional agriculture.

II.7 Permaculture

Permaculture is considered the most widely and widespread practice of agroecology (Ferguson et al. 2014). Permaculture not only brings together a compendium of ecological strategies but also provides “an ethical framework and principles that serve as a basis for discerning actions that enable the design of diverse, sustainable systems suited to a wide variety of cultural and ecological contexts” (Hathaway 2015).

The term “permaculture” was coined in the 1970s by Bill Mollison and David Holmgren in Tasmania, Australia. The antecedents of permaculture vary depending on the source and author. For instance, some consider permaculture to be a response to the major crises of the time and part of the counter-cultural rising of awareness about environmental issues. A series of events such as the publication of the study *Limits to Growth* by Meadows et al. (1972), the 1973 oil crisis, and protest over the flooding of Lake Pedder in 1972 led to a paradigm shift that provided the foundation for permaculture to rise (Gamble 2018). According to Collins (2010), Holmgren believed that the origins of permaculture were found in the first expressions of modern environmentalism in the 1970s, in which the first ideas that made up what we now call sustainability were generated. These ideas were associated with the energy crisis, the birth of the of the counter-culture of ideas of intentional community, organic agriculture, natural construction, and automous or more self-reliant ways of living. Smith (2012), however, traces permaculture’s main antecedents back to the Garden City social utopian movement of the late 1800s, Joseph Russell Smith’s (1929) classic book *Tree Crops*, and later influences such as Rachel Carson's *Silent Spring* (1962).

Permaculture is also a response to widespread concern about environmental degradation, which appeared as an integral system of ecological farm design. Similarly emerges as a framework for the imitation of ecosystems issues of high complexity such as natural ecosystems and the optimization of conventional agricultural systems. Permaculture principles facilitate the design, implementation, and maintenance of resilient agroecological systems (Krebs et al. 2018). In addition, permaculture proposes a balance between ethics and environmental well-being (Bellacasa, 2010; Brain & Thomas, 2013). According to Molison (1988), permaculture encompass three ethics: 1) Care of the earth 2) Care of people 3) Fair share (setting limits to population and consumption). These ethics promote the maintenance and regeneration of healthy ecosystems so that both human beings and the environment can meet their essential needs and at the same time share surpluses and safeguard the welfare of future generations (Akhtar et al. 2016).

The widespread adoption of permaculture principles methods has the potential to significantly reduce fossil fuel-based electricity, pesticides, and freshwater consumption. In the same way, permaculture has the potential to restore degraded soil, sequester large amounts of carbon and create more biodiverse agricultural systems, while meeting the human needs of healthy and nutritious food (De Tombeur et al, 2018; Hathaway 2015; Rhodes 2013; Toensmeier 2016). The transition from conventional agriculture to permaculture is a complex project that requires various contributions outside of traditional scientific institutions. Through permaculture, collaboration with the international community of traditional producers could be enhanced and thus together develop a form of agriculture that is less harmful to the environment (Ferguson et al. 2014).

II.7.1 Permaculture critics

Permaculture, even though it is the movement and the system design tool within agroecology with the highest public profile and most significant worldwide diffusion (Ferguson et al. 2014), it is not exempt of criticism. All the disapproval collected during the literary review against permaculture come from grey literature (specifically blogs and a magazine article). Among the greatest critics of permaculture is Peter Harpe's "Permaculture: The Big Rocky Candy Mountain" published in 1997 (republished in 2013). Harper strongly criticized some of the claims made by permaculture's founder Bill Mollison. His article revealed a frustrating tone on a personal level with comments such as "I was baffled by this, but later I understood that essentially there had been an unacknowledged split in the permaculture movement. David Holmgren had gone on to do what I expected...In contrast, Mollison created a global circus" (Harper 2013). Harper (2013) continued his criticism by arguing that the permaculture movement tends to emphasize how easy (Lazy Gardener concept) it is to implement this holistic and progressive agricultural system. However, he considers that there are no simple answers in agriculture.

On the contrary, agriculture requires dedication, hard work, and, above all, adequate management. In his critique, Harper tended to favour part of the work carried out by permaculture co-founder, David Holmgren, when he mentioned that the 12 principles developed by Holmgren are the best that the permaculture movement has proposed. Nevertheless, Harper (2013) also highlighted that these principles were so deep that they probably required a lifetime of experience in the field of ecology to be able to interpret them. Harper continues, "Most people attracted to permaculture are young, dreamy idealists looking for some system to structure their activities and impart meaning. It does not matter much whether things' work' because you are not obliged to depend on them."(Harper 2013). Though his comments were contradicting when he mentioned that he has visited "numerous 'permaculture gardens' with abysmal levels of productivity"(Harper 2013).
Frank Aragona (2014) summarizes in the blog "Resilience: Building world of resilient communities" some of the conclusions reached by Dr. Joe Kovach, Entomologist at the University

of Ohio State during a 1-acre field trial where he applied different agroecological strategies (polyculture, reduced soil disturbance, foster biodiversity, spatial diversity, and temporal diversity) which are listed below:

1) Farmer markets seem to convey a marketplace of smallholder farmers competing with, and undercutting, one another instead of competing against large supermarket chains or conventional agriculture
2) In his opinion, the sales in farmer markets are of low volume in comparison to the one produced or the cost of labor
3) In Kovach experience, it takes a lot of work to establish a proper permaculture system. Kovach believes this work can be dissuasive. It's lot of work on 1 acre and much more on 5 to 10 acres. The competition against the conventional agricultural sector is unfair due to the high degree of efficiency they have achieved and cheap cost of oil.

Finally, Curtis Ste (2018) disagrees with some claims from the permaculture's movement, such as self-sustaining farm, lazy gardener, mulch everything, swale everything, and no pest with beneficial insects and plants. For Ste (2018) "context is critical to understand before applying any solution to a problem" and to be scalable, an agricultural system needs to produce predictable yields in a consistency manner.

II.8 Biointensive Farming

The biointensive method seeks to reconcile humanity with the universe (Jeavons, 1982). The philosophy of this method promotes that the human interrelates with the sun, air, rain, plants, insects and animals as opposed to dominating them. According to this method, through profound observation and listening to the different natural elements, humans can be self-educated in sustainable agriculture, hence implementing appropriate conditions for plants to grow efficiently without the use of chemical fertilizers and pesticides. Jeavons (1982) in his book "How to Growth More Vegetables and Fruits", explains that the practices implemented in the biodynamic method have been applied for over 4000 years in China (Gong and Lin 2000), 2000 years in Greece (Denevan 1995) and 1000 years in Latin America (Isendahl and Smith 2013). The biointensive method arises from the combination of two forms of horticulture: 1) French Intensive Techniques,

which were developed in the 19th and early 20th centuries. This practice mainly used horse manure (more available source of compost). Seeds were planted in a 45 centimetres manure layer, very close to each other, to the point that when the plants reached their maturity, their leaves touched. According to Jeavons (1982) this type of system provides a living microclimate mulching that reduces the presence of weeds and maintains humidity. 2) The biodynamic techniques developed by Rudolf Steiner Austrian philosopher and educator in the 1920s. His work was motivated by his opposition to the introduction of chemical fertilizers and pesticides. Initially, the use of nitrogenous fertilizers was implemented, but gradually other fertilizers were commercialized to add phosphorus and potassium to the crops. Steiner continued working with organic fertilizers and studied the impact of organic fertilizers on crops, which included chemical changes in the soil, death of beneficial microorganisms, increased fatality of plants due to diseases, decreased nutritional value and crop yield (Jeavons 2001; 1982). Steiner's method rescued the use of raised beds for cultivation, which was developed by the Greeks based on observations of landslides on the slopes of the mountains. The Greeks observed that the growth of the plants in the landslides was favourable due to the following conditions: low compaction, higher penetration of air, humidity, heat, nutrients and roots. Unlike planting on flat surfaces, landslides generate a curvature that increases the area of interaction of plants with natural elements (Jeavons 2001; 1982).
Later in the 1920s and 1930s, English Alan Chadwick, who studied with Rudolf Steiner, French farmers and worked as a horticulturist with the government for the South African government, combines biodynamic techniques with intensive French methodologies (John 1982). The combination of these techniques gave rise to what is known today as the French intensive and biodynamic method. This method is applied for the first time in the world in California, United States. Chadwick developed an orchard in a 1.6-hectare area at the University of California at Santa Cruz in the 1960s (Jeavons 2001; 1982).

The garden was developed on a slope of poor clay soil and covered with weeds. Using picks and their own hands, Chadwick’s team removed the weeds and applied the method's strategies, creating vibrant and fertile soil for three years. Using compost, they managed to maximize humus, which in turn fostered a healthier soil capable of developing equally healthy plants and less susceptible to insect attacks and disease. In 1971, Stephen Kafka, who was part of the garden team, was invited by Larry White, director of the Department of Science and Nature of the City of Palo Alto, to teach a 16-hour course on the French intensive biodynamic method. Among the course participants were representatives of the recently created NGO, Ecology Action. The Ecology Action capitalized on the opportunity by knowing the interest of the citizens to replicate Chadwick's methodologies in public gardens and of the openness of the local government to provide these spaces (Jeavons 2001; 1982).

In 1999 Ecology Action coined the term "GROW BIOINTENSIVE® Sustainable Mini-Farming" intending to differentiate its working methodology from new emerging initiatives that used biointensive techniques but which in their consideration did not comply with the foundations of Chadwick's method. Even some of these emerging practices used chemicals, something that sharply contrasts with what Steiner and Chadwick proposed.
Some of Ecology Action's most challenging claims about the effectiveness (per unit of production) of this methods include but are not limited to the following (Jeavons 2001):

• Up to 88 % reduction in water consumption
• 50 to 100 % reduction in the amount of organic fertilizer required
• 99 percent reduction in the amount of energy used
• 100 % (or higher) increase potential in soil fertility compared to depleted soils

Other claims from the GROW BIOINTENSIVE® Sustainable Mini-Farming method include (Jeavons 2001):

1. In-depth soil preparation develops good soil structure to a depth of 60 cm (24 inches).
2. The soil must be nourished with appropriate amounts of compost, which is a significant source of food for microbes.
3. Organic certified fertilizers could be used if required.
4. Plants should be placed close to each other in the growing area, and in an offset or hexagonal shape, so their leaves touch or barely touch when they are mature.
5. Implement Companion Planting; according to Alan Chadwick, different crops have particular affinities for each other.
6. Open-pollinated seeds are highly encouraged.

7. Carbon farming – At least 60% of the crops in the bio-intensive method must be planted with a dual-purpose seed and grain crops. Plants such as corn, wheat, and oats generate large amounts of carbon material, which can be used to increase compost and, as a result, increase soil fertility. Likewise, the entrance of fertilizers or organic matter from abroad is reduced, thus creating a system that produces and retains nutrients in a closed loop.
8. Calorie farming– Bulb vegetables and plants with deep roots such as potatoes, sweet potatoes, garlic and burdock planted in at least 30% of the growing area, facilitate efficient calorie production and, in turn, generate large amounts of calories for the human diet per unit area.
9. Grow Biointensive method requires a whole system approach in which all the elements of the system are considered, guaranteeing the health and productivity of the soil in the long term. Otherwise, high yield production, such as intensive termination, would deplete the soil and, as a result, reduce yields. Another example is that the close spacing between plants applied without an adequate soil structure in at least 60 cm depth would not give good production results.

II.9 Ecological Engineering

There are several definitions of ecological engineering, which together suggest that it is a way of designing ecosystems by mimicking nature in such a way that they preserve, restore, and evolve for the good of humanity and the natural environment.

Some of these definitions are listed as follows:

- "Designing human society with its natural environment for the benefit of both" (Mitch and Jorgenson 2004)
- "Management that joins human design and environmental self-design, so that they are mutually symbiotic" (Odum 1988)
- "The process of designing systems that preserve, restore, and create ecosystem services." (Morgan 2011)

Ecological engineering comprises a series of axioms and principles listed below (Morgan 2011).

Axioms:

- Everything is connected

- Everything is changing
- We are all in this together

Principles:

- Voice for all people in an open and transparent process
- Respect for the rights of future generations
- Redefinition of the relationship between the human species and the ecosystems upon which we depend
- Science-based understanding of the limits of ecosystem services
- Understanding of the interconnected impacts of activities throughout a production supply chain (all the steps leading to a finished product) and across spatial scales
- Enhanced self-sufficiency at the community level
- Pragmatic implementations of practices to test, revise, and adapt to changing conditions

The greatest challenge facing ecological engineering is designing sustainable cities and communities capable of hosting and meeting the needs of a population of 9.25 billion people in prosperity while preserving the integrity of ecosystems and natural resources. Some of the most critical advances in the field of Ecological Engineering are reflected in the studies of Daily et al. (1997), Costanza et al. (1997), and the Millennium Ecosystem Assessment report. These studies make up the first and largest platform of knowledge on how humans have altered ecosystems in the last 70 years and how ecosystem service changes impact our well-being. These studies were the first to develop to some extent answers to the questions how have ecosystems changed? what factors of our existence affect ecosystems the most? how can we restore and conserve those that still exist? (Daily 1997; Reid 2005).

To be able to design based on the services offered by the systems, an understanding of the connections, interactions, and feedback of their components and functions is required (Matlock and Morgan 2011). The concept of ecosystem services is born from the recent interest (last 70 years) in understanding humans' role in the highly complex and interconnected life on our planet. Knowing the complexity of ecosystems, Ecological engineers are in charge of designing ecosystem services. These are services derived from ecosystem functions and processes and can include clean air by plants, filter water, microorganisms decomposing wastes, bees pollinating flowers, and tree roots holding soil in place to prevent erosion. According to Costanza et al. (1997), ecosystem services are flows of energy, materials, and information from natural capital, and they could also be seen as a stock of materials, energy, or information at a given time and space.

II.10 References

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CONNECTION BETWEEN CHAPTER 2 AND CHAPTER 3

Chapter 2 of this thesis presents a general literature review of agroecology’s state of the art. in conventional or industrialized agriculture, arguing that even with these improvements, conventional agriculture has also caused environmental degradation worldwide. Chapter 2 also delves into the term smallholder and its link in the literature with other terms, such as family farming. Finally, Chapter 2 presents the most popular systems to implement agroecology that have been emerging in the last 100 years, clarifying that many of its practices were developed thousands of years ago by the first nations of different regions in the world. While Chapter 3 delves into the concept of permaculture, which, according to some scientists, is one of the most widespread agroecology systems worldwide. This Chapter does a systematic literature review from when the term was coined until 2020 in three different languages and both gray and white literature. The primary purpose of this literature review is to analyze the acceptance of this set of practices in the scientific literature. Moreover, it provides a closer look at the evolution of the concept through the decades. Chapter 3 was submitted and accepted by the Agronomy for Sustainable Development journal on December 22, 2022. The journal's reviewers provided constructive feedback. Many of these suggestions and comments have been incorporated into the current thesis document. As part of this chapter's publication process, some of them will have to be implemented after the revision and defense of the thesis.

CHAPTER III: **A closer look at permaculture and its acceptance in the scientific community. A review**

Roberto Carlos Forte Taylor, Julien Jean Malard-Adam, and Osborne Grant Clark

III.1 Abstract

Permaculture has historically been regarded as a design system for creating ecologically sound and economically feasible sustainable human habitats. According to experts, permaculture can restore degraded land, improve yields, enhance system resilience, and increase carbon sequestration. The current literature suggests that permaculture can be interpreted as a movement or as a progressive agricultural practice. However, its potential contribution to the transformation of agricultural systems is perceived as limited due to its relative isolation from the scientific community. Critics suggest that despite its high profile and international popularity, the practice lacks a clear definition and has not been embraced by the scientific community. This work analyses the historical evolution of the concept of permaculture and its associated terms in both white and grey literature in three languages (English, Spanish, and French). A total of 418 publications were examined using bibliometric analysis, qualitative content analysis, H-index, and citation count. The major goals of the analysis were to: (1) identify the important concepts associated with permaculture, (2) track the evolution of the term by analyzing keywords and title content, (3) evaluate whether permaculture has changed from a philosophical approach to a set of technical practices, and (4) assess the impact of this topic on the scientific literature.

Keywords: Bibliometric analysis; Permaculture; Qualitative content analysis; Term evolution; Word cloud

III.2 Introduction

Fertile soil is being lost at a rate of 24 billion tons globally each year (United Nations Convention to Combat Desertification 2017). At least 1.3 billion people, mostly in developing countries, live in areas where agricultural lands are degraded and thus have limited possibilities for economic development (United Nations Convention to Combat Desertification 2017). The constant pressures of anthropogenic activity continue to degrade soils, impacting not only human welfare but also accelerating the loss of habitat of other species and intensifying the harmful effects of climate change. The increasing food requirements of the growing global human population is one of the main drivers of these anthropogenic pressures. The world's food production system feeds over 7.5 billion people and provides jobs to over 1 billion (International Labour Organization 2009). The sector has shown remarkable improvements in technology, yield, and production over the last century (Mazoyer and Roudart 2006). These improvements are due largely to industrial agricultural practices, defined here as the large scale, energy-intensive, highly mechanized production of monoculture crops for commodity markets, which is usually highly dependent on inputs such as chemical pesticides, mineral fertilizers, and irrigation. For many experts (Badgley et al. 2007; Méndez, Bacon et al. 2013; Reganold and Wachter 2016), although the technology, knowledge, and modern forms of management of the sector have considerably increased agricultural productivity, the sustainability and efficiency in the use of resources in general of these systems have not increased proportionally. Some scientists propose making substantial changes to current agricultural systems to lessen their negative impacts on humans and natural resources while meeting the world's food needs of the present and future generations (Teague 2015).

Despite the increased production, industrial agriculture can cause degradation of the soil and the broader environment, among other problems. Several alternative agricultural systems have been proposed to lessen the problems associated with industrial agriculture. As per experts, these farming systems fall within the framework of agroecology (Ferguson and Lovell 2014; Gallardo-López et al., 2018; Wezel, Bellon et al. 2009). Agroecology has been described as a transdisciplinary, participatory, and action-oriented approach (Méndez et al. 2013). It has been concluded by Gallardo-López et al. (2018) that agroecology has primarily been applied at the level of farming systems, followed by regional levels, agroecosystems, and then agri-food systems. In terms of farming systems, organic agriculture is the most prevalent (Gallardo López et al. 2018).

Nevertheless, other farming systems, such as bio-intensive farming, biodynamic farming, and permaculture, are currently framed within the agroecological concept. Permaculture has been widely disseminated and is becoming increasingly popular throughout the world (Ferguson et al. 2014). Permaculture is described by Hathaway (2015) as encompassing an ethical framework, guiding principles, and ecological strategies for the design and management of agricultural systems. This holistic approach allows the design of diverse, sustainable production systems suited to a wide variety of cultural and ecological contexts (Hathaway 2015). Proponents of permaculture claim that this farming system can meet human needs for healthy and nutritious food, while generating less CO_2 emissions than industrial agriculture and sequestering more carbon from the atmosphere by restoring degraded soil (Toensmeier 2016). Furthermore, they claim that permaculture is less energetically intensive (Conrad 2010), promotes a closed cycle of nutrients (Altieri 1989; Conrad 2014), and considerably reduces the use of pesticides, mineral fertilizers, and irrigation water (Akhtar, Lodhi et al. 2016; Altieri 1998; Bhandari and Bista 2019; Hathaway 2015). Despite its popular appeal, however, Ferguson and Lovell (2014) maintain that the study of permaculture has been largely shunned in scientific research.

Farmers who aspire to change from industrial agriculture to permaculture face a complex project. If adopted as a broader social initiative, the transition away from industrial agricultural production toward permaculture would require the combined efforts of scientific institutions and international communities of producers. Some researchers argue that such a transition should involve collaboration with communities of traditional producers, so that agricultural practices refined over millennia may be leveraged to develop a form of modern agriculture that is less harmful to the environment (Ferguson et al. 2014). Figure 3.1 illustrates permaculture designs developed in tropical regions.

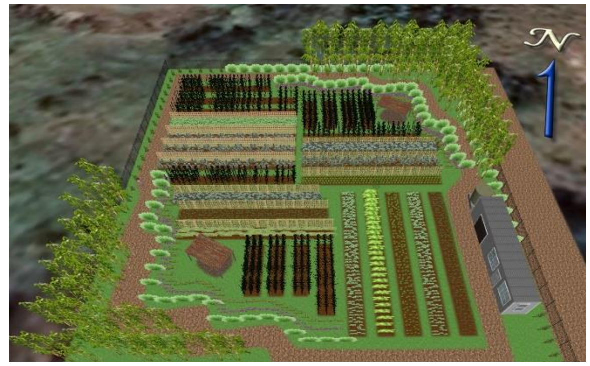
 

Figure. 3.1. Examples of permaculture designs for the tropics by Roberto Forte

This paper is a systematic review of permaculture in the academic literature. A structured literature review was used to identify the principal terms associated with the practice of permaculture, survey academic publications that engage critically with it, and evaluate how these have changed over time. There are four important results of this research: 1) Identification of the terms which have been associated with permaculture throughout its history; 2) Visual portrayal of the complexity, diversity, and evolution of the concept through time; 3) Review of the definition of permaculture, reconciling its seminal ideas and emerging aspects; and 4) Analysis of the acceptance of the concept by the scientific community over time.

III.3 Historical Background

The term "permaculture" was coined in the 1970s by Bill Mollison and David Holmgren, who were working in Tasmania, Australia (Tortorello 2011). The purported antecedents of permaculture vary according to author. Holmgren believed that the origins of permaculture were found in the environmentalist counterculture that arose during the 1970s (Collins 2010). Events such as the publication of the study *Limits to Growth* by Meadows *et al*. (1972), protests over the flooding of Lake Pedder, Tasmania, in 1972, and the 1973 oil crisis led to a paradigm shift in the way that people thought about the environment (Gamble 2018). During this period, current ideas about sustainability were also developed as part of the resurgent interest in intentional communities, organic agriculture, green architecture, and a self-reliant lifestyle (Collins 2010). Smith (2012), however, traces the antecedents of permaculture further back to the Garden City movement of the late 1800s, Joseph Russell Smith's (1929) classic book *Tree Crops*, and later influences such as Rachel Carson's *Silent Spring* (1962).

Permaculture is considered by other authors, such as Krebs & Bach (2018), to be a more focused, technical practice; that is, an integral system for the design, implementation, and maintenance of resilient agroecological systems, which was developed in response to widespread concern about environmental degradation. As such, permaculture balances the necessity for agricultural production with principles of ethics and environmental well-being (Bellacasa 2010; Brain and Thomas 2013). Mollison described permaculture as encompassing three core ethical principles: 1) care of the earth, 2) care of people, and 3) fair share (setting limits to population and consumption) (Akhtar 2016). These principles promote the maintenance and regeneration of healthy ecosystems so that both human beings and the environment can meet their essential needs while sharing surplus and safeguarding the welfare of future generations.

III.4 Definition and Principles

Early definitions of permaculture proposed by Mollison and Holmgren include:

"Permaculture (permanent agriculture) is the conscious design and maintenance of agriculturally productive ecosystems which have the diversity, stability, and resilience of natural ecosystems. It is the harmonious integration of landscape and people providing their food, energy, shelter and other material and non-material needs in a sustainable way" (Mollison and Slay 1988).

"Consciously designed landscapes which mimic the patterns and relationships found in nature, while yielding an abundance of food, fiber, and energy for provision of local needs. People, their buildings and the ways in which they organize themselves are central to permaculture" (Holmgren, 2013).

"Permaculture design is a system of assembling conceptual, material, and strategic components in a pattern which functions to benefit life in all its forms" (Mollison et al. 1988).

The principles of permaculture as articulated by Holmgren (2013) are paraphrased in Table 1.

III.5 Research Question and Objectives

Despite permaculture's high international public profile, few systematic literature reviews on the term and its associated concepts have been published in scientific journals. Fergusson and Lovell (2014) carried out one of the most recent attempts, focusing on the potential contribution that this practice could have in the agroecological production industry, its different strategies, and its potential as a grassroots movement.

However, a literary review focused on the evolution of the term and associated concepts through time has not been structurally carried out. For Fergusson and Lovell (2014), one of the barriers limiting permaculture's potential is its separation from the scientific community. In this research, we hypothesize that the concept of permaculture has evolved from a philosophical, ethical, and social framework to a more technical paradigm that has become more accepted by the scientific community through time. For this, we propose the following research question: Does the scientific community accept permaculture as a technical paradigm to a greater extent than it has in the past?

To answer this question, we propose a series of steps and methodologies listed as follows:

1) Conducting an exhaustive literature search of both grey and white literature on permaculture
2) Identification of the overall concepts associated with permaculture
3) Evaluation, through keyword and title content analysis, of the evolution of the term
4) Detection of trends and patterns that indicate whether permaculture has changed from a philosophical approach to a more technical set of practices
5) Evaluation of the impact of this practice in scientific publications

Table 3.1. Permaculture principles

Principles		General description
Observe and interact	BOTTOM – UP PERSPECTIVE OF ELEMENTS	Careful observation and thoughtful interaction provide design inspiration and patterns. Continuous and reciprocal interaction with the land and its ecosystems is crucial.
Catch and store energy		Capture local flows of renewable and non-renewable forms of energy (sun, wind, runoff water flows, and fossil fuels, amongst others).
Obtain good yields		Elements that generate good and immediate yields will proliferate. Systems that obtain a yield and use it effectively tend to prevail over alternatives.
Apply self-regulation and accept feedback		By designing self-regulated systems, the work involved in harsh corrective management can be reduced significantly.
Use and value renewable resources and services		Permaculture design should aim to make the best use of renewable natural resources to manage and maintain yields.
Produce no waste		Waste or pollution is "an output of any system component that is not being used productively by any other component of the system".
Design from patterns to details	TOP- DOWN PERSPECTIVE OF ELEMENTS	Complex systems that work in nature tend to evolve from simple ones that work. Finding the most appropriate pattern for the design in question is more important than understanding all the details of each component in a system.
Integrate rather than segregate		In self-regulating design, elements should be placed in such a way that each serves the needs and accepts the products of other elements.
Use slow and small solutions		Systems should be designed to perform functions at the smallest scale that is practical and energy-efficient for that function.
Use and value diversity		Diversity is a result of the balance and tension in natural environments between variety and possibility on one hand and productivity and power on the other.
Use edges and value the marginal		Value and contribution of the edges, as well as marginal aspects, should be recognized and conserved because the expansion of these aspects could increase productivity and system stability
Creatively use and respond to change		Change should be deliberately and cooperatively included in the design. The design should be capable of responding or adapting to large-scale system changes that are beyond control or influence.

* Adapted from Holmgren (2013)

III.6 Materials and Methods

In order to respond to the objective number 1 of this research work, we adapted a series of methodologies previously used in the generation of similar systematic literature reviews (Ferguson et al. 2014; Guitart et al. 2012; Peter et al.2019; Wezel et al. 2009; Wezel and Soldat 2009). We applied these to the existing body of literature (1900 - 2020) related to the concept of permaculture. We conducted a structured literature review in combination with a quantitative bibliometric analysis using the term permaculture and the derived terms (*permanent agriculture* and *permanent culture*). An understanding of the technical aspects, ideas, arguments, and concepts related to permaculture is crucial for practitioners, farmers in transition, communities, decision-makers, and policy developers to satisfactorily implement it. To carry out these analyses, we reviewed a body of literature comprised of 418 publications, including white and grey literature in three languages – English, Spanish and French.

We performed searches in databases such as Web of Science (WOS), Google Scholar, Scopus, the Tropical Agricultural Research and Higher Education Center/ Centro Agronómico Tropical de Investigación y Enseñanza (CATIE), Érudit, Archives HAL, and scientific journals using the search terms "permaculture", "permanent agriculture" and "permanent culture." The last two terms were included since, while defining our search protocol, we found permaculture practitioners that linked permaculture both to agriculture as a practice based on whole system thinking, as well as to social and ethical aspects. After conducting initial searches using the term "permanent culture" in databases such as Web of Science and Scopus, we noticed that the term was mostly associated with studies related to the field of microbiology and the application of techniques for propagating microorganisms in growth medium. Hence, we decided to limit the literature search based on the terms "permaculture" and "permanent agriculture" and in their respective translations in Spanish and French.

Searches in Google Scholar were constrained to publications using the term permaculture in the title. Google Scholar provides two search options 1) "anywhere in the article" and 2) "in the title of the article." By using the option "in the title of the article," the analysis was limited to those articles focused explicitly on permaculture and excluding those that may contain the term in some parts but have nothing to do with the subject in question. For WOS, Scopus, and CATIE, we included only the publications in which the term permaculture (and derivatives) appeared in the title and keywords. The searches in the different databases were carried out until July 15, 2020.

Initial searches on Google Scholar, Web of Science, Scopus, Érudit, Archives HAL, scientific magazines and CATIE returned a total of 1027 references from which 804 were in English, 164 in French and 59 in Spanish (Table 3.2). These totals represent the complete set of references thrown by the search engines without accounting for the repetition of sources between one or another database or broken links. A deep process of revision and cleaning of the search results obtained was carried out because they yielded many broken links, duplicates, or links from which it was not possible to obtain a digital file with the minimum information required for the analysis (such as author, editorial, country, and methodology, among others).

Table 3.2. The initial result of searches in several databases and three languages (English, Spanish and French)

Navigator/Database	Keywords	No. of queries	Language
Google Scholar	permaculture	517	English
Google Scholar	permanent agriculture	27	English
Scopus	permaculture	105	English
Scopus	permanent agriculture	8	English
Web of Science	permaculture	119	English
Web of Science	permanent agriculture	13	English
CATIE – Cab Direct	permaculture	13	English
CATIE – Cab Direct	permanent agriculture	2	English
CATIE – Cab Direct	permacultura	0	Spanish
CATIE – Cab Direct	agricultura permanente	0	Spanish
Google Scholar	permacultura	58	Spanish
Google Scholar	agricultura permanente	1	Spanish
Google Scholar	permaculture	69	French
Google Scholar	agriculture permanente	0	French
Archives HAL	permaculture	31	French
Archives HAL	agriculture permanente	0	French
Érudit	permaculture	64	French
Érudit	agriculture permanente	0	French
All databases	All keywords	1027	All languages

A database was compiled using Excel. The complete literature dataset can be found in the Supplementary Information of this article. From the complete set of data, preliminary analyses were carried out, such as reference counts by type and by language and distribution of references by type and by year. Subsequently, the references were subjected to content analysis of their titles and keywords.

We implemented the Word Cloud tool provided by ATLAS TI software in response to objective number two. Using this tool, we built a visual representation of the most common words in a text or series of contents. Words that appear more frequently in this tool have a larger size. References were grouped by decade (except for the first period from 1905 to 1980) to visualize the trends in the evolution of associated terms based on the established periods. The word cloud analysis was only run in the English literature because, in the other two languages (Spanish and French), more than 90% of the references were published in the 2011 to 2020 period.

To achieve objective number three, we use ATLAS TI software to extract the most relevant terms from literature's titles, keywords, and other sources. We collected terms directly from the titles and keywords of scientific publications. The McGill University Library catalogue was used to collect terms from titles and keywords of other types of literature (books, chapters, magazines, and others). This system applies subject headings standardized by the Library of Congress Classification (LCC) to ensure consistency across all entries in the catalogue. Then, using the same periods used for objective one, we created an excel table that listed the 12-15 terms that occurred most frequently during each period. Our choice was based on the fact that in some periods, we did not reach 15 terms that were repeated at least once. Our final step was to highlight terms that crossed over at least three periods using colour coding. Using these terms, we presented a permaculture definition, within the scope and methodology documented in this literature review.

Responding to objective number four of this study, we proceeded to categorize 98 (three out of 101 where not possible to classify) scientific publications (English) according to their emphasis. They were categorized into two main areas: those with a scientific/technical focus (engineering, natural sciences, finance, economy, agriculture, technology, ecology, environment, and others) and those with a philosophical emphasis (philosophy, religion, dance, art, politics, law, and social sciences). Searches were carried out in databases with a scientific approach such as WOS and SCOPUS and databases with more a sociological approach such as AgeLine (EBSCO), Social Work Abstracts (OVID), and Social Sciences Citation Index (SSCI, Web of Science). Through WOS, we were able to categorize 46 publications. In WOS, the categorization was carried out by taking as a reference the "Research Areas" combined with the "Web of Science Categories" provided by the tool.

At SCOPUS we were able to categorize another eight references using the "SciVal Topic Prominence", which according to the tool, represents "unique areas of research." The other 43 references could not be categorized in this way. Therefore, we implemented a third and fourth method. The third method categorized publications based on keywords obtained from the digital versions of the publications or through the McGill Library Catalogue. Through this method, we were able to categorize another 29 references. Finally, the remaining 14 references were categorized based on the journal "Aim and Scope" or using the "Home or About" section for those who did not specify aim or scope.

For the purpose of responding to objective number five of this research work, a total of 98 scientific publications in English were considered. Scopus and WOS databases were used to collect the number of citations per publication. The number of citations considered for this analysis excluded self-citations. Only those references that presented at least one citation were used for the analysis. Of the 98 publications, the information could only be collected for 49 references. The majority of citation counts were obtained from WOS, while the remainder were collected from Scopus. Using citation count, we compiled a list of 20 publications in which information could be collected in either Scopus or WOS or both, and that contained at least one citation. We collected information on the number of citations for 20% of the references and 10% of the H-index. Our proposal was to combine the citation count indicator with the H-index in order to avoid the ambiguity inherent in the citation count indicator. The use of citation count and the H-index is widely used in estimating the impact of authors, research groups, and scientific journals in various fields (Caulley, Cheng et al. 2020; Hassan, Kamdem et al. 2020; Kreinovich, Kosheleva et al. 2021; Li, Lei et al. 2020; Oliveira Filho and Pereira 2020; Tietze, Galam et al. 2020). We used the H-index to summarize citation frequency and not as a measure of scientific quality or success. The H-index was proposed by Hirsch (2005) as a research performance indicator for the evaluation of individual single research output (micro level). However, researchers such as Van Raan (2006) has been applying the H-index to evaluate university research groups (meso level) (Bornmann and Daniel 2007). According to Hirsch (2005), “A scientist has index h if h of his or her Np papers have at least h citations each and the other (Np – h) papers have fewer or equal than h citations each”. Unlike other indices (for example, the total number of papers, the total number of citations, or citations per paper), the H-index is considered to provide a robust estimate of the impact of a scientist's cumulative research contributions (Bornmann et al. 2007; Hirsch 2005).

III.7 Results

III.7.1 First appearances of the term “permaculture” (1900 to 2020)

According to Web of Science, the term permanent agriculture was used for the first time in 1911, as part of a book review published by the Political Science Quarterly, Vol. 26. Two years later, the term appeared in the book Permanent agriculture in China, Korea, and Japan by F.H. King (1913). In Scopus, the first appearance of the term dates back to 1929 in the book "Farm Relief and a Permanent Agriculture ", published by Annals of the American Academy of Political and Social Science, while the term permanent agriculture appears for the first time in a peer-reviewed publication within the article The maintenance of soil organic matter under continuous cultivation at Samaru, Nigeria (1971) published in The Journal of Agricultural Science.

Interestingly, the term permanent agriculture was linked to the potential application and negative effects of continuous conventional practices of agriculture in savannahs in Africa where subsistence agriculture was traditionally practiced. It was in Soil Deterioration and the Growing World Demand for Food" (Brink, 1977) that the term is used to propose alternative forms of agriculture in the United States as a way to combat the degradation of agricultural soils resulting from conventional agricultural practices. In Web of Science, the term "permaculture" appears for the first time linked to a peer-reviewed publication in the article “Permaculture - Practical Design for Town and Country in Permanent Agriculture” published in *Ecologist* (Strange 1983).

III.7.2 Literature distribution by language

Some scientists have claimed that, despite the high public profile, international distribution, and unique approach to system design of permaculture, the concept remains isolated from scientific research (Ferguson et al. 2014; Krebs and Bach 2018). We implemented the search protocol described above to collect and pre-screen the bibliography for analysis. We only consider literature from which we could obtain a record containing as a minimum the title, author, and co-authors, abstract, publication journal, and methodology. In the case of books, only those that included a digital file or online version of the book where the title, author(s) and introduction could be found were included. After removing duplicates and false results, the bibliography contained 328 English, 50 French and 40 Spanish references (Table 3.3). Each reference in the bibliography was identified as a peer-reviewed journal article, book, thesis, conference proceeding, or other publication form. Each of the citations extracted from the different databases was thoroughly verified, especially those obtained from Google Scholar, to effectively classify and differentiate peer-reviewed publications from the grey literature.

Table 3.3. Final reference dataset breakdown by document type and language

Document type	English	Spanish	French
Peer-reviewed scientific journal article	101	10	15
Generic	75	12	-
Book	49	2	6
Thesis	47	25	7
Conference proceeding	41	1	9
Booklet	5	-	-
Presentation	4	-	-
Interview	3	-	-
Report	3	-	3
All document types	328	50	40

Figure 3.2 shows the distribution of the 406 references (excluding those that did not have publishing year) by type over time. References were grouped by decade except for the first period from 1905 to 1980, when the concepts of permanent agriculture and permaculture were coined and therefore mentioned sporadically in different types of literature. For all types of collected literature

(except conference proceedings, interviews, booklets, reports, and presentations), the behavior is very similar. From 1990 onwards, rapid growth in the generation of publications (peer-reviewed journal article, book, generic, and thesis) was shown, which intensified significantly in the decade of 2011-2020, particularly for peer-reviewed publications. This is a clear indicator that in the last decade, the publication of literature on permaculture has taken a more scientific direction. However, this fact is not enough to conclude that the term permaculture has been accepted as a more technical practice within the scientific community.

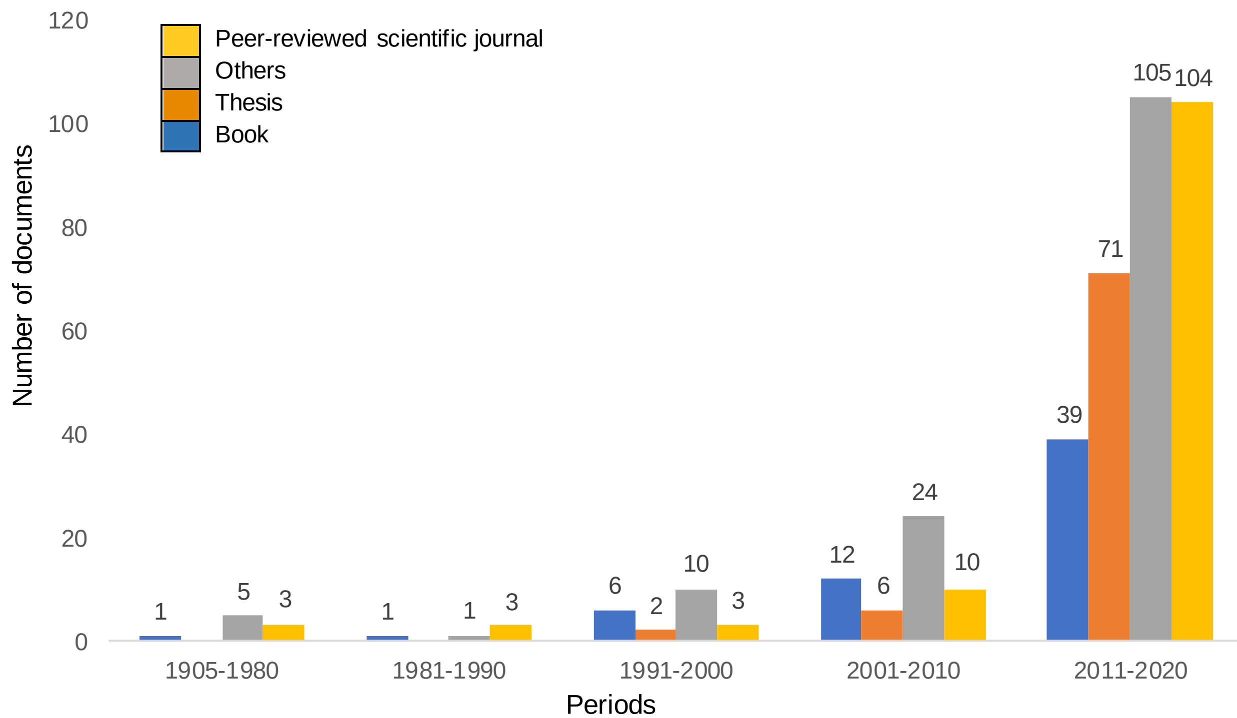


Figure 3.2. Total numbers of documents as grouped by type and time period

We also grouped the database into five main groups of literature: others (generic, booklets, brochures, interviews, presentations, and reports), peer-reviewed scientific journal, books (chapter and sections), thesis, and conference proceedings. Figure 3.3 shows that, for all types of publications (white and grey), sustained growth of publications related to permaculture began between 2009 and 2011.

cuments

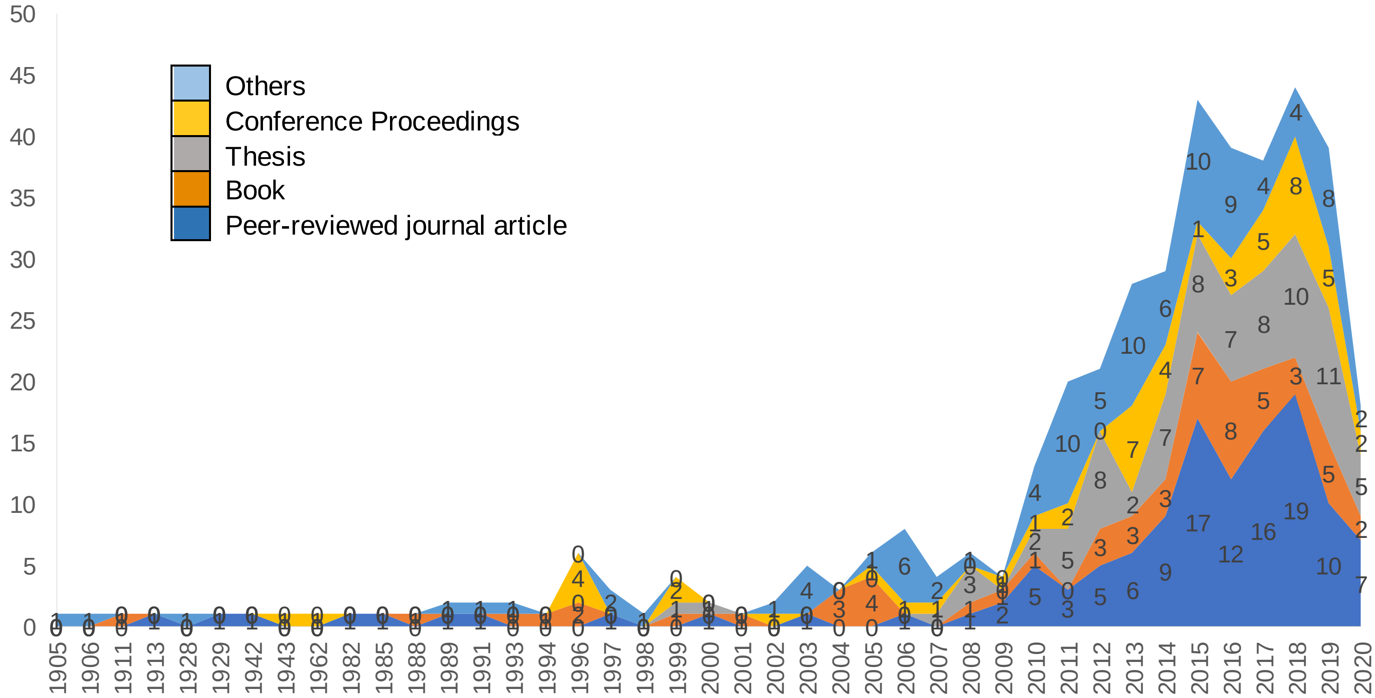


Figure 3.3. Evolution of permaculture publications through time

The 406 references were also analyzed to identify trends in the evolution of the term permaculture and its associated terms. A content analysis of titles and keywords was carried out using the ATLAS TI tool. Trends in the evolution of terms associated with the practice of permaculture were identified. The complete list with the 100 terms most associated with the permaculture practice in scrutinized literature (English, Spanish and French), along with the appearances count are found in the Supplementary Information of this article.

III.7.3 Evolution of the concept of permaculture and associated terms over time

Figures 3.4 and 3.5 show the word clouds for each of the established periods in the English, Spanish, and French literature related to permaculture.

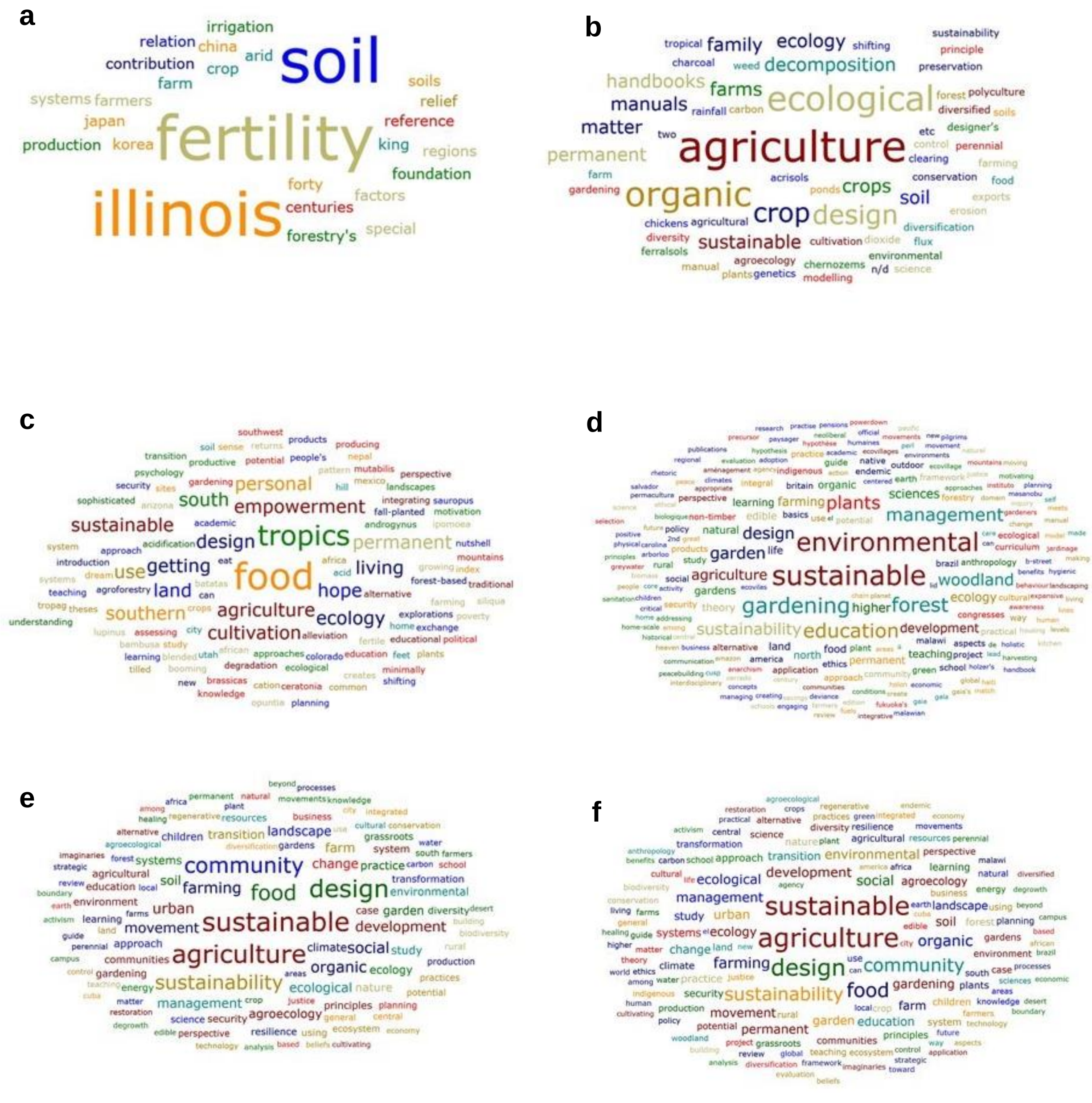


Figure 3.4. Word cloud analysis showing the most prominent terms in the English-language dataset.

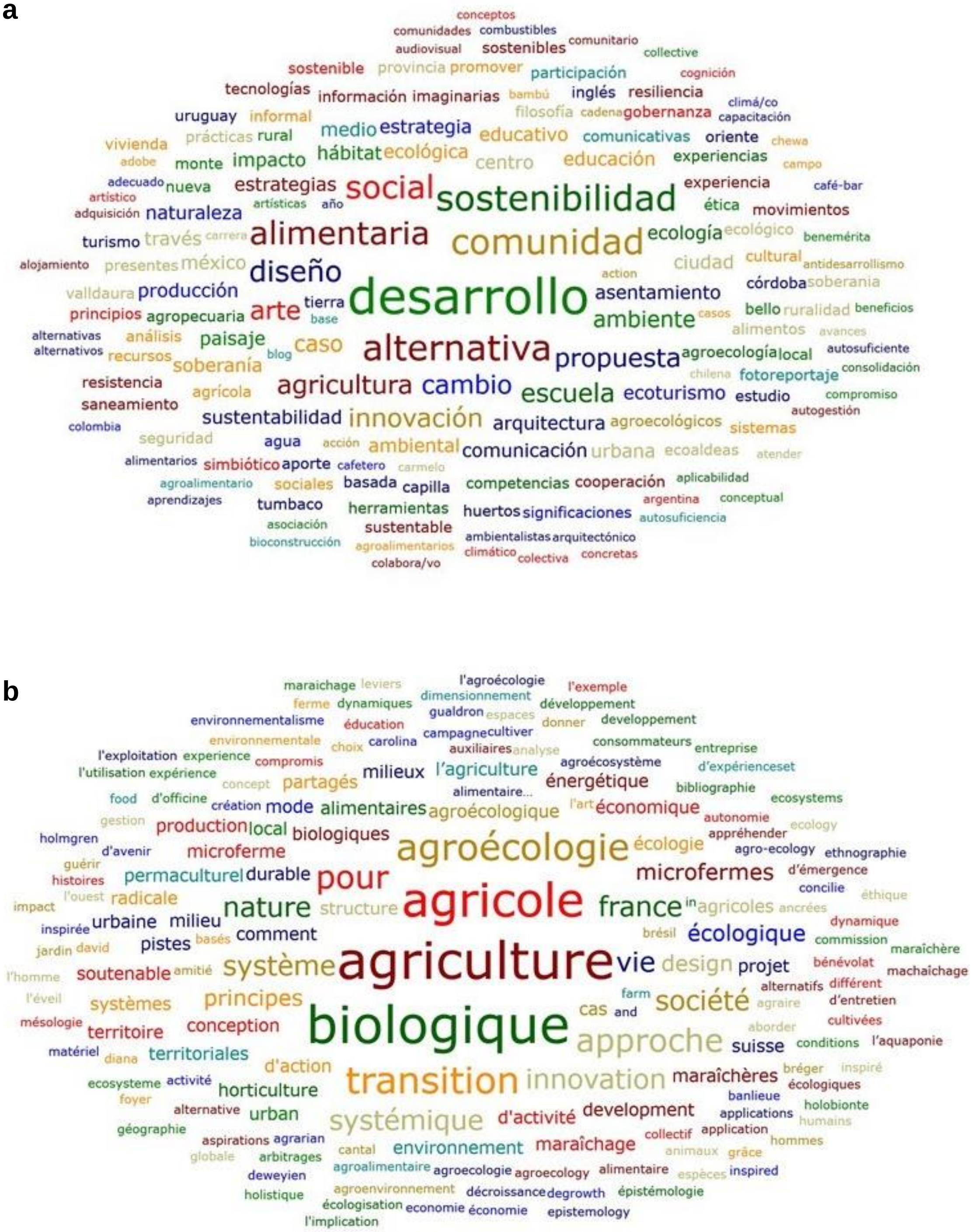
a
b


Figure 3.5. Word cloud analysis showing the most prominent terms in the Spanish and French datasets.

Table 3.4 shows the 15 most prominent terms related to the permaculture concept in English (including all periods). To generate this table, we proceeded by eliminating those concepts that expressed the same meaning, in which case we kept the one with the highest number of repetitions. Some of the pairs of similar items that were merged included: sustainability/sustainable, agriculture/farming, community/social and ecology/ecological. We also merged concepts that maintained a critical link such as food/organic and urban/gardening.

Table 3.4. The most prominent English terms associated with permaculture (1900-2020)

Term	Occurrences
agriculture	70
sustainable	68
design	59
food/organic	47
community	42
farming	30
development	25
ecological	25
environmental	25
management	25
urban/gardening	23
movement	22
permanent	22
soil	22
education	20

A color-coded analysis is presented in Table 3.5 to identify which terms related to permaculture have been consistently used throughout the literature over the periods examined. As a result of this analysis, we were able to identify the concepts that have persisted over three decades and those that have emerged in the last decade. Among the concepts that have persisted for at least three decades are soil, agriculture, design, sustainable, and food-related terms. The last two decades have seen the emergence of new terms. For instance, community, urban gardening, development, movement, and change (as a result of climate change). This could be in response to advances in the identification, quantification, and communication of anthropogenic impacts on nature (climate change, desertification, loss of biodiversity, eutrophication of the oceans, among others) as well as global efforts to mitigate these impacts.

Table 3.5. A color-coded analysis of the terms related to permaculture

1905 - 1980		1981 - 1990		1991 - 2000		2001 - 2010		2011 - 2020	
Term	**Count**	**Term**	**Count**	**Term**	**Count**	**Term**	**Count**	**Term**	**Count**
fertility	2	agriculture	5	food	4	Sustainable	12	sustainable	52
Illinois	2	ecological	4	tropics	3	Environmental	11	agriculture	49
soil	2	organic	4	agriculture	2	Gardening	9	design	48
arid	1	crop	3	cultivation	2	Education	8	community	40
centuries	1	design	3	design	2	Forest	8	food	39
China	1	decomposition	2	ecology	2	Management	7	organic	24
contribution	1	family	2	empowerment	2	Plants	7	urban	22
crop	1	handbooks	2	hope	2	Design	6	development	21
factors	1	matter	2	land	2	Agriculture	5	movement	21
farm	1	permanent	2	living	2	Development	4	change	18
forestry	1	soil	2	permanent	2	Ecology	4	ecological	18
forty	1	sustainable	2	personal	2	Sciences	4	management	18
foundation	1			south	2			soil	17
irrigation	1			sustainable	2			agroecology	16

- To make it easier for the reader to track those terms that persist over time, we implemented a color-coding system. Although some terms are not written exactly, they are close variants, while others are highly binding even if they are not written exactly.

III.7.4 Evolution of the perspective of the scientific literature in English related to permaculture

Figure 6 highlights how the last decade is where most publications of a scientific nature concerning permaculture have been generated. The scientific articles of both emphases reached their publication peak in the last decade. However, the generation of publications with a technical-scientific approach exceeds the philosophical ones by over 70%. In fact, in the philosophical group of articles, there is only one publication before 1980 (dating from 1929), and it refers to the concept of permanent agriculture and not to the set of practices that conform to what is now known as permaculture. This suggests that the philosophical aspect of permaculture emerged in the 2000s as far as scientific literature is concerned. In contrast, Fig. 3.6 suggests that permaculture practice (since its inception), was conceived and continues to be conceived (by the scientific community) as a set of technical and scientific principles and practices.

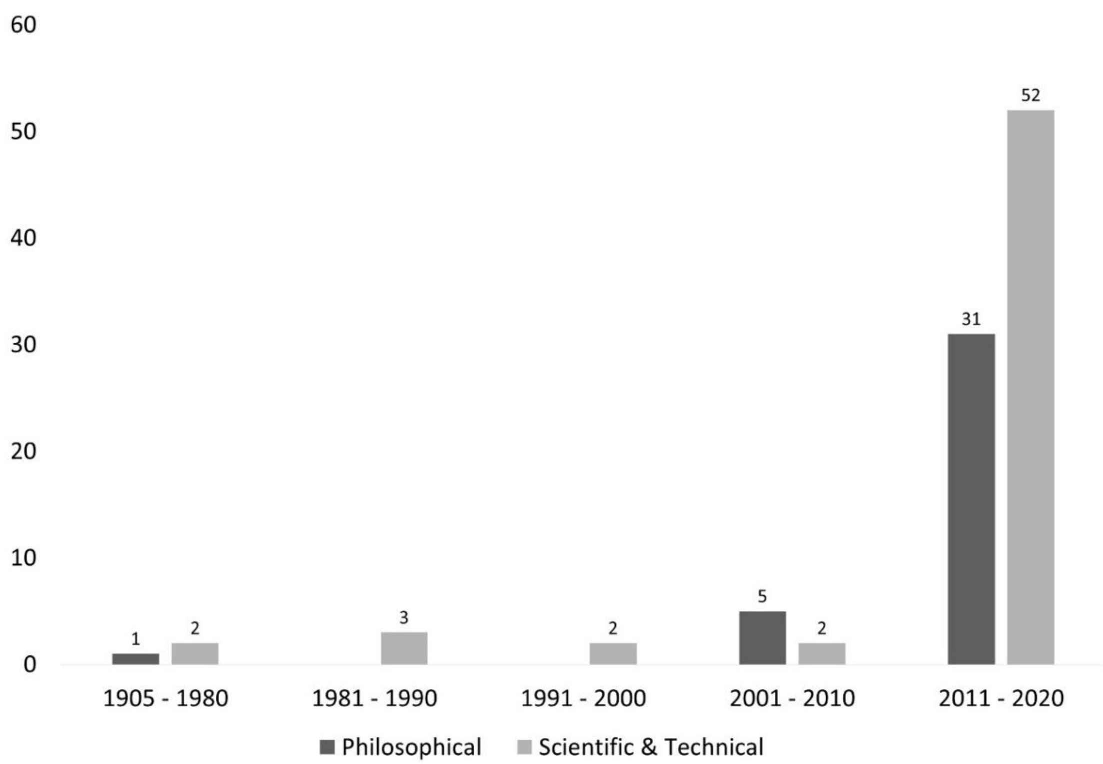


Figure 3.6. Evolution of the nature of publications concerning permaculture over time

III.7.5 Estimation of the impact of the permaculture literature on the scientific community

Based on the citation count indicator, Fergusson and Lovell (2014) literature reviewed on the potential contribution of permaculture on the agroecological production industry is widely the most popular publication within the scientific community. However, counting the number of scientific publications related to permaculture is not enough to conclude whether or not the concept exists in relative isolation from the scientific community. Table 3.6 shows the most highly cited publications within the scientific community related to the subject of permaculture.

Table 3.6. Comparison of citation counts for top English publications in different databases

Publication title	Scopus	Web of Science
Nature as therapist: Integrating permaculture with mindfulness- and acceptance-based therapy in the Danish Healing Forest Garden Nacadia.	ND	14
Permaculture for agroecology: Design, movement, practice, and worldview. A review	55	65
A cation exchange index for assessing degradation of acid soil by further acidification under permanent agriculture in the tropics	32	41
Grassroots engagement with transition to sustainability: Diversity and modes of participation in the international permaculture movement	16	17
Agroecology and permaculture: Addressing key ecological problems by rethinking and redesigning agircultureal systems	15	ND
Learning in the permaculture community of practice in England: An analysis of the relationship between core practices and boundary processes	14	17
Examining innovation for sustainability from the bottom up: an analysis of the permaculture community in England	14	ND
Feeding and healing the world through regenerative agriculture and permaculture	13	ND
Sustainable management models: Innovating through permaculture	11	9
Plant genus *Elaeagnus*: Underutilized lycopene and linoleic acid reserve with permaculture potential	11	12
Towards sustainable agricultural stewardship: Evolution and future directions of the permaculture concept	10	ND
Permaculture – Scientific evidence of principles for the agroecological design of farming systems	7	5
“The right to food is nature too”: Food justice and everyday environmental expertise in the Salvadoran permaculture movement	7	8
Tree crops, a permanent agriculture: Concepts from the past for a sustainable future	7	10
Livelihoods and production diversity on U.S. permaculture farms	6	5
Modeling organic matter decomposition and rainfall erosion in two tropical soils after forest clearing for permanent agriculture	6	ND
Sustainable organizing: A multiparadigm perspective of organizational development and permaculture gardening	5	6
Alternative visions: Permaculture as imaginaries of the Anthropocene	5	6
Environmental anthropology engaging permaculture: Moving theory and practice toward sustainability	3	30
Local scale water-food nexus: Use of borehole-garden permaculture to realise the full potential of rural water supplies in Malawi	1	6

1 Color coding: Green > 29, Yellow 28–12, Orange <12. Excluding self-citations

As for the H-index, only the information of those ten publications that presented five or more citation counts was collected. The H-index for all ten publications were collected from WOS database. Table 3.7 shows the summary of the H-index of the first and second author listed in the most prominent scientific publications on permaculture.

Table 3.7. H-index analysis based on data from Web of Science

Publication	Author 1	H-index	Author 2	H-index
Permaculture for agroecology: Design, movement, practice, and worldview. A review	Ferguson	3	Lovell	17
A cation exchange index for assessing degradation of acid soil by further acidification under permanent agriculture in the tropics	Noble	30	Gillman	22
Learning in the permaculture community of practice in England: An analysis of the relationship between core practices and boundary processes	Ingram	17	Maye	17
Sustainable management models: Innovating through permaculture	Vitari	7	David	13
Plant genus *Elaeagnus*: Underutilized lycopene and linoleic acid reserve with permaculture potential	Patel	20	-	-
Permaculture – Scientific evidence of principles for the agroecological design of farming systems	Krebs	3	Bach	2
"The right to food is nature too": Food justice and everyday environmental expertise in the Salvadoran permaculture movement	Millner	3	-	-
Tree crops, a permanent agriculture: Concepts from the past for a sustainable future	Molnar	10	Kahn	18
Environmental anthropology engaging permaculture: Moving theory and practice toward sustainability	Veteto	7	Lockyer	4
Local scale water-food nexus: Use of borehole-garden permaculture to realise the full potential of rural water supplies in Malawi	Rivett	22	Halcrow	ND

III.8 Discussion

Our analysis of 418 references in three different languages indicates a significant growth in the interest in publishing topics related to permaculture in different audiences, including academic and scientific. This growth started in the 2000s and was established in the 2010s in the three languages analyzed in this literary review. According to Ferguson and Lovell (2014), permaculture remains relatively isolated from scientific research despite the high public profile and international distribution. Few efforts have been made to systematically review, based on peer-reviewed articles, the background and core themes of permaculture. This study is the first to systematically review the evolution of the term permaculture (especially in peer-reviewed scientific literature) and its impact on the scientific community over time. Furthermore, it was carried out by analyzing literature in three languages (English, Spanish, and French).

The initial promoters (Bill Mollison and David Holmgren) of the concept of permaculture provided the original visions for the term. Their definitions are separated by 25 years and provide us with an initial and a more modern vision of their conception. Terms such as consciousness design, ecosystems, diversity, food, local, and energy are significant in their vision of permaculture. The study results show that some of these concepts have transcended, while others were displaced (depending on languages and type of literature), and many are emerging. It is evident that the concept of permaculture is evolving rapidly and adapting to the changing conditions of a world that suffers from overconsumption and, as an effect, a degradation of vital ecosystem services (clean water, pure air, and healthy soil).

Table 3.5 presents the most prominent permaculture concepts based on our English literature dataset. As part of the development of an updated definition of permaculture, we considered both concepts that have transcended and those that have emerged in conjunction with the concept. Below is our definition of permaculture:

"An **agricultural movement** and set of practices based on **ecological design** principles, to produce **food** with a strong focus on **subsistence**, that meets or exceeds **organic-farming** standards while **regenerating the soil** and reducing the burden on **rural and urban environments**."

Due to the limitations described in this study and the fact that it is a rapidly evolving term, we anticipate that the definition may not align with current or future views, and opinions. Therefore, further refinement might be necessary.

III.8.1 Permaculture's growing popularity and prominent terms

The most ambiguous terms related to permaculture included community, design, sustainability, system, and agriculture (Ferguson et al. 2014). Our analysis reaffirms some of the terms proposed by Ferguson and Lovell (2014); however, in this investigative work, we highlighted other terms that have transcended through time, such as soil, ecology, and food. Moreover, in the seven years following Sarah Lovell's literary review, other terms have emerged as relevant in the English literature, such as: organic, social, management, climate change, urban gardens, and education. In Spanish, words such as development, alternative, food, art, and change (desarrollo, alternativa, alimentaria, arte, y cambio) take a more significant role. A similar phenomenon occurs in French literature, in which terms such as design, sustainability, and community are displaced by terms such as organic, poor, transition, approach, and life (biologique, pour, transition, approche, and vie). Other terms that are emerging in recent publications in English include security (related to food), diversity (polyculture, intercropping and animals), resilience, and regeneration (mainly focused on soils).

III.8.2 Permaculture is more technical than philosophical

The result of our analysis shows a marked trend in which scientific publications tend to address the technical issues of the practice of permaculture. The majority of scientific publications are found in the decade 2010-2020 for each of the three languages. Since the conception of the term "permanent agriculture", its publications have been of a more technical nature. In contrast, the philosophical aspects of permaculture begin to emerge in the decade 2000-2010. In the decade 2010-2020, there was exponential growth in the publication of scientific literature related to this practice. However, this technical-scientific character continues to predominate over the more recent philosophical element.

III.8.3 Permaculture enjoys a growing acceptance by the scientific community

The growing phenomenon of publications related to permaculture in both white and grey literature is evident. The analysis of 98 scientific publications reveals a marked growth in literature, especially in the decade from 2010 to 2020. On the other hand, our analysis, based on the H-index, shows that various successful researchers are involved in publications on the concept of permaculture. Among the most prominent, we can list Patel Seema, Julie Ingram, Maye Damian, Molnar Thomas J. and David Christophe, which show promising H-index values greater than the number of years they have of research work according to WOS records which have been suggested as a reliable source for this type of analysis (Bornmann et al. 2007; Hirsch and Buela-Casal 2014). Other renowned researchers such as Andrew Noble, Sarah Lovell T., Michael O. Rivett, and Peter Kahn exceed or are very close to reaching H-indexes of 20. Our analysis's purpose is not to evaluate the quality of the publications at the individual level or to compare them, but to highlight through the use of this indicator some of the most significant researchers involved in permaculture. However, we recognize the previously reported limitations in the indicators themselves (Bornmann et al. 2007; Hirsch et al. 2014; Van Raan Anthony 2006).

III.9 Conclusion

This review is a systematic evaluation of the definitions and concepts associated with permaculture in 418 peer-reviewed and non-peer-reviewed publications in three languages: English, Spanish, and French. The objective of this multilingual systematic literature review was to investigate whether the scientific community accepts permaculture as a technical paradigm to a greater extent than in the past. Methodologies used to answer this question included bibliometric, content (title and keywords), H-index, and citation count analysis. Some of the concepts associated with permaculture have persisted for at least three decades, such as soil, agriculture, design, sustainable, and food-related terms. Other terms have emerged in the last two decades. On the other hand, terms such as community, urban gardening, development, movement, and change (related to climate change) emerged in the last two decades.

Among the most important findings of this study are that: 1) permaculture is a concept whose interest continues to increase in all types of audiences, including scientific and academic; 2) The definitions of permaculture continue to evolve and adapt to the new challenges to our planet's sustainability; 3) since its inception, permaculture has been and continues to be a concept associated with technical practices, but its philosophical aspect began to emerge in the 2000s and shows a general growth trend; and 4) the concept of permaculture is gradually becoming a scientific discipline, attracting the attention of groups of recognized scientists at an international level.

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APPENDIX

Appendix 3A. The 100 terms most associated with the practice of permaculture in the English literature

Word	Repetition	Word	Repetition	Word	Repetition	Word	Repetition
agriculture	70	transition	18	planning	10	general	7
sustainable	69	agroecology	17	resilience	10	guide	7
design	59	study	17	rural	10	justice	7
food	48	practice	16	transformation	10	knowledge	7
community	43	approach	15	use	10	matter	7
sustainability	43	forest	14	using	10	movements	7
Organic	32	learning	14	business	9	plant	7
Farming	30	nature	14	energy	9	theory	7
Social	26	security	14	grassroots	9	water	7
development	25	children	13	natural	9	Africa	6
ecological	25	climate	13	production	9	areas	6
environmental	25	plants	13	resources	9	carbon	6
management	25	agricultural	12	school	9	earth	6
Urban	25	communities	12	south	9	ethics	6
Ecology	23	land	12	teaching	9	future	6
Garden	22	principles	12	alternative	8	higher	6
gardening	22	system	12	biodiversity	8	human	6
movement	22	case	11	central	8	indigenous	6
permanent	22	diversity	11	conservation	8	integrated	6
Soil	22	environment	11	cultural	8	living	6
education	20	gardens	11	ecosystem	8	local	6
Farm	20	perspective	11	practices	8	Malawi	6
Change	19	potential	11	edible	7	perennial	6
landscape	18	science	11	farmers	7	policy	6
systems	18	crop	10	farms	7	project	6

Appendix 3B. The 100 terms most associated with the practice of permaculture in the Spanish literature

Word	Repetition		Word	Repetition		Word	Repetition		Word	Repetition
desarrollo	12		educación	3		bello	2		local	2
alternativa	8		educativo	3		bioconstrucción	2		monte	2
comunidad	8		estrategia	3		can	2		movimientos	2
Social	8		estrategias	3		capilla	2		nueva	2
sostenibilidad	8		hábitat	3		competencias	2		oriente	2
alimentaria	7		impacto	3		comunicativas	2		participación	2
Diseño	7		México	3		cooperación	2		prácticas	2
Arte	6		naturaleza	3		córdoba	2		presentes	2
agricultura	5		paisaje	3		cultural	2		principios	2
ambiente	5		producción	3		eco aldeas	2		promover	2
Cambio	5		soberanía	3		ecológico	2		provincia	2
Escuela	5		sustentabilidad	3		estudio	2		recursos	2
innovación	5		tierra	3		ética	2		resiliencia	2
propuesta	5		través	3		experiencia	2		resistencia	2
Caso	4		urbana	3		experiencias	2		rural	2
Medio	4		vivienda	3		filosofía	2		ruralidad	2
ambiental	3		agrícola	2		fotorreportaje	2		saneamiento	2
arquitectura	3		agroecología	2		gobernanza	2		seguridad	2
asentamiento	3		agroecológicos	2		hacia	2		significaciones	2
Centro	3		agropecuaria	2		herramientas	2		simbiótico	2
Ciudad	3		agua	2		huertos	2		sistemas	2
comunicación	3		alimentos	2		imaginarias	2		soberanía	2
ecología	3		análisis	2		información	2		sociales	2
ecológica	3		aporte	2		informal	2		sostenible	2
ecoturismo	3		basada	2		inglés	2		sostenibles	2

Appendix 3C. The 100 terms most associated with the practice of permaculture in the French literature

Word	Repetition	Word	Repetition	Word	Repetition	Word	Repetition
biologique	9	soutenable	3	radicale	2	aspirations	1
agricole	7	agricoles	2	structure	2	automie	1
Agriculture	7	agroécologique	2	systèmes	2	auxiliaires	1
Agroécologie	6	alimentaires	2	urbaine	2	banlieue	1
Pour	6	bibliographie	2	urban	2	basés	1
transition	6	cas	2			bénévolat	1
approche	5	conception	2			bien	1
Vie	5	d'action	2			bréger	1
Dans	4	d'activité	2			brésil	1
france	4	david	2			campagne	1
innovation	4	development	2			cantal	1
principes	4	écologie	2			carabidés	1
société	4	économique	2			Carolina	1
système	4	énergétique	2			choix	1
Systémique	4	environnement	2			collectif	1
Biologiques	3	Holmgren	2			comme	1
design	3	horticulture	2			commission	1
Ecologique	3	l'agriculture	2			comparative	1
Maraîchères	3	local	2			compromis	1
Microformes	3	maraîchage	2			compte	1
Mode	3	microforme	2			concept	1
nature	3	milieux	2			concilie	1
Pistes	3	partagés	2			conditions	1
Projet	3	permaculturel	2			consommateurs	1
Sein	3	production	2			création	1

CONNECTION BETWEEN CHAPTER 3 AND CHAPTER 4

While Chapter 3 of this thesis focuses specifically on the practice of permaculture, Chapter 4 seeks to characterize and compare different small-scale farming systems identified in rural areas of Panama. Chapter 4 begins by depicting a stakeholder analysis process in the study area whose purpose is to include the most significant representation of stakeholders within the Mariato community, including those actors traditionally marginalized. The chapter continues with a participatory process by implementing semi-structured interviews with stakeholders. Subsequently, these interviews are exhaustively analyzed, and from them, individual causal loop diagrams are implemented that, once integrated, allow the generation of conceptual maps of the systems studied in the field. Finally, the sensitivity and stability of the systems are evaluated through a loop polarity analysis.

CHAPTER IV: Implementing causal loop diagrams in the early stages of a participatory process to identify drivers and barriers when developing small-scale farming systems: a case study in rural Panama.

Roberto Carlos Forte Taylor, Julien Jean Malard-Adam, and Osborne Grant Clark

IV.1 Abstract

The small-scale agricultural sector continues to be the sector with the most food-producing farms worldwide. The literature shows that this sector is characterized by productive systems of high diversity, low mechanization, and reduced environmental impact. Therefore, for many scientists, the promotion, development, evolution, and scaling of some smallholder management practices are crucial for rural tropics' environmental sustainability and food security. Even though they are small-scale systems, their ecological evaluation comprises a highly complex work that requires integrating different climatic factors, soil quality, barriers, and motivators. There have been efforts in developing approaches to analyze the overall sustainability of agricultural systems. Some of these attempts include economic, social, and environmental-based indicators or a combination of these. Some of these efforts even seek to compare the sustainability of small-scale systems in different regions of the globe. However, there are limitations and shortcomings in some of these approaches. For example, some of these attempts are limited in their participatory component or in visualizing the complex structures, components, and feedback loops of the agricultural systems understudy.

In this research work, we propose a novel qualitative analysis of the data collected in the field through semi-structured interviews using modern software for this task. This qualitative analysis is complemented by using causal loop diagrams in a stakeholder participatory process to identify the main elements of small-scale agricultural systems and thus compare their ecological sustainability. This methodology successfully allowed the compilation of relevant information on the different agricultural systems studied. In addition, it allowed identifying the motivators and barriers in implementing this type of agricultural practice in rural areas of Panama. The drivers identified by this methodology were subsistence and respect for nature, and the most prominent barriers were the quality of the soil and the extreme temperatures of the summer. At the same time,

the most influential variables in the ecological sustainability of the system were soil quality, crop production, and regenerative practices.

The results obtained in this study show that the systems implemented in the rural region of Panama under study present a high diversity of crops. They are systems that tend to be stable in the long term, whether the scenario is favourable or not. Furthermore, the ecological sustainability of these systems depends mainly on the total production of crops, the quality of the soil, and the regenerative practices implemented. This methodology can also be used for planning by non-governmental organizations in their quest for the evolution of the small-scale agricultural sector towards ecological sustainability. Community-based organizations in future agricultural interventions can also identify barriers and challenges in the manner presented in this study. Likewise, best practices identified through this type of methodology can be replicated to accelerate the sector's evolution.

IV.2 Introduction

Agricultural systems are highly complex, from their design to their operation, since they involve several feedbacks between different aspects such as biological, physical, social, and economical. Added to this are cultural, climatic, market, and environmental factors that further increase its complexity. In a world with increasingly limited natural resources, the sustainability of these systems over time is further tested. Many have been attempts that have been made to measure and compare the sustainability of agricultural systems. These attempts could be grouped as follows (1) methods based on indicators such as soil quality, resilience, biological and management practices (De Vito, Portoghese et al. 2017; Marandure et al., 2020; Walters, Archer et al. 2016) (2) studies that measure the impact of the values and motivations of farmers in aspects such as land use, labor allocation (Howley et al., 2014), pollution, and production (Girard et al., 2008; Pelzer, Fortino et al. 2012; Zhu et al., 2012) (3) Qualitative studies based on surveys and focus groups (Bernués et al., 2014; Goma et al., 2001) (4) Comparison of case studies by applying models that compare or generate predictions related to the economic value of an ecosystem or the impact of management practices on its sustainability (Morel et al., 2015).

Assessing the sustainability of agricultural systems is one of the most important and current challenges facing farmers and scientists. Many indicators have been developed to estimate agricultural systems' productivity, resilience, economic viability, and adaptability. Many of these indicators seek to provide farmers with a quick and straightforward tool that allows them to deduce the health of the soil, economic viability, or sustainability of their agricultural systems. Adducing that, farmers can make more informed and strategic decisions that help overcome poor performance and increase functions in their designs. These tools are standardized, facilitating comparisons between one or several agricultural systems. However, the results obtained by these indices do not provide much information on the causes, effects, and practices that lead to the level of sustainability achieved or not.

Furthermore, they do not provide detailed information on the dynamics and feedbacks that occur over time in these agricultural systems. Many of these indices are developed in-house by researchers, and therefore their results do not represent the local context. Finally, these indicators provide a precise picture of the status of an agricultural system but lack actions that help farmers improve their environmental, social, or economic performance over time.

Qualitative approaches seek to measure the social, environmental, or economic impact of agricultural systems based on the perception of a community and its decision-makers. For instance, qualitative studies have been used (Bernués et al. 2014) that combines surveys and focus groups on determining and quantifying the impacts of livestock on the environment or a community. In the same way, they are used to analyze the level of understanding about concepts such as ecosystem services and the value (cultural or economic) that they would be willing to assign to it. The data obtained from this type of study is used to develop and propose different policies to mitigate an existing problem. Other qualitative studies (Goma et al. 2001) seek to identify a problem and develop indicators through participatory processes. These techniques claim that local communities have deep traditional ecological knowledge and are therefore well aware of the problems their environment faces. It has been suggested that this type of study could accelerate and improve the adoption of sustainability indicators or better agricultural practices (Goma et al. 2001). However, many of these approaches are based on rigid questionnaires previously developed by researchers that limit the ability of participants to contribute meaningful problems and solutions. On the other hand, these approaches do not consider the systems' dynamics, interactions, and feedback over time, which determines their ecological sustainability. Lastly, many of these participatory systems lack decision-making analysis methodologies that guarantee an inclusive sample, considering traditionally excluded stakeholders.

Other approaches implement complex models capable of comparing the performance of different agricultural systems based on their economic viability, the motivations that farmers have in their strategic choices (Marshall et al., 2013), or the efficient use of resources such as water or energy. For example, Morel et al. (2017) examined the viability of different agricultural systems. For this, they were based on 20 farms in rural areas and 10 in urban areas of London. The study used an inductive approach combining a qualitative analysis of farmer interviews and a quantitative model. The qualitative research allowed the development of a conceptual framework to analyze the strategic choices of farmers. These strategic decisions included ethical aspirations, which may have a degree of subjectivity. However, it should be noted that there will always be some subjectivity regardless of the type of analysis. Even economic studies tend to assume scenarios that do not necessarily resemble reality. Morel et al. (2017) explored the economic viability of the systems by developing and implementing a stochastic simulation model of income and workload. Although this study proposes an inductive and participatory approach, for the development of a model, it is limited to a single type of audience. By lacking a stakeholder analysis, a key source of contributions that strengthen the relevance of the model in the local context is lost. In this sense, Participatory system dynamics modeling (PSD) promotes the inclusiveness of stakeholders and facilitates the development and understanding of dynamic models. Moreover, PSD allows the comparison of complex systems such as agrosystems. PSD was developed in 1950 to make it easier for entrepreneurs to understand complex industrial and economic processes. It has also been used to analyze and design policies. PSD has been widely used in the field of healthcare and wellness (Di Lucia, Peterson et al. 2021; Inam, Adamowski et al. 2017), and much more recent in the agricultural field (Kopainsky, Hager et al. 2017; Malard, Adamowski et al. 2015).

Even more scarce are attempts to complement socioeconomic with physically-based environmental models considering the participation of critical stakeholders in sustainability and agroecology (Inam et al., 2015; Malard et al. 2015). These qualitative dynamic participatory models are part of the so-called soft system models, including cognitive mapping and fuzzy cognitive mapping (Mendoza and Prabhu 2006). In many cases Cognitive maps (CM) were developed to represent complex decision problems, composed of dynamic entities interrelated in complex ways. Entities are represented as nodes, and their correlations are expressed with arrows, while the arrow's direction illustrates the direction of influence (Mendoza et al. 2006). In comparison, fuzzy cognitive maps are extensions of CMs. The FCM is composed of three main elements:

1. Signed causality indicates positive or negative relationships
2. A "fuzzy" value determines the strength of the relationships between nodes.
3. Casual links are dynamics where a change in a node or concept affects other nodes in the path.

In many cases, designing the general relationships of elements in a system (Cognitive Mapping) is sufficient. However, in situations where there is more information or knowledge about the different cognitive aspects, they could be structured through "influence diagrams." In these diagrams, the relationships are described in terms of causality between the nodes connected by arrows (Mendoza et al. 2006).

A range of methodologies combines integrative, collaborative modeling with participatory processes regarding quantitative models. These methodologies include: 1) Computer-Aided Negotiation (CAN), which combines computer modeling/simulation with dispute resolution (McCrodden 2011) 2) Mediated modeling, implements computer modeling as invaluable tools to guide policy and management decisions (Van den Belt 2004) 3) Shared Vision Planning refined by the U.S. Army Corps of Engineers, combines water resources planning, structured public participation, and an integrated computer model (Hagen 2011) 4) Complementary modeling, equally incorporates multiple opinions and contradictory points of view of the stakeholders in a single model, through a role-playing game (Bos, Cornioley et al. 2020). Nevertheless, these methods do not include an in-depth stakeholder analysis that fosters the participation of traditionally excluded stakeholders, nor does it contain an inductive analysis of the content of the interviews that provides transparency to what is reflected in the casual loop diagram. Finally, they do not provide a mechanism for stakeholders that facilitates the understanding and visualization of the components and their socio-environmental and physical interrelationships. For all these reasons, systems dynamics models developed through inclusive and structured participatory processes represent a powerful tool for understanding complex problems, revealing potential solutions, and developing policy.

This research seeks to promote the development of small agricultural projects in rural Panama. Here we propose an inclusive methodology for the visualization, understanding, comparison, and evaluation of the sustainability of different agricultural systems through the implementation of participatory processes and qualitative and quantitative modeling methodologies. The objective of this paper is to develop conceptual models using CLDs that represent the interaction of the different components and dynamics of the studied small-scale agricultural systems, as well as the barriers and motivations for developing these systems by the stakeholders. Furthermore, these

CLDs serve as a foundation for developing a quantitative model that simulates the dynamics between the different components of the studied agricultural systems and compares their ecological sustainability (Kotir et al., 2016; Marandure et al., 2020; Sorensen 2016; Tey, Ibragimov et al. 2019; Walters et al. 2016).

We acknowledge various definitions of sustainability (financial, ecological, and social). For this research work, ecologically sustainable systems are those that are not highly mechanized and therefore operate with little or no use of fossil fuels or external inputs (synthetic fertilizers, herbicides, and pesticides), and can remain productive over time compared to the baseline (conventional monoculture) while maintaining soil quality.

The research presented in this document contains three main objectives:

(1) propose a simple methodology that allows stakeholders, including those traditionally excluded, to promote the development of small-scale agricultural systems in developing countries where local governments are limited in knowledge, resources, and time.
(2) implement the methodology to identify the possible factors that hinder the implementation of small-scale agricultural systems. In turn, the motivators that make the community interested in implementing it, even with existing barriers.
(3) Identify through the implementation of this methodology the different agricultural systems evidenced in the community of Mariato. In addition, we compare and argue about their differences using loop polarity analysis and other indicators identified.

IV.3 Study Area

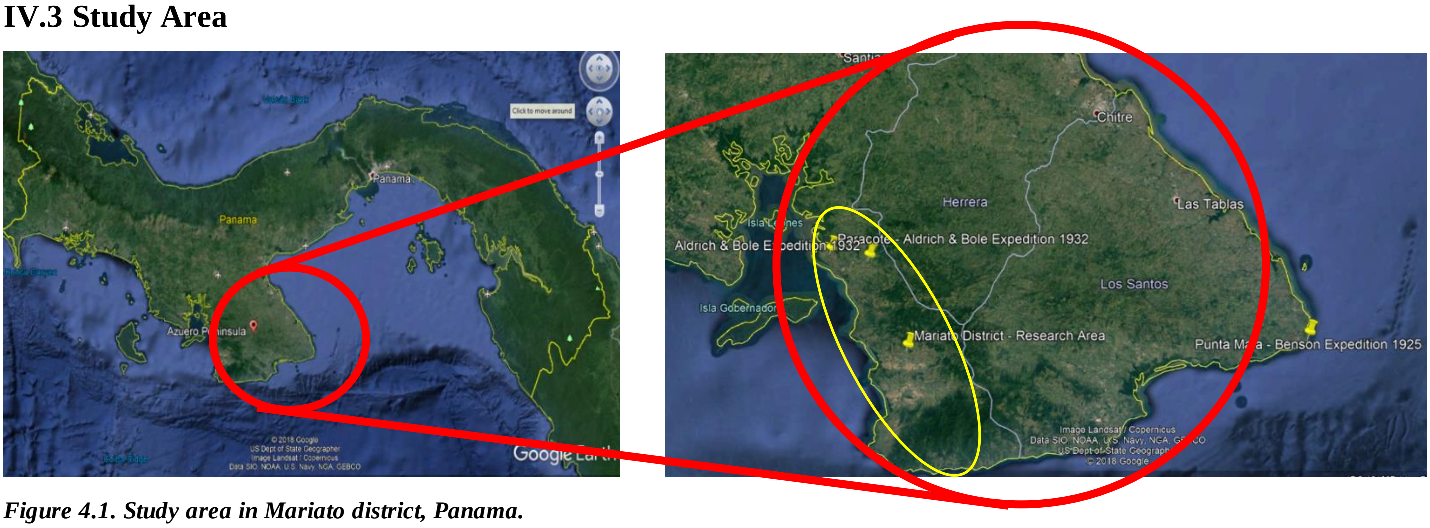
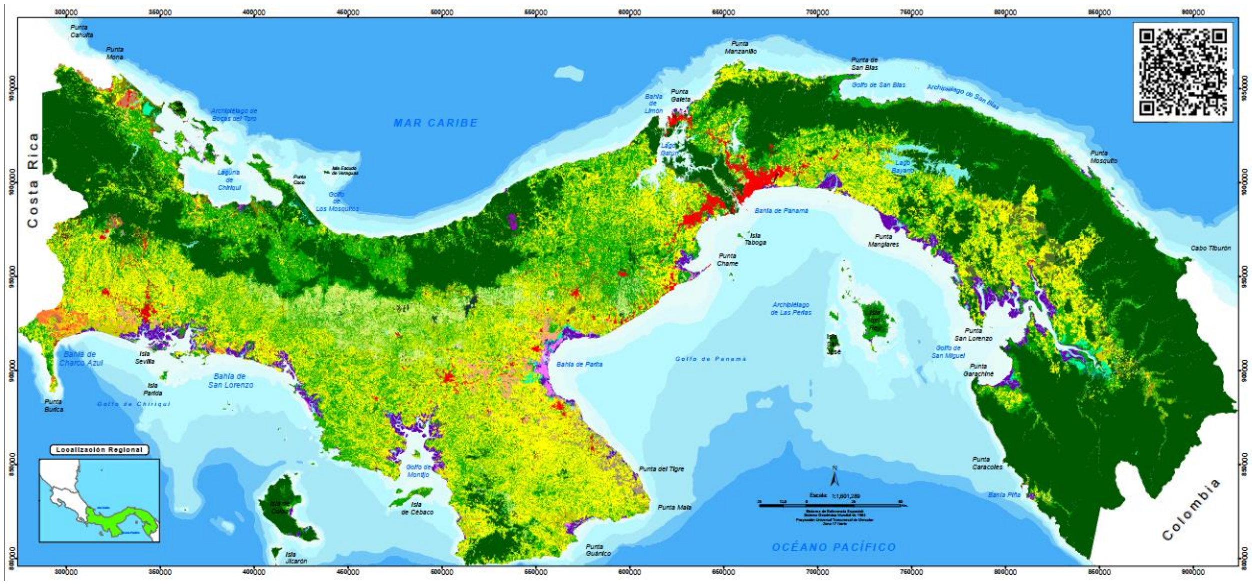


Figure 4.1. Study area in Mariato district, Panama.

Panama is located in the intertropical zone close to the equator, and it is an isthmus oriented from East to West. The Isthmus of Panama limits to the North with the Caribbean Sea and to the South with the Pacific Ocean. Figure 4.1 illustrates satellite images of Panama and the Mariato District, where this research was conducted. The climate in Panama is highly influenced by the oceans due to the narrowness of the isthmus (Empresa de Transmisión Eléctrica S.A., 2009). Mariato is a coastal district in the southern part of Panama in the Azuero Peninsula. The economy in Mariato is mainly based on livestock, monocultural agriculture, shrimp farming, and, recently, tourism. In the District of Mariato the annual average temperature is 23.8 °C; nevertheless, high and low temperatures of 34 °C and 14 °C respectively have been recorded (44 years of data collection). In general, the dry season lasts about four months (December to April) and the rainy season lasts about eight months (April to December). The details of the study area, along with collected data, are provided in Chapter 1.

According to Figure 4.2, at least 30.43% of the Isthmus' surface is covered by pasture (21.62%), monocultures, vegetables, fruit trees and shrubs (MiAmbiente, 2022). The national forest cover map, published in the Official Gazette in 2017, shows that the District of Mariato is dominated mainly by pastures. There are also mature, secondary, and mangrove forests in lesser presence. (Ministerio de Ambiente, 2012).



	Category	Area (km²)	%		Category	Area (km²)	%		Category	Area (km²)	%
Forest and other wooded land	Mixed broadleaf forest mature	27,491.37	36.50	No Forest	Rocky outcrop and bare soil	49.39	0.07	No Forest	Pineapple	25.99	0.03
	Secondary mixed broadleaf forest	15,970.59	21.20		Beach and natural sand	44.83	0.06		Other annual crop	292.42	0.39
	Mangrove forest	1,837.82	2.44		Coffee	97.49	0.13		Agricultural and livestock production	121.75	0.16
	Ore forest	64.60	0.09		Citrus	30.97	0.04		Pasture	16,288.73	21.62
	Cati forest	33.60	0.04		Oil palm	217.99	0.29		Populated area	1,068.06	1.42
	Raff forest	153.21	0.20		Plantain/banana	127.25	0.17		Infrastructure	321.41	0.43
	Conifer planted forest	88.95	0.12		Other permanent crop	66.69	0.09		Mining	41.02	0.05
	Broadleaf planted forest	665.53	0.88		Rice	805.82	1.07		Aquaculture pond	132.50	0.18
	Stubble and shrubby vegetation	4,867.98	6.46		Sugar cane	350.11	0.46		Salt production	13.72	0.02
	Herbaceous vegetation	1,805.78	2.40		Mixed horticulture	30.70	0.04		Albinas	5.71	0.01

Figure 4.2. Forest cover and land use map of Panama.

In terms of the capacity of the soil for agricultural production, the Catastro Rural de Tierras y Aguas de Panama (CARTAP) map generated between 1965 and 1968 reported that in the Azuero Peninsula predominates, non-arable soils with very severe limitations for agriculture, suitable for pastures, forests and natural reserves.

	Plowable, some limitations in plant selection, requires moderate conservation.
	Plowable, severe limitations, in plant selection, require special conservation of both.
	Plowable, very severe limitations in plant selection or require careful management.
	Not plowable, low risk of erosion, but with other limitations, with qualities for pasture and woodland.
	Not plowable, with severe limitations, with qualities for pasture, forest and reserve land.
	Not plowable, with very severe limitations, with qualities for pasture, forest and reserve lands.
	Not plowable, with limitations that exclude its use for commercial plants production, it can be used for recreation, reserve, water supply and aesthetic appreciation.

Figure 4.3. Taxonomy of soil quality in the Mariato District area.

Experts have proposed regenerative agriculture as an option to restore degraded land and sequester atmospheric carbon (CO_2) underground while producing healthy and nutritious food. This paper's primary goal is to compare the sustainability of different agricultural systems based on the indicators and drivers identified through the participatory process and our working definition of the term. For this research work, "sustainability" refers to the ability of an agroecological system to operate energetically efficient, with little or no use of non-renewable energy and external inputs (fertilizers, chemicals, pesticides, among others) and can still perform overtime productively as compared to the baseline (conventional monoculture), while regenerating the soil and reducing stress on the surrounding environment.

IV.4 Methodology

Our approach adapts and combines different qualitative and stakeholder engagement methods (Inam et al., 2015; Malard et al. 2015; Marandure et al., 2020; Sorensen 2016; Walters et al. 2016). It involves semi-structured interviews with farmers, experts, authorities, and field observations. The proposed participatory modeling process can be categorized into three successive stages: (a) stakeholder analysis, (b) framing the problem and primary motivators, (c) construction of a conceptual model using CLDs.

The first stage describes selecting and categorizing stakeholders according to their roles, attributes, power, and interests. The second stage describes the qualitative approach used to identify the significant barriers that hinder the development of small-scale agricultural systems in the study region. The third stage consists of representing the barriers and motivations of the community through a conceptual model in the form of CLD.

Results from the participatory process were analyzed transparent and traceable through the implementation of two tools (Happyscribe and ATLAS TI). The Happyscribe online tool allows the transcription and organization of interview content based on time and speaker. Happyscribe was selected based on an analysis of the different options available (SpeechPal, Spext, Otter, and Temi). Happyscribe transcribed in multiple languages and presented the most affordable costs per minute of transcribable audio. Moreover, its interface was amicable compared to other options in the market.

It should be noted that the interviews used in this study were carried out a few weeks before the start of the pandemic and were suspended for the same reason. The follow-ups and subsequent developments were conducted through virtual and other digital means.

All interview transcripts were imported into the ATLAS TI tool. This tool facilitates the analysis of the content of the interviews and allows the different citations (key data) and their interrelationships with other data to be viewed through networks. ATLAS TI was also selected after a thorough analysis of the available tools (ATLAS TI, NVIVO, MAXQDA, Dedoose, and QDAMINER). We decided on ATLAS TI because it offers an affordable price, analyzes all types of files (text, audio, video, among others), and offers a friendly interface.

We adopted a series of methodologies previously used in qualitative studies (Scheppingen et al., 2008; Velten et al., 2015). The interviews were tape-recorded and later transcribed verbatim. All data were analyzed in their original languages in order to preserve their meanings. Later the transcribed interviews were subjected to content analysis by applying the qualitative software ATLAS.TI. This tool systematically facilitates the extraction, comparison, exploration, and administration of different significant pieces of texts (quotations) from large amounts of data. The quotes represent data critical to the achievement of the study objective. Quotations are later coded. Some of the codes created included barriers or challenges, interviewees' motives, strategies and beliefs, and lot size. Eighty-nine codes were developed, some previously, and others were created as the data were analyzed. The Network tool provided by the software helped with the codes analysis. Networks are the visual expression of those created codes linked to their respective documents (in this case, individual interviews) and citations (individual sentences/key data). ATLAS TI allows analyzing each sentence of each transcript document and linking each one with one or N number of codes as the researcher determines in the analysis. Once the codes have been generated and assigned, the entire network can be viewed using ATLAST TI "Open Network" and "Add Neighbours Quotations" tools.

Figure 4.4 represents a network of a single code. The code in the center is one of the "Motives" reported by the interviewees. In this case, it is The Protection of Nature or its Regeneration.

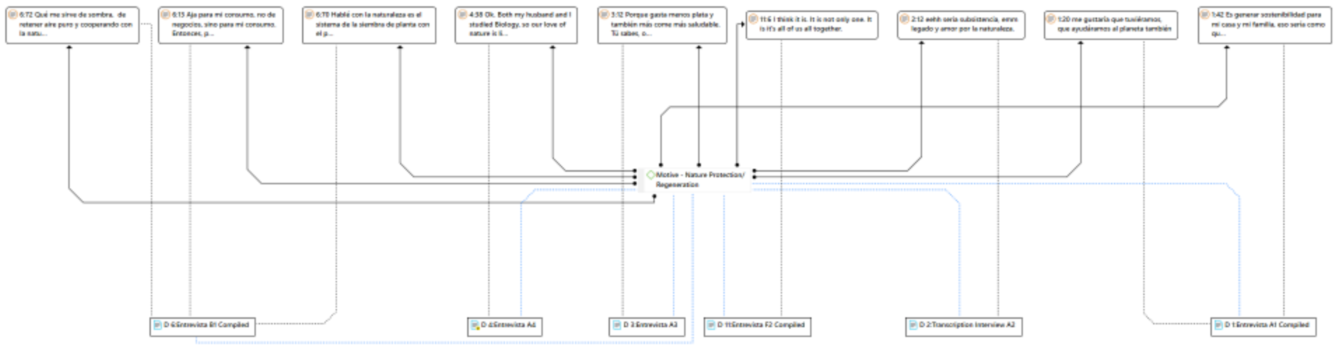


Figure 4.4. Example of the qualitative analysis used to identify the most relevant drivers and challenges reported during the stakeholders' participatory process.

In the lower part of the graph, each interviewee is represented by a Document (D1, D2, D3, D4, D6, and D11). Documents are linked to motives, and in turn, the top of the graph shows the specific comment (s) that each interviewee made concerning that motive.

Once the reasons, barriers, and variables that influence them were identified, we consolidated them into causality diagrams for each visited system. This project's system dynamics modeling method allows one to quickly identify the feedback loops found in the visited systems, which tend to be challenging to conceptualize (Malard, Rojas and Carrera, ND).

CLDs serve us to represent complex decision problems. They are composed of interrelated dynamic entities, usually including feedback links. These complex entities are represented as nodes, and edges or arrows represent the causal links with the direction of the arrow representing the direction of influence. CLDS are essentially structured ideas arranged on purpose to understand the relationships and dynamics of a system. The process begins with the generation of ideas or concepts with the participation of stakeholders. These ideas are arranged in a diagram that shows the relationships and interactions between them. Relationships are organized following a node and arrow scheme (nodes represent concepts or ideas and arrows denote the interactions or links between these ideas) (Mendoza and Prabhu, Mendoza et al. 2006). In systems dynamics models, arrows contain polarity (positive or negative) that visually express the relationships between the variables. To determine the polarity of one of these arrows connecting two variables, we have to consider the effect that the first variable has on the second regardless of the rest of the cycles and variables of the system. When we compare two variables, and the first increases causing an increase in the second, the relationship is considered positive. Otherwise, if the first variable increases cause a decrease in the other variable, the association is negative (Malard, Rojas and Carrera, ND).

For example, in the figure 4.5 diagram, more organic matter in the soil promotes an increase in total production, so a positive sign (+) has been placed next to the arrow (**1**). On the contrary, total crop production causes a decrease in the nutrients available in the soil (arrow **2**). Because of this, the arrow is marked with a negative sign (-). Given that the more nutrients available in the soil, the less the need to apply natural fertilizers, the third (**3**) arrow is also marked with a negative (-). The fourth (**4**) arrow is marked with a positive sign (+) since increasing the application of natural fertilizer increases the amount of organic matter in the soil.

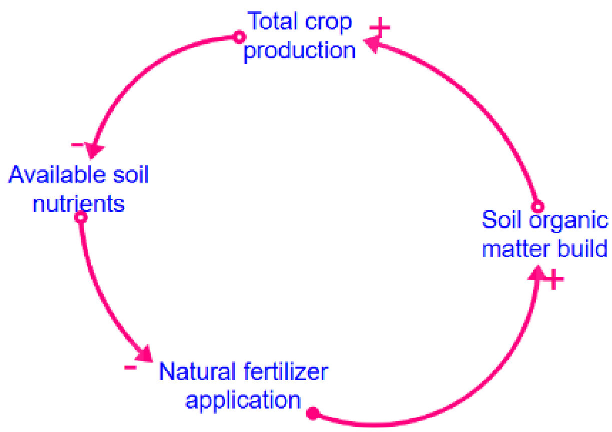


Figure 4.5. Example of a causal loop diagram representing variables influencing the total production of crops

Once the CLDs were built for each visited system, the stakeholders (experts) were contacted again to obtain their feedback. The expectation was that their feedback would ensure that the models of each system were indeed a close representation of them.

The next step was to compare the polarity of the loops. By comparing the loop polarities for each agricultural system, we can assess their sensitivity and stability. We do this by quantifying the relative difference between reinforcing and balancing loops. Table 4.7 quantifies the polarity of the loops for the three systems (S1, S2, and S3). The values of interest show the absolute difference and the difference between the number of reinforcing loops and balance loops that directly involve each system. Evaluating the absolute difference between the number of reinforcing and balancing loops for each system reveals information about the system's stability. A high difference would indicate high stability (balancing) or high instability (reinforcing). Evaluating the difference between the relative number of loops, characterized by a positive or negative difference, helps us to assume the general behavior of each system. A positive difference indicates that the system is dominated by reinforcing loops (a volatile and potentially destructive influence), and a negative difference means that the system is dominated by balancing loops (an excess of stability and potentially limiting influence) (Walters et al. 2016).

It is important to note that this methodology assumes that all loops contain the same weight. Therefore, the conclusions could present a certain degree of inaccuracy. However, we consider that even knowing the limitations of this qualitative methodology could help stakeholders visualize and understand the components, critical parameters, and influences of the different variables of a small but complex agricultural system.

This research work is innovative as no previous attempts have been made to propose a straightforward methodology to encourage stakeholder participation in promoting and developing small-scale agricultural systems. The method combines inductive qualitative studies with causal loop diagrams to determine and solve problems in adopting these systems. This methodology is applicable when stakeholders lack resources, such as time and money. Figure 4.6 describes the qualitative modeling process implemented in this paper (Malard 2020).

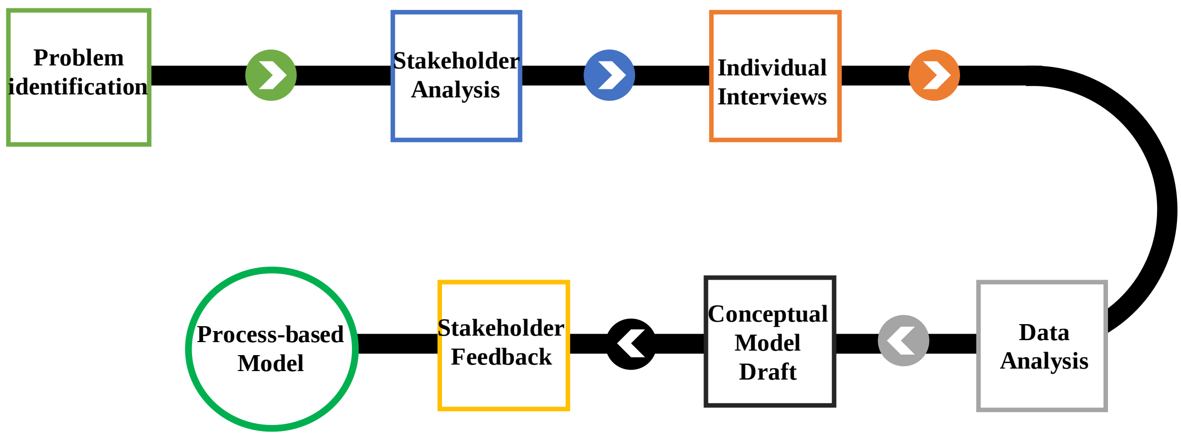


Figure 4.6. General diagram showing the participatory model-building process.

IV.4.1 Problem definition

An essential input for the whole modelling process, its stakeholder analysis and the development of CLDs is an adequate definition of the problem. The SDM must be customized, adapting to specific problems and particularities. They must also be progressively tested to ensure their resemblance to reality and usefulness for "What if" tests (Homer 1996). Therefore, developing an SDM model is iterative, which implies trials and errors that often require much time and effort to come to fruition (Homer 1996). In this research work, potential problems were explored through visits to the Mariato community prior to the study kickoff. Subsequently, a literary review was conducted (studies carried out in the Mariato district by research centers or government entities). Finally, based on preliminary feedback from the semi-structured interviews, the problem to be analyzed in this study was articulated. The main focus of this study was to explore the sustainability or not of different small-scale agricultural systems found in the region, considering the already existing state of degradation of soils.

This research work follows the model's development process described by Sterman 2000. The process begins with identifying the system to be modeled and the stakeholders who will contribute and use the model. Following a clear statement of the problematic behavior must be developed. Subsequently, the model's limits should be defined. The model's scope must be limited so that it is as complex as necessary to answer the questions that arise related to the problem of interest. Since the models are inherent simplifications of the system they seek to resemble, it is the job of the modeler to determine which aspects of the system contribute to its purpose and therefore be included and which are not and should be eliminated. Problem definition is an iterative process; After conducting the stakeholder analysis, the problem statement could be modified if deemed necessary by the stakeholders.

IV.4.2 Stakeholder analysis

A methodology proposed by similar studies(Elias et al., 2002; Inam et al. 2015; Malard et al. 2015; Mitchell et al., 1997) was implemented. Once the problem was defined, an initial list was generated through a brainstorming process, including marginalised stakeholders (minorities, women amongst others). This list was enriched and adjusted as the interview process was carried out since some interviewees proposed other interested parties or suggested eliminating others as they considered them irrelevant. Through a literary review and opinion of experts in agriculture at the national level, it was concluded that the Institute of Agricultural Innovation of Panama (IDIAP) was an important stakeholder. IDIAP is a government institution whose primary function is to generate, validate and disseminate agricultural knowledge and technologies at the national and local levels. Another important organization that emerged from the opinion of experts and interested parties was the Ministry of Agricultural Development (Ministerio de Desarrollo Agropecuario - MIDA) and its respective National Directorates of Plant Health and Rural Development.

Stakeholders were categorized as experts, decision-makers, implementers, or users based on the European Commission (2003) framework to ensure representation of the different interested parties. A list with the assignment of the roles of the various stakeholders is illustrated in Appendix 4A (European Commission, 2003).

Finally, a power vs. interest grid approach (Ackermann and Eden 2011) was implemented to prioritize stakeholders (see appendix 4C). This analysis shows that The National Directory of Rural Development and the National Directory of Plant Health from the Ministry of Agriculture are the ones that possess the most power concerning smallholder's agricultural development in the region. However, The National Directory of Rural Development holds high power and interest since it is part of its political guidelines and mandates.

IV.4.3 Individual interviews

Individual face-to-face semi-structured interviews of an hour of length on average with stakeholders were conducted. A total of eleven (11) semi-structured interviews were carried out. Recorded interviews totaled 10 hours and 47 min of audio, and the transcription process required 54 hours to complete. From eleven (11) interviews, eight (8) were carried out with farmers or agriculture early adopters from the Mariato Community. The other three interviews were carried out with government institutions and IDIAP.

The interviews were used to collect data in the form of opinions of smallholder farmers and early adopters to identify essential drivers for their implemented agricultural practices and must significantly challenge. Similarly, the interviews were used to examine some production systems in detail and explore the production practices used. We used an outline with questions for the producers (Appendix 4D) to explore a few production systems (Sassenrath, Halloran et al. 2010). The question's outline was proposed as a guideline to stimulate discussion and not as a rigid questionnaire. We also sent a letter with the background and research objectives to the smallholder farmers through digital means.

The interviews were subjected to content analysis through the ATLAS TI software to identify the processes and practices of each agricultural system identified during the interviews and field visits.

IV.4.4 Causal Loop Diagram

A Causal Loop Diagram (CLD) is a systems-based conceptual framework used to characterize the dynamic drivers of a specific behavior (Walters et al. 2016). This study implemented CLDs to represent processes, drivers, and elements from three agroecological systems. We use Stella Architect software to create individual CLDs covering all the elements, processes, and practices of the systems studied in the field. Figure 4.7 represents a CLD modeling population dynamic built on Stella Architect, with reinforcing (R) and balancing (B) loop.

The CLDs were generated based on interviews' content analysis results. The researcher also identified the main barriers to establishing an agricultural system in the area. In addition, the content analysis also helped define the primary motivators that these smallholders farmers had to initiate a farming system. A review of the literature and the results from the interview's content analysis determined processes involved in each agricultural system. Also, the links between processes and the most significant barriers detected (Soil quality, lack of knowledge, and hot summer temperatures)

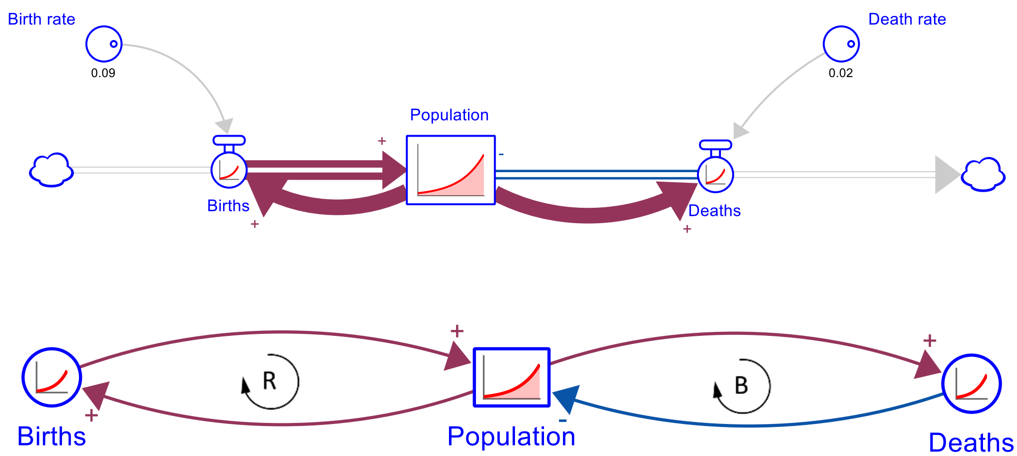


Figure 4.7. An example of a causal loop diagram modeling population dynamics built on Stella Architect.

Figure 4.7 shows that in a CLD, there are both positive and negative influence polarities (Walters et al. 2016). For instance, as births increase, the population increases; this is an example of a positive influence. The opposite case would be a polarity of adverse effect, as is the case when deaths increase, the population decreases. CLDs also represent loops. For example, in figure 4.7, the loop on the left is a reinforcing loop; any change in a variable (for example, an increase in population) results in a series of situations that reinforce the initial change. The loop on the right is a balancing loop; it equilibrates any change in any of its variables. For example, An increase in deaths leads to a reduction in population, thus offsetting the initial increase in population.

IV.5 Results and Discussion

This section presents the results of our participatory process and the qualitative evaluation of the different agricultural systems found during this process. Finally, we discuss the differences found between the different agricultural systems and their implications.

Figure 4.8 shows the system's geographic location. While S2 is not located within the Azuero peninsula, it is located in the Arco Seco region, an area to the south of Panama that is widely deforested and extends beyond the Azuero peninsula. The system (S2) is selected because it is considered one of the most successful organic systems in the country by IDIAP. In addition, the distance between S2 and S1, and S3 does not exceed 150 km, so it can be considered negligible.

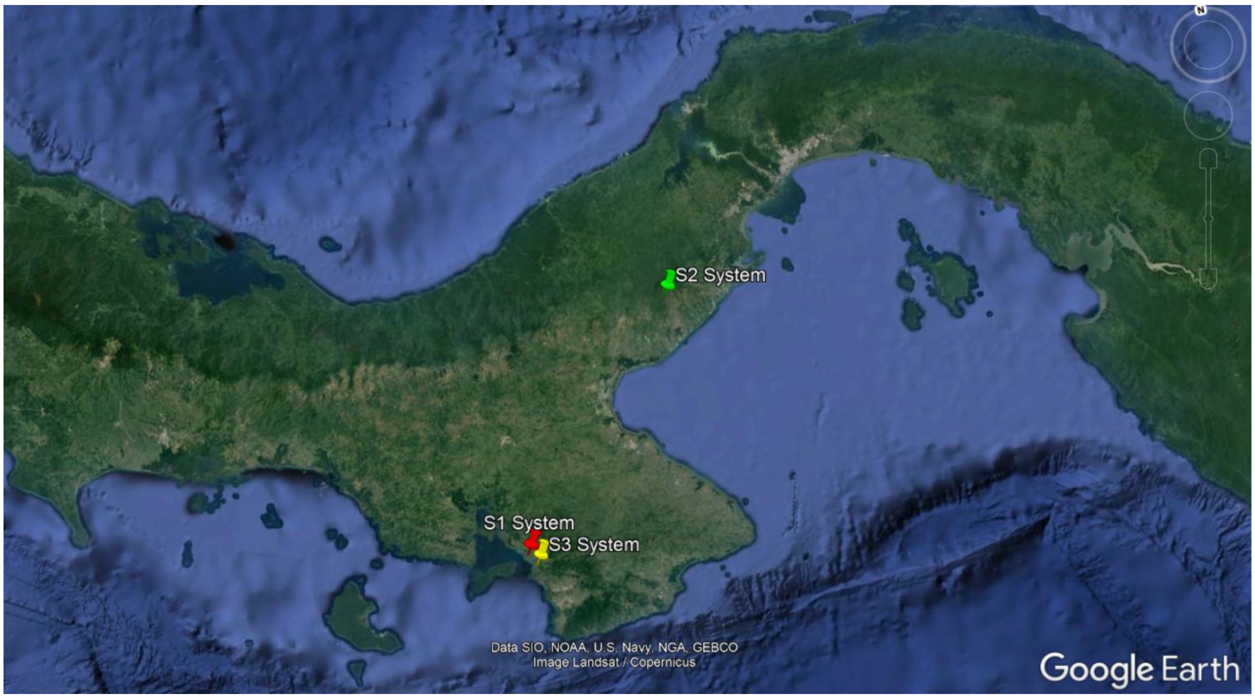


Figure 4.8. The geographical location of the small-scale agricultural systems understudy.

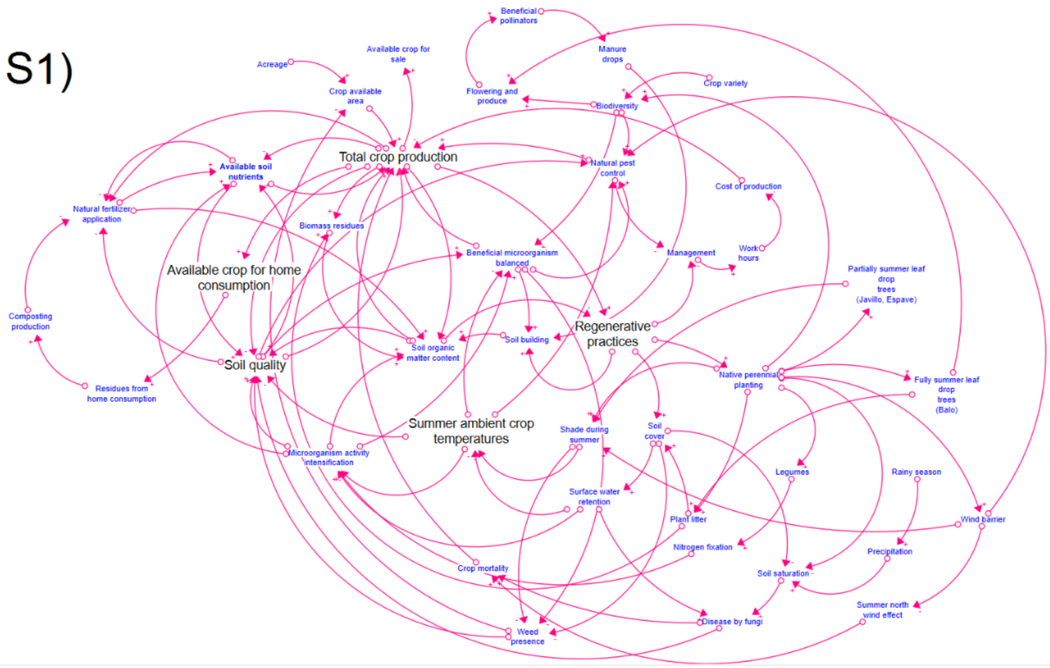
Table 3.7. Average distances between each agricultural system in kilometers.

	Estimated Distance (km)
S1 - S2	142.29
S1 - S3	6.62
S2 - S3	140

Figure 4.9 shows the three CLDs representing the agricultural systems visited (S1, S2, and S3).

To develop the CLDs, challenging and complex assumptions were made regarding the polarity of influence between the drivers. For example, acreage, crop production, biomass generation, soil organic matter, and their associated effect on soil quality. In other words, the increase in the cultivated area has a positive (+) influence on the rise in crop production, which in turn generates a positive effect (+) on the generation of biomass residues; therefore, it increases the organic matter in the soil. This reinforcement loop impacts the soil quality positively or negatively. The assignment of polarities between each process and variables of the qualitative model allowed the creation of individual CLDs of each agricultural system.

S1)



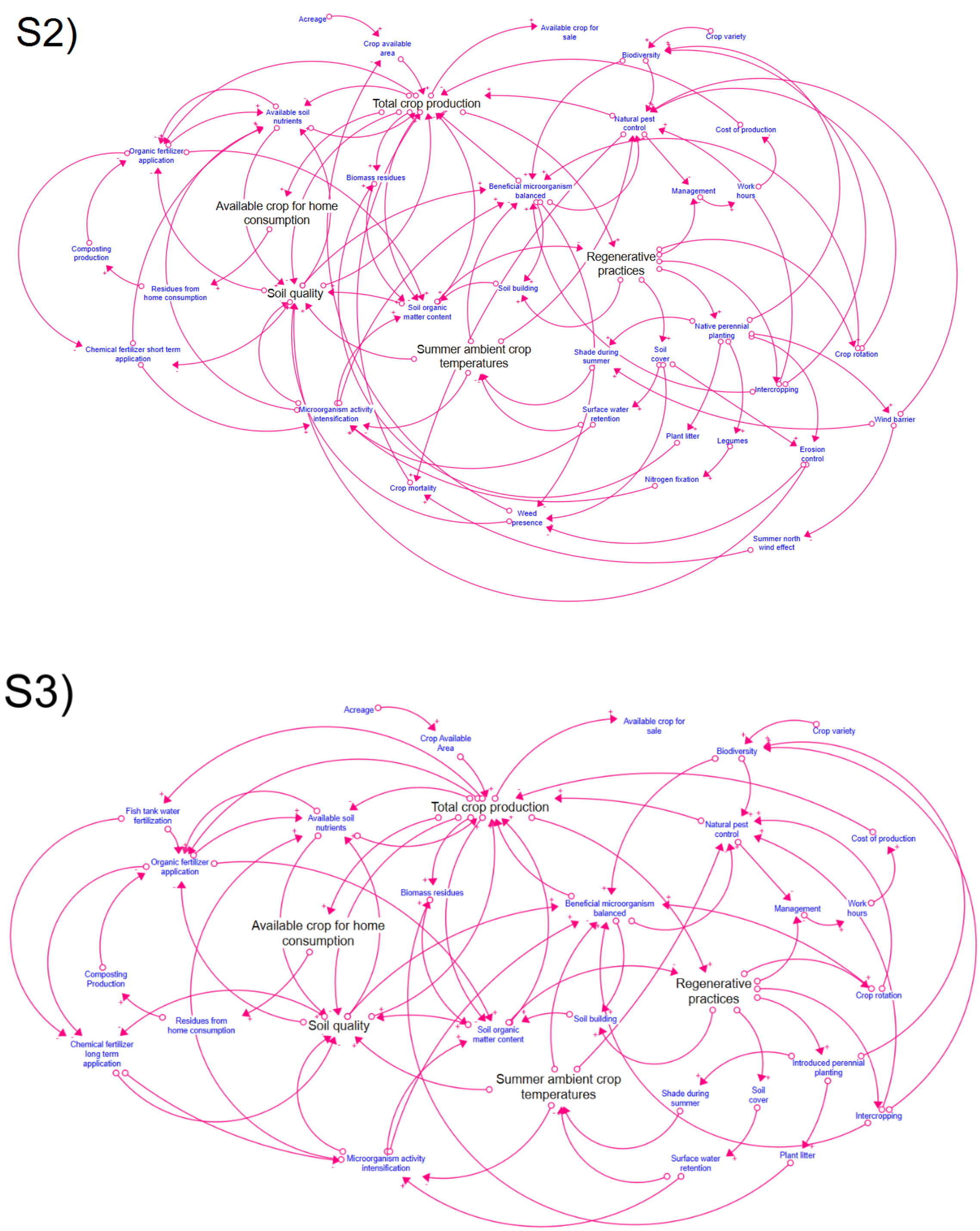


Figure 4.9. Causal loop diagram of the individual agricultural systems from Mariato.

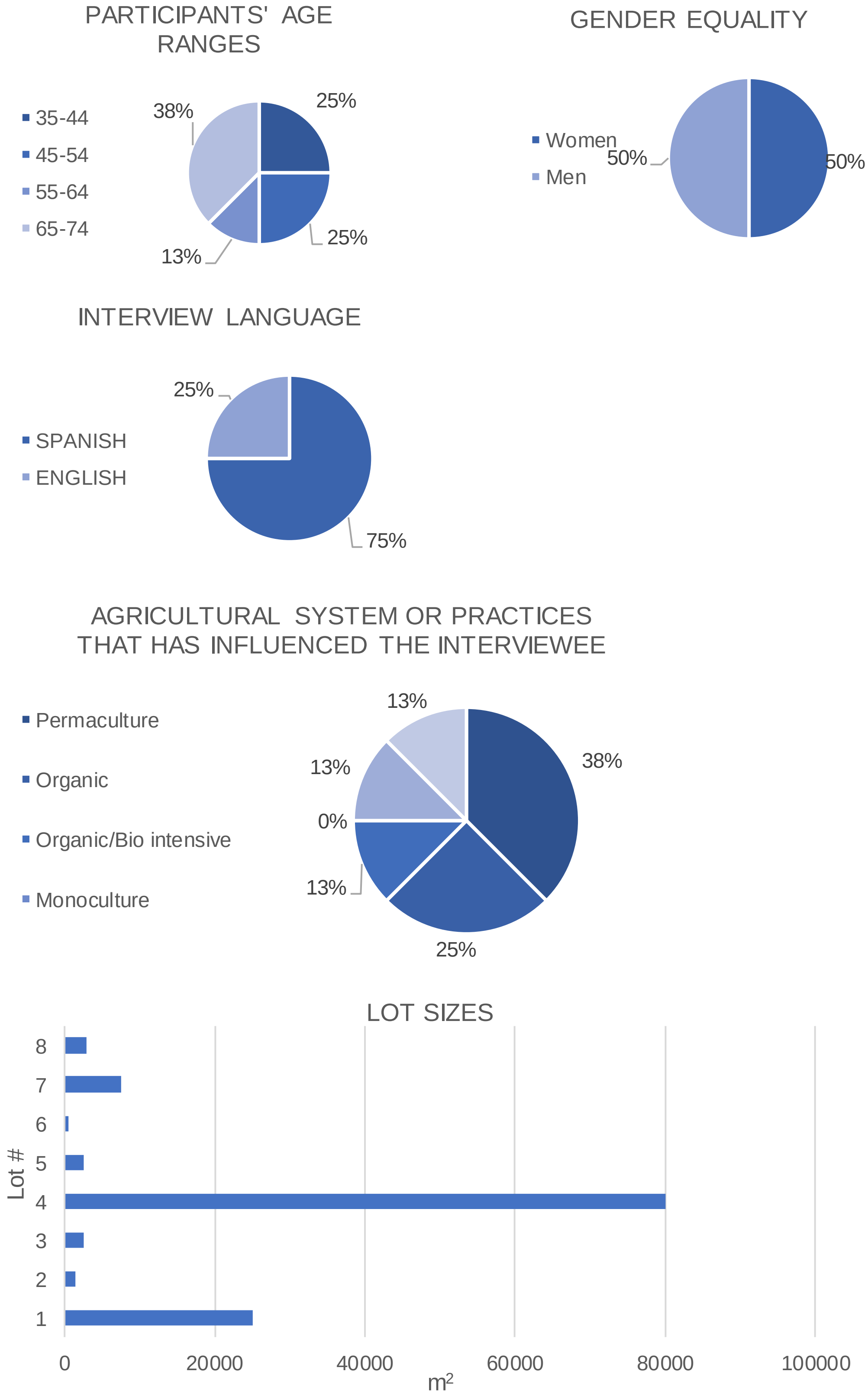


Figure 4.10. Demographic and related data on farming systems resulted during the interviewing process

A total of eleven interviews were carried out, of which eight were with smallholders farmers or agriculture early adopters from the Mariato Community. Through the content analysis of the interviews carried out in ATLAS TI, the following generalities of the sampling could be deducted:

1) 38% of the respondents were over 64 years old, and the highest percentage (50%) of respondents were between 35 and 55 years. Based on these results, we can argue that the sample comprises people who have found in agriculture an activity to retire, young people with an idea of breaking with current professional development schemes, or people in their productivity stage planning their retirement opportunely.

2) Regarding gender equality, 50% of those interviewed were women, and 50% were men. Interviews were conducted in Spanish (75%) and English (25%).

3) 63% of the interviewees mentioned permaculture as one of their references for the system they have implemented or would like to develop. Another practice mentioned was organic agriculture.

4) 62% of those interviewed reported that the size of their plots was much less than one hectare, close to 2000 m2. Two interviewees reported plots of more than one hectare. However, they also expressed interest in developing agriculture in a small area of their property surrounded by other practices such as reforestation and conservation.

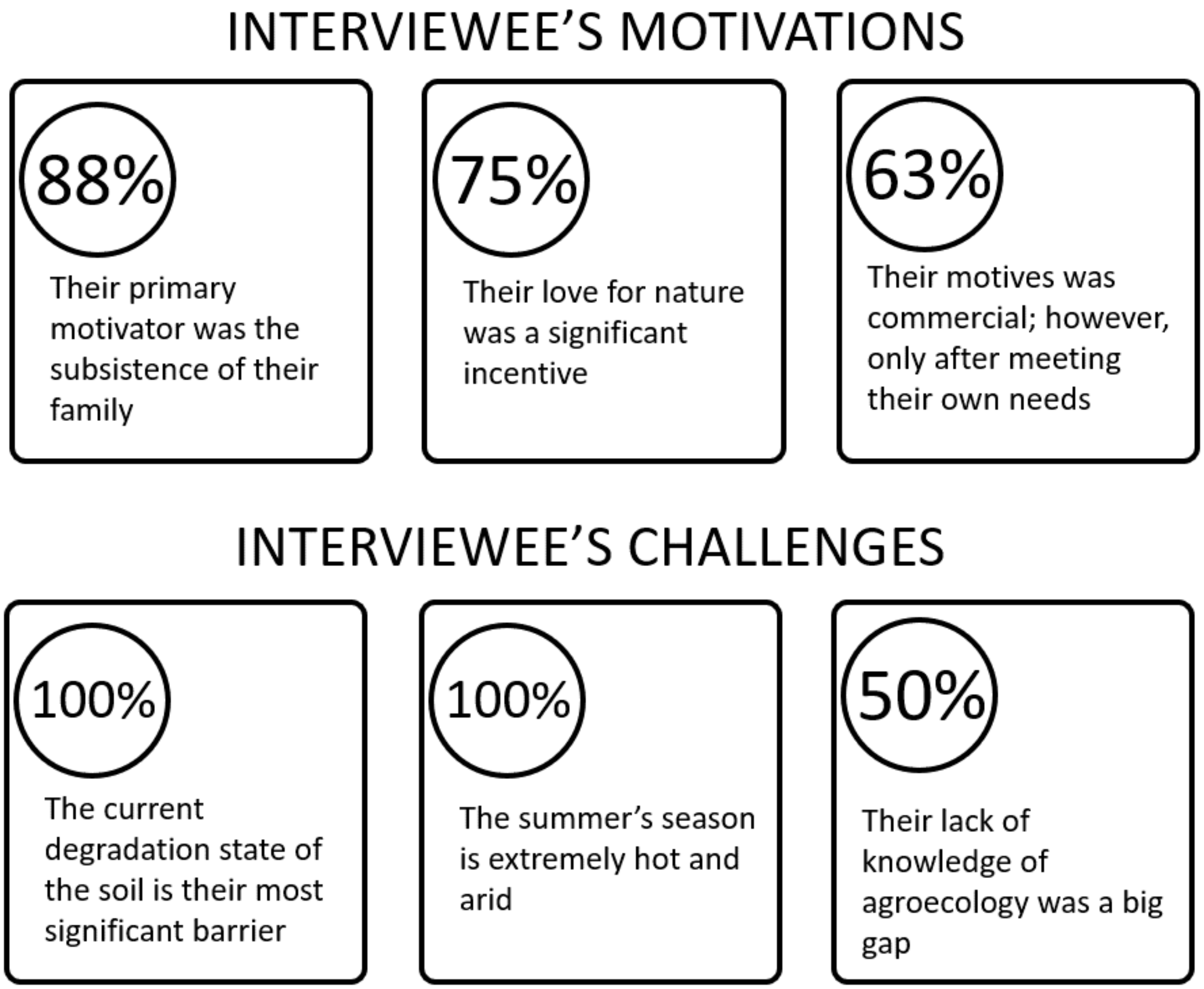


Figure 4.11. Summary of the results of the stakeholder's interview process

The most significant findings that emerged from the semi-structured interviews are presented in figure 4.11 and summarized below:

88% of the interviewees expressed that their primary motivator was their family's subsistence. At the same time, 75% mentioned that their love for nature was a significant incentive. However, another motivator was the commercial (63%), but only after satisfying their food needs. Other motivators mentioned include leaving a legacy to their family or community, education, health, and sustainable philosophy.

In terms of the most significant challenges, 100% of interviewees responded that the current degradation of the soil is their main barrier. In addition, 100% also indicated that the temperatures in the summer are incredibly high. Therefore, it is a highly arid time in which it is not efficient to plant and provide water to the crops. 50% responded that their lack of knowledge about agroecology represented a significant gap. Other barriers mentioned by the interviewees included the lack of quality seeds, time availability, adequate planning and design. In contrast, only 1 or 2 people expressed pest attack on crops as a significant challenge.

IV.5.1 Agricultural systems comparison

To respond to objective number three of this research work, we compared the CLDs of the different systems obtained during the field visits. Based on the results obtained by our participatory stakeholder process, we proposed soil quality as a sustainability indicator of the comparison of the systems. We also included subsistence (available crop for home consumption) and total crop production (highly linked to subsistence) since they are widely mentioned motivators in the participatory process).

Identification of the systems visited in the field is presented below in response to objective three of this research work. All the systems found in the field were small-scale, highly diverse systems, some with little or no external inputs (organic or inorganic fertilizers) and chemicals (pesticides). Their owners depended extensively on them to supply their food and medicine needs in all three systems. Two of the systems were linked to agricultural practices by their developers and other stakeholders as follows:

Table 4.1. Linking the systems studied with universal practices

System's identification	Practices with which systems were linked
S1	Permaculture
S2	Organic agriculture
S3	Not specified

IV.5.2 Causal loop diagram loop polarity analysis between systems

We use a polarity analysis of the cycles of each CLD To respond to objective 4 of this research work. The comparison between loop polarities of each system allowed us to evaluate the sensitivity and stability based on the relative difference between the number of reinforcing and balancing loops (Walters et al. 2016). Table 4.2 shows a quantitative description of the loop polarity for the different agricultural systems (S1, S2, and S3).

Table 4.2. Loop polarity analysis results for the three systems.

System	Indicator	# Of Reinforcing Loops (+)	# Of Balancing Loops (-)	Total Loops	Absolute Difference	Differ ence	Dominance
S1	Regenerative practices	10	23	33	13	-13	Balancing
S2	Regenerative practices	12	22	34	10	-10	Balancing
S3	Regenerative practices	8	13	21	5	-5	Balancing

The results of the causality loop analysis presented in table 4.2 indicate that the three systems are dominated by balance cycles. In other words, they are systems that tend to stabilize with a potentially limiting influence. In the three systems, the presence of reinforcement cycles is low and very similar, 33% (S1), 34% (S2), and 35% (S3).

Table 4.3 allows us to compare the S1 system vs. the S2 and S3 systems to visualize the variables that appear in S1 and do not appear in S2 and S3 and vice versa. We achieve this using the CLD comparison tool provided by the Stella Architect software.

Table 4.3. Comparing the variables that appear or not within S1 vs S2 and S3

Model Variable	Model S1	Model S2	Model S3
Beneficial pollinators	X		
Crop mortality	X		
Disease by fungi	X		
Flowering and produce	X		
Fully summer leaf drops trees	X		
Legumes	X		

Table 4.3. (continued)

Model Variable	Model S1	Model S2	Model S3
Manure drops	X		
Native perennial planting	X		
Plant residues application	X		
Nitrogen fixation	X		
Partially summer leaf drops trees	X		
Soil saturation	X		
Chemical fertilizer short term application		X	
Chemical fertilizer long term application			X
Summer north wind effect	X		
Weed presence	X		
Wind barrier	X		
Crop rotation		X	X
Erosion control		X	X
Intercropping		X	X
Organic fertilizer application		X	X
Fish tank water fertilization			X
Introduced perennial planting			X
Soil saturation	X		

The main variables that appear in S2 and S3 but not in S1 are those related to the use of Chemical Fertilizers application in the short (S2) or long (S3) term. Erosion control was a strategy mentioned explicitly in the S2 system, while crop rotation, organic fertilizer application, and intercropping were practices mentioned during the interviews of S2 and S3. In S1, no synthetic or organic fertilizer was used either at the beginning or during the establishment of the system. The only fertilizer that the S1 system uses is plant residues collected from riverside forests that border the limits of the property and biomass production of the practice of chop and drop, widely promoted by permaculture. (Albrecht and Wiek 2021; Hirschfeld and Van Acker 2019). Among the most significant differences that the S3 system presents is that it does not discriminate the use of introduced plants, especially fruit trees, since this system has mostly a commercial motivation and focuses on higher-margin markets (exotic fruits). S1 and S2 systems favor the use of native or adapted species (mango, avocado, and breadfruit, among others).

The three systems showed a high component of biodiversity that included dozens of vegetables, fruit trees, and bulbs.

Although the systems were relatively close to each other (see table 3.7), there is no evidence of close collaboration between the different stakeholders, indicating that one system influences the other. Some practices (chop and drop, mulching, natural pest control, among others) are evident in all scenarios; however, this may be because some techniques are universal and adapted in different methodologies (permaculture, bio-intensive, and organic agriculture). Neither was it evidenced in the interviews and during the process that they had a common knowledge transfer mechanism. The owners of the three systems revealed sources of influence with different origins (international, generational, and training). Interviews show that the S1 system is primarily motivated by this movement and similar schemes around Panama and the world. In comparison, the S3 system is influenced by the knowledge transfer of at least two generations from French Guiana. Finally, the S2 system was mainly influenced by the knowledge passed on by two generations of Panamanian peasants and strengthened with workshops organized by institutions such as the Japanese cooperation agency (JAICA) and the German one (GIZ).
In the S2 and S3 systems, the issue of soil saturation did not emerge as a significant problem as it did in S1. But this may indicate that the topography at the sites is different. For example, in the S1 system, the issue of soil saturation occurred in low areas of the land where possibly the water table during the rainy season is relatively high. In the case of the other two systems (S2 and S3), they were found on hills, which facilitated water drainage. S2 reported that erosion control and adequate water drainage strategies had been widely established.

IV.5.3 Causal loop diagram loop polarity analysis between key model parameters

For this analysis, we used indicators and barriers identified by the qualitative study carried out in the ATLAS TI tool. Table 4.4 shows these and a brief overview of their importance.

Table 4.4. According to the qualitative analysis, the following leading indicators motivators, or barriers were identified.

Indicator	Type	Relevance
Soil quality	Sustainability indicator/ Barrier	Mentioned as one of the main barriers by all respondents
Available crop for home consumption	Driver	Subsistence was mentioned as the main motivator by 88% of the sample
Crop production	Sustainability indicator	CLD analysis shows that crop production intervenes extensively in the different loops of the three systems
Other potential indicators	**Type**	**Relevance**
Summer ambient crop temperatures	Barrier	Mentioned as one of the main barriers by all respondents
Regenerative practices	Sustainability indicator	Sustainability was mentioned as a significant motivator by 75% of the sample

In this section, we apply the reasoning explained above about the stability of the critical parameters. In other words, the most significant positive and negative loop differences imply a high potential for instability (reinforcement) or stability (equilibrium). The system, as we have interpreted it here in the CLD (figure 4.12), would tend to a stable production "state" over time, whether that state is favorable (sustainable) or unfavorable (unsustainable). More relevant information is available by looking at the interaction of factors in the equilibrium loops surrounding the drivers. For example, figure 4.12 shows that total crop production has a considerable influence on the quality of the soil, that is, on the ecological sustainability of the system. The CLD shows us that an increase in total crop production induces a decrease in soil organic matter, which thus limits the quality of the soil. In turn, this decrease in soil quality influences the capacity of the production system (total crop production).

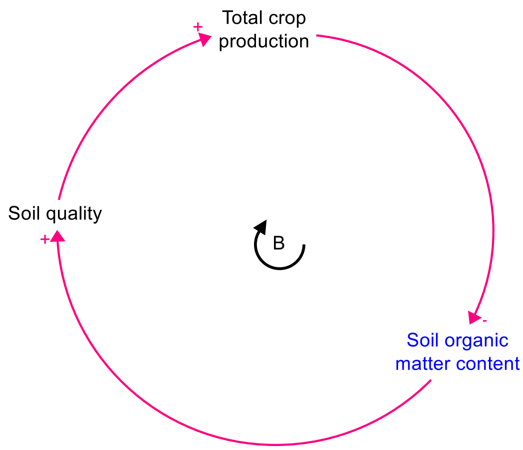


Figure 4.12. Influence of total crop production in the loop

Table 4.5. Correlation between different variables in the loop from figure 4.12

Variables correlation		-		+		+	
	Total crop production	Soil organic matter content	Soil Quality	Total crop production	Balancing		

In contrast, figure 4.13 shows us the equilibrium effect generated by including the variable regenerative practices in the loop. In this CLD, the increase in total crop production induces an increase in regenerative practices that promote an increase in soil organic matter content, which improves soil quality. In turn, this increase in soil quality influences the capacity of the system to produce (total crop production). By including the variable regenerative practices, the loop goes from a balancing loop to a reinforcing loop.

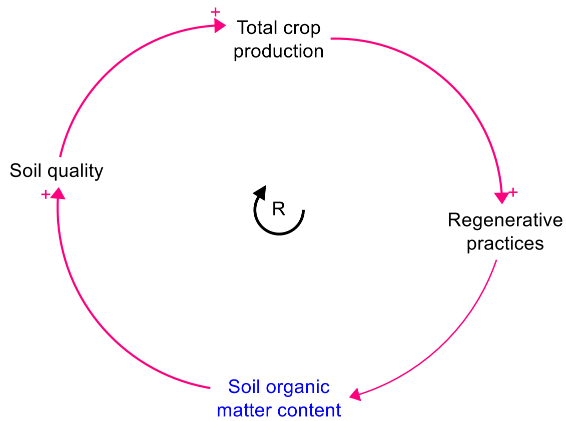


Figure 4.13. Influence of regenerative practices application in the loop

Table 4.6. Correlation between different variables in the loop from figure 4.13

Variables correlation		+		+		+		+		
	Total crop production		Regenerative practices		Soil organic matter content		Soil Quality		Total crop production	Reinforcing

According to table 4.6, all the key parameters analyzed tend towards stabilization. That is, they tend to balance any reinforcing behavior of the system. In other words, all the key parameters would act to limit exponential growth or deterioration in the behavior of the agricultural system (overproduction or environmental deterioration). The most influential drivers in all three systems are total crop production, regenerative practices, and soil quality, given its proportionally higher average loop polarity difference.

Table 4.7. Loop polarity analysis results for each driver

Indicator	System									Average difference	Key parameter involvement		
	S1			S2			S3						
	+	-	Difference	+	-	Difference	+	-	Difference		S1	S2	S3
Total	**13**	**39**	**-26**	**15**	**43**	**-28**	**11**	**31**	**-20**				
Soil Quality	6	15	-9	9	16	-7	7	16	-9	**-8**	29%	28%	38%
Available crop for home consumption	0	2	-2	0	3	-3	0	2	-2	**-2**	4%	5%	5%
Total crop production	12	34	-22	14	39	-25	10	27	-17	**-21**	65%	67%	64%
Summer ambient crop temperatures	0	5	-5	0	5	-5	0	7	-7	**-6**	10%	9%	17%
Regenerative practices	10	23	-13	12	22	-10	8	13	-5	**-9**	44%	38%	31%

Table 4.7 allows us to identify the factors that most influence the system. The column "key parameter involvement" shows us on a percentage basis the level of involvement that each parameter has in each scenario. Also, it allows us to identify three parameters with the most significant influence across the three systems: soil quality (29%, 28%, and 38%), total crop production (65%, 67%, and 64%), and regenerative practices (44%, 38 %, and 31%) respectively. While the parameters "available crop for home consumption" and "summer ambient crop temperatures," widely mentioned as a critical motivator and barrier respectively by most of those interviewed, do not have a determining influence on the ecological sustainability of the systems.

The comparison between loop polarities of the model for crucial parameters allows us to evaluate the sensitivity and stability of each one. It is accomplished by calculating the relative difference between reinforcing and balancing loops. Table 4.7 presents a quantitative description of the loop polarity for soil quality, available crop for home consumption, crop production, summer ambient crop temperatures, and regenerative practices. Evaluating the difference between the number of reinforcing and balancing loops for each key parameter allows us to reach meaningful conclusions about the influence of the parameter on the sustainability of the agricultural system. Evaluating the absolute difference between the number of reinforcing and balancing loops for each parameter reveals information about its stability. A high difference would indicate high stability (balancing) or high instability (reinforcing). Table 4.7 shows us the average differences for each indicator from the largest to the smallest as follows: Total crop production (-21), Regenerative practices (-9), Soil Quality (-8), Summer ambient crop temperatures (- 6), and Available crop for home consumption (-2).

One of the conclusions reached during this study was the impact of the use of chemical fertilizers depending on their application time. Although chemical fertilizers are not seen as a highly influential factor, I consider it relevant to share the stakeholders' perceptions concerning this parameter. In figure 4.14, we can observe the cycle involving chemical fertilizers in the S2 system. In this system, the use of this type of fertilizer positively influences the quality of the soil, which in turn positively impacts the total crop production.

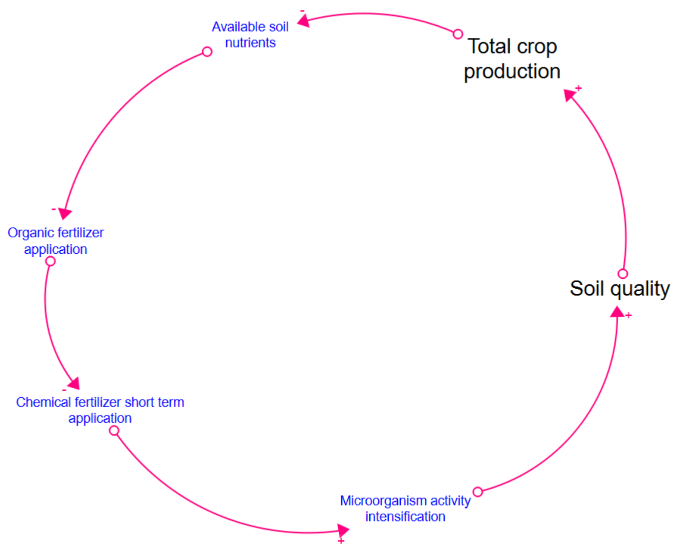


Figure 4.14. Positive influence of chemical fertilizer uses over Soil Quality

For stakeholders, the use of chemical fertilizers in the short term is positive and necessary at the beginning of the project implementation. The initial conditions of the soil (high deterioration, low organic matter, and high compaction); hence, it is necessary to boost the soil's microbial activity according to them. This application of chemical fertilizers at the beginning of the project can significantly influence the establishment of the agricultural system.

The opposite case occurs in figure 4.15, which represents a similar cycle in S3, where the use of chemical fertilizers is long-term. S3 reveals that prolonged use of chemical fertilizers causes a decrease in microbial activity because the soil only receives limited components (N, P, and K). However, other essential elements are required to maintain a healthy balanced microbial activity that impacts the development of plants' production, and they are not replenished.

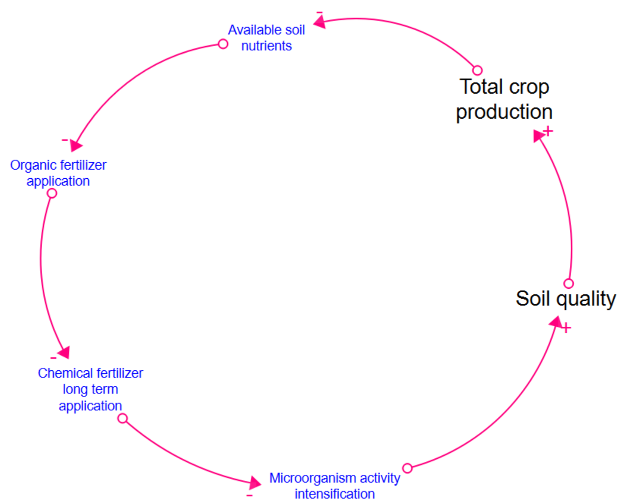


Figure 4.15. Influence of Chemical fertilizer long term application

Although it is valid for 100% of the stakeholders, extreme summer temperatures are one of the main barriers to developing these agricultural systems; the impact of soil saturation during some months (September-November) of the rainy season was also mentioned by some stakeholders, a challenge. Figure 4.16 shows the stakeholder's perception of the influence of high precipitation in the winter season, which in turn increases (+) soil saturation, causing an increase (+) in the presence of diseases due to fungi which in turn increases (+) plant mortality, thus reducing (-) total production.

Figure 4.16 also shows how regenerative practices play a balancing role. Total crop production decreases (-) due to the increase in the mortality of diseased plants due to fungi attacks. However, regenerative practices tend to generate mulch on the soil surface, which in turn absorbs moisture from it, reducing (-) soil saturation in winter, in addition to providing habitat for the development of macro and beneficial microorganisms. At the same time, it maintains humidity and habitat in the summer when plants and microorganisms need it most.

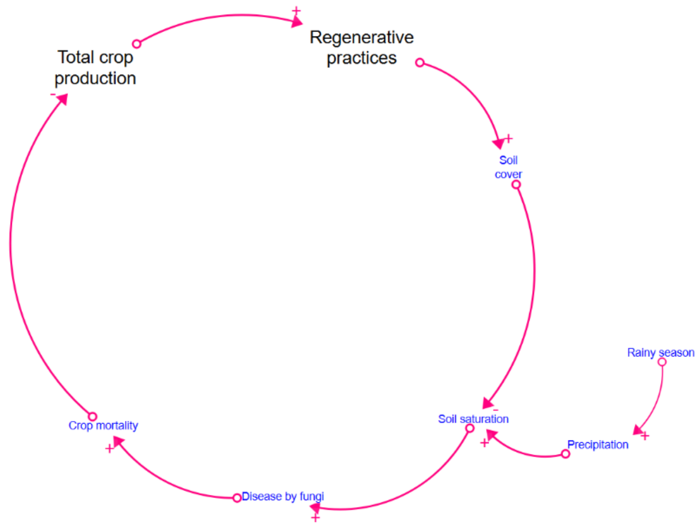


Figure 4.16. Influence of regenerative practices in crop mortality

A similar balancing effect from regenerative practices also occurs on the variable summer ambient crop temperatures (Figure 4.17). By increasing (+) regenerative practices, the planting of perennial native species increases (+), which in turn increases (+) the shade resulting in a decrease (-) in summer ambient crop temperatures. This decrease (-) in summer ambient crop temperatures influences an increase (+) in the balance of beneficial microorganisms that in turn has a positive influence (+) on total production.

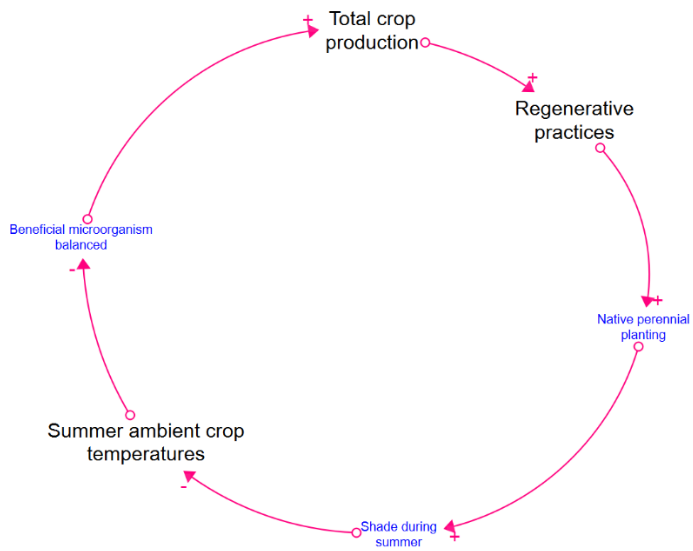


Figure 4.17. Influence of regenerative practices in summer ambient crop temperatures

IV.6 Conclusions

In this research work, we propose a participatory methodology for constructing qualitative systems dynamics models of small-scale agricultural systems in rural areas of Panama. This methodology was successful when compiling the opinion of different stakeholders, including farmers, early adopters, community leaders, government representatives, and scientific institutions. This level of integral participation succeeded in creating a shared vision of the systems in question that can influence future policy development. The methodology helped identify three small-scale agricultural systems and compare them based on their ecological sustainability. The systems under study were in regions impacted by soil degradation due to deforestation and conventional farming practices.

The results of the study are listed below:

1) The primary motivators of the Mariato community are subsistence and the development of environmentally friendly agricultural systems.

2) The biggest challenges extracted from the qualitative study are the deterioration of the soil and the extreme temperatures of the summer season.

3) The three systems investigated present unique vulnerabilities and advantages. All of them showed a high level of crop diversity.

4) The three systems show an evident leaning stability (balancing), which can have a potentially limiting influence on the system. In other words, the long-term system will tend towards stability whether that state is favorable (ecologically sustainable) or unfavorable (ecologically unsustainable).

5) The analysis indicates that the most significant variables influencing the system's sustainability are total production, regenerative practices, and soil quality, respectively.

6) Pest management did not appear as a significant barrier. This possibly occurs because the investigated systems have a degree of maturity that exceeds ten years; therefore, it can be adduced that they have been able to cope with the attack of pests by implementing different agricultural or ecological practices. Literature suggests that systems in highly diverse systems such as those studied in this work tend to be more resilient to stress shocks such as climate change and pests.

7) Although the systems were relatively located close to each other (see table 3.7), there is no evidence of close collaboration between the different stakeholders to indicate that one system influences the other. The interviews show that the S1 system is motivated mainly by the permaculture movement and similar schemes around Panama and the world. At the same time, the S3 (Unidentified) system is influenced by the transfer of knowledge of at least two generations from French Guiana. Finally, the S2 (organic) was mainly influenced by the knowledge passed on by two generations of Panamanian farmers and strengthened with workshops organized by institutions such as the Japanese (JAICA) and German (GIZ) cooperation agencies. Some practices are evident in all systems. However, this may indicate that some methods are universal and adapted in different methodologies (permaculture, bio-intensive, and organic agriculture), such as biomass application, mulching, and natural control of plagues.

8) Some stakeholders agree that given the initial poor soil conditions, the use of inorganic fertilizers at the beginning should not be seen as a degenerative practice. For most stakeholders, the use of inorganic fertilizers in the early stages of the system is necessary. Similarly, stakeholders agree that prolonged use can have legacy effects on crops.

9) In the S2 and S3 systems, the issue of soil saturation did not emerge as a significant problem as it did in S1. Nevertheless, this may be because the topography at the sites is different. For example, in the permaculture system, the issue of soil saturation occurred in low areas of the land. In the case of the other two systems, they were found on hills, which facilitated water drainage. Even in the organic system, erosion control and drainage were vital strategies that were historically established.

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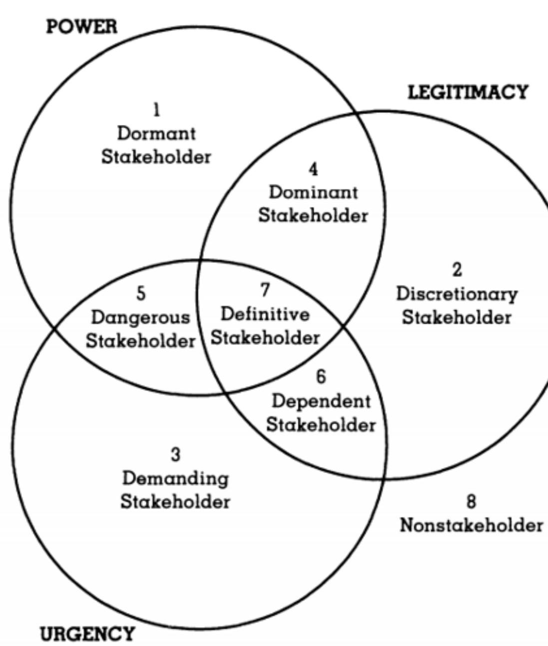
APPENDIX

Appendix 4A. Preliminary list of stakeholders with their respective roles.

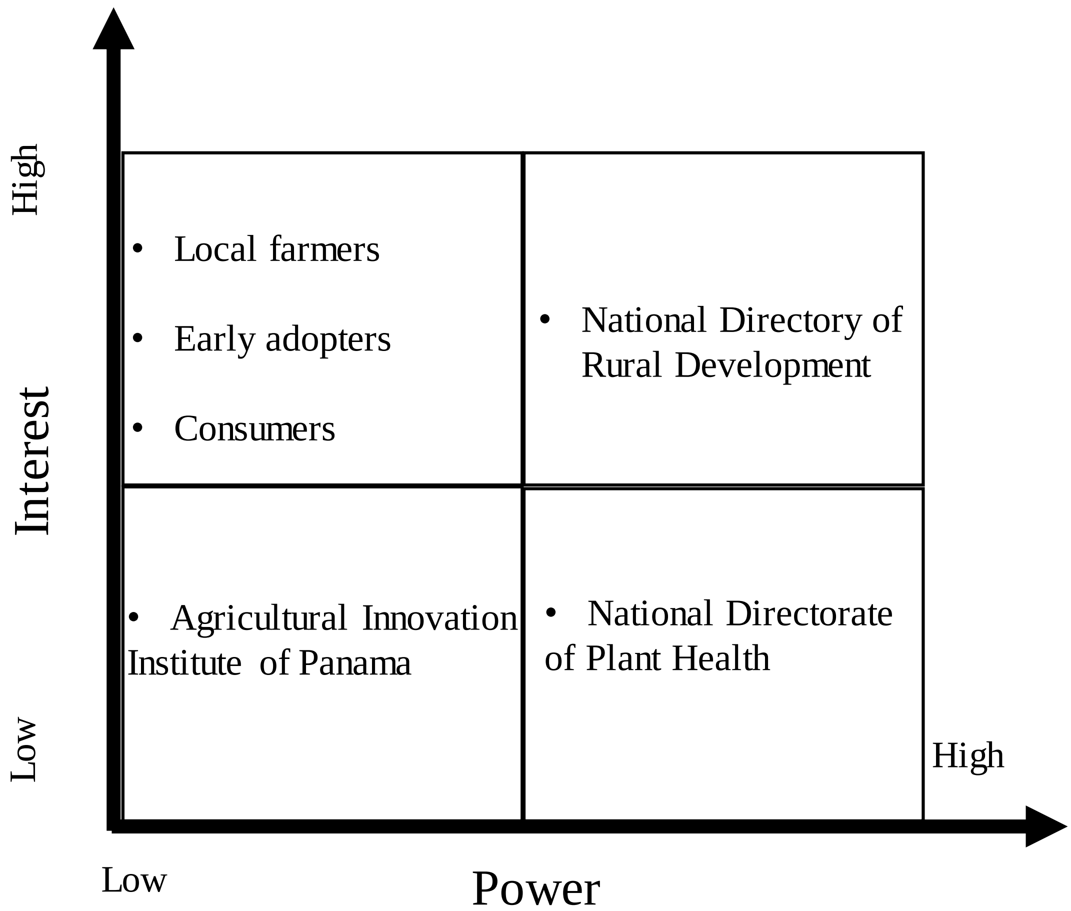
<u>EXPERTS</u> * Agricultural Innovation * Institute of Panama * National Seed Committee * Consultants * Farmers	<u>DECISION MAKERS</u> * National Directory of Rural Development * National Directorate of Plant Health * Local Government
<u>USERS</u> * Local farmers * Consumers * First Nation * Early adopters	<u>IMPLEMENTERS</u> * Community leaders * NGOs * Agricultural Research Institute of Panama (IDIAP)

Appendix 4B. Preliminary list of stakeholders by typology and attributes.

Dormant stakeholders
Discretionary stakeholders o Agricultural Research Institute of Panama (IDIAP) o Consultants (entomologist, biologist) o Non-governmental organizations o National Seed Committee
Demanding stakeholders
Dominant stakeholders o Municipality of Mariato o Agricultural industry
Dangerous stakeholders
Dependent stakeholders o Local farmers o Domestic consumers o First Nations o Community food cooperatives
Definitive stakeholders o Minister of Agricultural Development (MIDA) o Rural Development Directory



Appendix 4C. Power vs. interest grid of stakeholders



Appendix 4D. Example of support outline format used by the researcher during semi-structured interviews with stakeholders.

Items to cover	Recording minute	Discussed (checkmark)
1) Estimated of: a. Age range 25-34 years old 35-44 years old 45-54 years old 55-64 years old 65-74 years old 75 years or older b. Approximate time to live in the area c. Estimated size of your lot (if applicable) d. Geographical location of the lot e. What is your or a typical house made of? - Materials - Size f. What is the construction labour cost?		
2) Vegetables, fruits, and crops in general a. What has significant value in the market and why? b. From what of them do you believe you can make a better living and why? c. What trees and plants are the most adaptable to the dry summer and the flooding of the rainy season? d. What are the most popular crops or plans in the area? e. What are the easiest medicinal plants to find in the area? f. What of the flowers do you think to attract more beneficial pollinators and why?		
3) Traditional ecological knowledge/traditional growing practices a. How does your grandparents or ancestors use to grow crops? b. How do they take care of the soil and nature so that it can stay healthy to provide produce for many years? c. With what did your parents feed the soil before starting using commercial fertilizers? d. How did your ancestors reduce pest attacks?		
4) Would the participant be starting the design of the farm from scratch?		
5) Does the participant have prior knowledge or practice in conventional, traditional, or sustainable agriculture?		

6) Does it belong to any community or association related to sustainable agriculture?		
7) How did you know about sustainable agriculture? Was it through friends, online, through in-person courses?		
8) Does the participant have his own lot to carry out?		
9) Did the participant have the capital to invest in the design and implementation of sustainable agriculture in his lot? A range of money considered acceptable and able to invest in it?		
10) Does the participant want to implement it as their livelihood or just as a hobby?		
11) What difficulties do you foresee in implementing sustainable agriculture in your lot?		
12) Would you use native seeds and/or plants? Where would you get them?		
13) Have you received or would you apply to fund from the government?		
14) Do you know about programs or funding from the government to promote or implement sustainable agriculture?		
15) Do you believe enhancing biodiversity will foster resiliency to climate change and pest shocks?		
16) Does the participant consider that a tool that facilitates the design (selection of native species, location of permanent and semi-permanent structures, climatic considerations, and water management principles, among others) could encourage (him/her) to accelerate the implementation process?		
17) From a financial and market perspective, does the participant consider that these sustainable practices can generate enough income to support a family and even surplus?		
18) What problems and difficulties the participant foresee in the future?		
19) What is him/her relationship with the Mariato community?		

CONNECTION BETWEEN CHAPTER 4 AND 5

Chapter 4 identifies the main components of small-scale systems in the study region, implementing participatory methods and causal loop diagrams. The causal loop diagrams are integrated to generate conceptual maps of three systems studied in the field. These conceptual maps are the foundation of Chapter 5 since it proposes developing a system dynamic model (stock and flow model) using the conceptual maps in question as a reference. Chapter 5 presents an early proposal for a stock and flow model to compare the ecological sustainability of small-scale farming systems using indicators identified in Chapter 4 during the participatory process. Furthermore, Chapter 5 proposes an integration between stock and flow and process-based models to improve the handling of these tools by end users such as farmers, community leaders, and extension workers. Finally, Chapter 5 proposes a panel-structured interface depending on the user and their technical knowledge of these small-scale farming practices.

CHAPTER V: A novel methodology to promote the discussion on the integration of agricultural models based on processes with more accessible and easy-to-use tools for critical actors in the transformation of the agricultural sector towards sustainability.

Roberto Carlos Forte Taylor, Julien Jean Malard-Adam, and Osborne Grant Clark

V.1 Abstract

Small-scale agricultural production systems commonly involve a high degree of diversity, and their components are multi-dimensional. Therefore, these systems interact in complex ways that influence their sustainability over time. In this research, we have proposed a scientific methodology to promote the development of agricultural models (applicable on a small scale) based on participatory processes that respond to the needs of the local context. Furthermore, to promote the inclusion of users such as farmers, stakeholders, extension agents, and community leaders from the model's design early stages. We have also proposed an early model version that links system dynamic modeling tools such as Stella Architect and Vensim with a process-based model such as DNDC. This integration seeks to enhance the benefits of the user-friendly interfaces proposed by Stella Architect and Vensim with the precision and versatility of process-based models such as DNDC. Through this investigative work, we achieved the following results:

1) We propose a methodology that considers end users (farmers, community leaders, and stakeholders) in the early stages of model design that facilitates decision-making in developing these small-scale agricultural systems.
2) We built an early version (still incomplete) of a stock and flow model that could be integrated with a process-based model to promote discussion about this type of integration in the future.
3) We showcase how, by complementing this type of tool with indicators proposed by local communities, the sustainability of these small-scale agricultural systems can be compared.
4) We propose an example of a friendly user interface in Stella Architect, which could facilitate understanding the complexities of a small-scale agricultural system in the tropics.

Keywords: Smallholder farming; System dynamic modelling; Stock and flow modelling; Process-based modelling; Participatory modelling; Model integration

V.2 Introduction

According to Lowder et al. (2016) and Graeub et al. (2016), there are approximately 570 million farms in the world, of which 72% (410 million) occupy land areas of less than 1 hectare, and 84% (475 million) occupy less than 2 hectares of land. Family farms occupy 98% of all farms and produce at least 53% of the world's food. Multiple studies are conclusive about the imminent need to implement significant changes in the global food system. Agriculture must face three main challenges: 1) The sector must feed a growing population with a growing demand for high-calorie diets 2) the industry must minimize environmental impacts at a global level (De Ponti et al., 2012; Seufert et al., 2012; Thapa 2014) and to foster climate-resilient agriculture (Ahmed, Aslam et al. 2022).

Small-scale agricultural production systems are highly diverse and interact in complex ways that influence their sustainability. Analyzing the behavior of these complex systems in specific circumstances by collecting and interpreting empirical data alone is impractical and potentially impossible in many situations. In addition, on-farm experiments require innumerable resources (time, money, workforce, equipment, and technology) (Jones, Antle et al. 2017). They often do not provide enough information in space and time to identify appropriate and effective management practices (Bawden 1992). Hence models are presented as a tool that facilitates the scientific study of the components and interactions of an agroecosystem, integrating production, the use of natural resources, human factors, and economic factors (Jones et al. 2017). The empirical data helps us to develop and support the usefulness of the models. However, the models allow us to understand and predict the general performance of simplified versions of agroecosystems. In addition, agricultural system models help in sustainable land management, facilitating decision-making on management practices that maximize sustainability objectives through space and time, which is valuable information for land managers and policymakers (Jones et al. 2017). The models can also help detect possible risk areas that require more detailed field studies and recommend more precisely field-customized pest, crop, and land management practices, among other benefits (Jones et al. 2017).

According to Ahmed et al. 2022, the link between modeling and agricultural systems begins with several relevant events, among which we list the following: the development of models of farm systems based on components of biology and economics (1950s) 2) the development of the International Biological Program (IBP) (1964-1974) that promoted the creation of grassland models for livestock grazing (1960s - 1970s) 3) crop models development (1972) (Ahmed et al. 2022). After the early development of crop models, the United States government focused on more projects involving this type of model in combination with remote sensing to predict food crops production. These events together result in the development of crop models such as CERES-Maize and CERES-Wheat (Ahmed et al. 2022). These models are now part of the group identified as the Decision Support System for Agrotechnology Transfer (DSSAT) (Jones et al. 2016). Since then, many other models have been developed to analyze different aspects of farming systems. Nutrient dynamics are among the most complex factors of small-scale farming systems that considerably impact their sustainability. Crops require the availability of nutrients (nitrogen, phosphorus, potassium, calcium, magnesium, and sulphur) for their proper growth and development. In the absence or limitation of these nutrients, the productivity and sustainability of the systems would also be limited (Ahmed et al. 2022). On the other hand, the overuse of these nutrients can also impact the adjacent natural resources (bodies of water, aquifers, among others) in addition to an increase in the emission of greenhouse gases that intensify global warming and the harmful effects of climate change. Some of the most relevant models that have been developed to study nutrient dynamics and their link to climate change are APSIM (Agricultural Production Systems Simulator), CropSyst, CERES-EGC, DayCent, DNDC (DeNitrification DeComposition), Century, and RothC (Rothamsted Carbon Model) (Ahmed et al. 2022)

Biogeochemical cycles refer to the movement of elements such as nitrogen, oxygen, water, phosphorus, potassium, and carbon, among others, through various natural media, including the biosphere, cryosphere, hydrosphere, and atmosphere, among (Engel and Macko 2013). There is a variety of biogeochemical models that study the dynamics of nutrients, their absorption, assimilation, and mobilization in the soil (Ahmed et al. 2022). According to Ahmed and Hassan 2011, most biogeochemical models have focused on carbon dynamics and its integration with nitrogen dynamics. The most popular biogeochemical models that simulate integrated carbon and nitrogen dynamics are RothC, DAISY, DNDC, EPIC, CENTURY, and SPACSYS. These models have been used to simulate future changes in soil biogeochemistry (Ahmed et al. 2022).

According to Falloon et al. (2000), RothC is one of the first computer-based models to study soil organic matter (SOM) turnover rates (Falloon et al., 2000). Roth has been widely used to calculate variations in carbon stocks and simulate long-term changes in SOC in different land use (Setia, Smith et al. 2011), management practices (Liu et al., 2009) , soil types, and regions (Falloon et al., 1998; Xu et al., 2011) worldwide. Although decades have passed since the RothC was introduced (Jenkinson and Rayner 1977), it is still widely used. For instances, Jha et al. (2021) parameterized RothC version 26.3 to study SOC changes and storage under climatic conditions, soil types, and management practices particular to India. Wang et al. (2022) applied RothC version 26.3 to spatiotemporally study the sequestration potential of SOC on agricultural land in China and the influence of Climate Change on it from 2021 to 2040. Wang et al. (2022) were able to quantify the impacts of climate change on agricultural land and concluded that they would reduce the potential for SOC sequestration unless practices such as Climate Smart Agriculture were adopted, increasing Carbon inputs and, as a result, offset the negative impacts of climate change (Wang et al., 2022). The tool has a website that includes detailed information for the operation and parameterization of the model. RothC is a versatile tool that can assess C storage potential under different agricultural management practices (Chenu, Angers et al. 2019).

CENTURY Model was developed by Schimel et al. (1996). Initially, the model was used to evaluate the influence of the water and nitrogen content variables on net productivity constraints (NPP) spatially and in response to climatic variability. In their study, Schimel et al. (1996) concluded that annual data sets on NPP, water, and nitrogen use efficiencies from different ecosystems could be a valuable tool to test environmental models (Schimel, Braswell et al. 1996). Bandaranayake et al. (2003) applied the Century model to evaluate its capacity and effectiveness in simulating long-term changes in SOC in highly managed turfgrass ecosystems and a golf course fairway near Denver and Fort Collins. Their study indicated that the CENTURY model could simulate this type of system and also established that warm temperatures significantly influenced SOC changes in the turf system compared to native grasslands (Bandaranayake et al., 2003). Very recently, Zhang et al. (2021) successfully calibrated the CENTURY to simulate C dynamics over a long period (1968-2018) with significant accuracy in the Gansu region of China. Zhang et al. (2021) calibrated CENTURY using soil and grassland maps of the province, along with climatic, and historical data on management practices (Zhang et al., 2021).

DNDC (denitrification and decomposition) is a biophysical model developed by Li et al. (1992) (Findley 2009). Initially, the model was aimed at simulating changes in nitrous oxide (N_2O), carbon dioxide (CO_2), and dinitrogen (N_2) in agricultural soils and the influence of rainfall events on them (Li et al., 1992). In its early development, the model consisted of three sub-models (thermohydraulic, decomposition, and denitrification). Based on the input of climatic data, the model simulated trends in temperature, soil moisture, and changes in its conditions (aerobic-anaerobic). In their conclusions (based on the application of the DNDC model), Li et al. (1992) established that rainfall patterns significantly influenced the N_2O emissions generated in soils. However, according to Li et al. (1992), the presence of soluble carbon and nitrate could offset this N_2O generation. Similarly, they concluded that variations in temperature and precipitation, together with the content of organic carbon, clay, and pH levels, were highly influential factors in denitrification rates and N_2O emissions (Li et al., 1992). DNDC continued to evolve; by 2000, other sub models such as nitrification, crop growth (empirical), and fermentation had been added (Gilhespy, Anthony et al. 2014). Other modifications that have been made to the model included a forest (Li et al., 2004) and a wetland (Zhang & Li, 2002) version, soil evaporation estimates (Smith, Grant et al. 2010) and CH4 fluxes in permafrost conditions (Zhang et al., 2012) among several others. Recently DNDC has been used, for example, by Zhang et al. (2017) to investigate its applicability in agricultural systems under discontinuous fertilization over time in a rotational crop of wheat (winter) and corn (summer). Zhang et al. (2017) analyzed the changes in the SOC when implementing this type of fertilization and the reintroduction of residual biomass (straw) to optimize the ratio of straw incorporation to fertilization rate. The study concluded that the rates of increase in SOC content due to the rise in fertilization rates were lower than the increases due to the amount of straw incorporated (Zhang et al., 2017). With these results, Zhang et al. (2017) suggested that the DNDC model can effectively predict the SOC dynamics under discontinuous fertilization conditions in the soils of Hengshui, China.

Regarding models mainly focused on simulating the growth of crop systems, the first attempts were carried out in the 70s when De Wit et al. (1970) developed a model that sought to simulate the growth of a corn crop taking into consideration factors such as photosynthesis rate, light distribution, leaf area, and temperature (De Wit et al., 1969). Meanwhile, Arkin et al. (1976)

developed a practical approach to calculating the daily growth and development of an average sorghum plant in a field. In the Arkin et al. (1976) tool, the appearance and growth rates of leaves were developed in the model, while other processes, such as photosynthesis, respiration, and water intake, were modeled independently in sub models (Arkin et al., 1976). Currently, one of the most used tools for simulating the productivity of crop systems is CropSyst. For crop productivity modeling, CropSyst considers different factors such as climate, soil types, and management practices (Stöckle et al., 2003). Outa et al. (2021) studied the effect of different deficit irrigation treatments in Egypt to reach conclusions that would help reduce costs, time, and money in Wheat cultivation systems. The CropSyst model accurately simulated wheat grain and total dry matter under different deficit irritation treatments. Outa et al. (2021) concluded that the Cropsyst models could help to develop effective deficit irrigation strategies for wheat production under dry environments.

According to Argent (2004), process-based models are rarely designed to interact with other models from other disciplines. This is especially notable in models developed in natural resource management (hydrology, ecology, and agriculture-related) (Argent 2004). In the past, models related to the agricultural sector have been used interactively with economic models through manual links or interfaces; however, the cases are minimal (Stöckle, Kemanian et al. 2014).

Recently one of the most legitimate attempts to promote the integration of this type of model is promoted by The International Soil Modeling Consortium (https://soil-modeling.org/). The organization was established in 2016 as part of community efforts to quantify soil functions and better understand soil changes concerning land use, climate change, and soil degradation (Baatz (Baatz, Tarquis et al. 2019). The objectives of this organization are listed below:

- Congregate experts in modeling soil dynamics
- Identify and address the main gaps in the understanding of critical processes and impacts related to the different functions of the soil and its ecosystem services
- Motivate the integration of models that study different aspects (climate, hydrology, nutrient cycle, among others) of agricultural systems
- Promote soil characterization studies at a local and global level and compare them

- Encourage the consolidation of data from the different platforms at a global level that integrates social and environmental aspects in the functioning of the soil, thus improving the modeling of agricultural systems

According to their objective, the organization is mainly focused on technical issues and do not prioritize the development of these complex integrations to facilitate their management, understanding, and dissemination to end users such as extension workers, small farmers, and other stakeholders.

On the one hand, there is a constant demand for higher levels of integration of models that help address complex environmental problems and develop policies in harmony with the local context. On the other hand, there is a need for these integrations to be developed with users such as extensionists, farmers, and stakeholders in mind, who have different educational levels and backgrounds. This way, friendly interfaces can be developed for users who lack technical expertise but handle much empirical information.

An attempt to develop more accessible tools for these stakeholders is the AquaCrop model developed by the Land and Water Division FAO. Although AquaCrop lacks deep integration with multiple models from different aspects of agricultural systems, it is a friendly tool mainly aimed at professional end users (extensionists, consultants, and NGOs, among others) (Food and Agriculture Organization 2022). The model seeks to balance simplicity, precision, and robustness. AquaCrop is capable of simulating crop growth with the idea of evaluating the environmental impact of these systems while promoting food sovereignty (Food and Agriculture Organization 2022). The model operates with a few parameters that can be determined by simple methods, which simplifies its handling (Food and Agriculture Organization 2022).

The Participatory System dynamic modeling field is quite promising in developing customized tools that put commonly underrepresented users (small farmers, community leaders, and extension workers) in the conception of process-based models. System dynamics offer a variety of benefits, among which are 1) the integrated combination of materials, structures, information, and experiences (Zomorodian 2018) 2) the link between social and natural sciences (Saysel, Barlas et al. 2002) 3) The facilitation of representing non-linear, complex, multiple feedback and unstable problems (Zomorodian 2018) 4) the study of the law of motion of complex systems (Zomorodian 2018) 5) prediction of the consequences of disturbances to the system (Zomorodian 2018) and 6) facilitated sustainable planning of natural resources (Zomorodian 2018).

Finally, PSD provides a much broader vision of the socio-environmental problems experienced by a community. Many methodologies are limited in scope or potential to compare ecological sustainability of agricultural systems, other approaches also present difficulties for using the results obtained in the development of policy proposals or to describe the dynamics of a complex system. Many of these different approaches are based on rigid surveys, which do not contemplate the dynamic aspects of a system. Neither allows the community to jointly discern its socio-environmental problems nor formulate solutions congruent with their problem and local context.

Very few attempts have been made to implement PSD to analyse the sustainability of smallholder agroecological systems. For instance, Marandure et al. 2020 developed an integrated system dynamics simulation model with which they sought to evaluate the sustainability of smallholder low-input ruminant farming systems. For this, they established a series of ecological indicators (soil organic matter content), economic (productivity), and social (capacity building) (Marandure et al., 2020). The model analyzed the different feedbacks and interactions between the proposed indicators for ten years. Meanwhile, Ha et al. 2020 implemented PSD to devise strategic actions toward resilient climate livelihoods and ensure income for smallholder farmers in Vietnam. Through the implementation of PSD, Ha et al. 2020 revealed government policies' shortcomings related to climate change adaptation that negatively impacted smallholder farmers by disregarding their community initiatives, learning needs, and ownership (Ha et al., 2020) .

Tey et al. 2019 examined the potential outcomes of involving smallholders beyond the primary rice production stage through a dynamic system approach. Tey et al. 2019 proposed PSD to model and understand the interaction of elements within a rice value chain and, ultimately, to identify effective policy designs for moving away from business as usual. Their study revealed greater profitability in the sale of conventional rice vs. certified rice, in addition to highlighting potential barriers and delays in the adoption of these standards (Tey, Ibragimov et al. 2019).

The PSD methodology allows us to identify and visualize a problem from an integral perspective, grouping together many actors, opinions, experiences, and knowledge. PSD challenges the paradigms in the design and planning of agricultural systems by considering a more significant number of feedbacks, aspects, and impacts that, if not identified, could result in ecologically or economically unsustainable systems. Various tools allow us to visualize and model the complexities of the interactions of the components of an agricultural system. Among these tools are VENSIM, POWER SIM, and STELLA Architect.

The objective of this paper was to use the conceptual models developed in Chapter 4 in the community of Mariato as a basis to propose an early attempt at an interface that fosters the argument of how to link end users such as farmers, community leaders and extensionists in future model integrations of different aspects of farming systems. This is an incomplete version of an integration between a system dynamic model (stock and flow model) with a process-based model hence it does not represent a real small-scale agricultural system in the region, nor is intended to be predictive or can be validated. On the contrary, it proposes a methodology for developing models that help farmers and stakeholders in the small-scale agricultural sector understand the complexity of the systems they seek to develop or have developed, compare their sustainability, and close the gap between these users and the technicality of traditional agricultural system's process-based models. This research work also proposes a very early version of what the structure of this model could be, what tools would make it easier for its users to handle, and what other tools it could be integrated with that would provide the required rigor and precision.

V.2.1 The questions that guided these research efforts are listed below:

1. How the barriers and motivators identified in Chapter 4 can influence and shape the design and development of an applicable small-scale farming systems model for the Mariato community.
2. How do drivers systemically and dynamically interact to influence ecological sustainability?

3. How can we bridge the gap between the technicality of agricultural models and the need to facilitate their manipulation by small farmers?

Agricultural production systems must undergo rapid changes in response to the challenges and the growing concern about food safety, security, and environmental impact (Walters, Archer et al. 2016). Several definitions of sustainability have been suggested; however, the definition proposed in this research work concerns the ecological sustainability of small-scale farming systems and refers to “those systems that are not highly mechanized and therefore operate with <u>little or no use of fossil fuels</u> or external inputs (synthetic fertilizers, herbicides, and pesticides), and can remain <u>productive over time</u> compared to the baseline (conventional monoculture) while <u>maintaining soil quality</u>” (Chapter 4).

Different efforts have been made to evaluate the sustainability of agricultural or livestock systems in the tropics (Mandarino, Barbosa et al. 2019; Munyaneza et al., 2019). These approaches propose a series of indicators that help determine its sustainability, evaluate it and monitor its progress (Mandarino et al. 2019; Munyaneza et al. 2019). The indicators used in this research work are selected from the quantitative study carried out in rural Panama (Chapter 4).

V.3 System Dynamic Models: Applications and Limitations

System dynamic models (SDM) allow us to understand the components, processes, interactions, and relationships within a system; however, SDM cannot be used as predictive models. A predictive model is one developed in the quest to generate an accurate prediction, and what is sought is to predict future events based on information and experience that is currently available. Predictive modeling is commonly associated with machine learning, pattern recognition, and data mining (Kuhn and Johnson 2013). On the contrary, with SDM, we can obtain a sense of directionality (for example, as organic matter decreases, soil quality decreases, and therefore production is limited) and magnitude (for example, a reduction in precipitation has “n” times more significant impact on non-native or adapted plants) (Sorensen 2016). Besides SDM developed through participatory methods, ensure that we build a model influenced by the social circumstances of a community and its stakeholders. In addition, SDM allows the community to express their own needs and definitions, as in our case, the definition of sustainability. Finally, SDM models allow us to model systems with a certain degree of uncertainty, leaving it up to the designer to minimize these uncertainties through methodologies that build confidence in the model and sensitivity analysis that identify the variables with the greatest and least impact on the model's simulation results.

There is a wide variety of tools on the market for system dynamic modeling, including Vensim DSS, MapleSim, and Powersim, among many others. To answer the questions of this research and achieve its goal, we implemented the SDM software STELLA Architect version 2.1.5 from ISEE Systems. STELLA architect gives you a practical way to dynamically visualize and communicate how complex systems work. It facilitates the visualization of complex systems through universal modeling iconography. The software does not require extensive language programming knowledge since it is carried out by the tool in the background. It is a reasonably intuitive, affordable tool and even provides an interface that makes it easy for stakeholders to use and understand complex system models.

In this research work, we are using an incomplete version of a small-scale agricultural system model. Hence, the model does not represent an actual small scale agricultural productive system in Mariato, Panama. However, this rudimentary version of a process-based model serves three purposes:

1) It is the result of a methodology that encourages the involvement of end users (farmers and stakeholders) as well as the local context (crops, climate, and barriers, among others) in the early steps of designing small-scale farming systems models.

   It contains and allows us to visualize critical elements collected from field interviews carried out by Roberto Forte (2020) and described in Chapter IV simply in the Stella Architect tool.

2) Serve as an operational foundation for the friendly interface proposed in this research.

V.4 Political Boundary

The model was developed for the community of smallholder farmers in Mariato. The district of Mariato is located on the Azuero Peninsula and is bordered to the west by the Pacific Ocean. The economy of the Mariato district is mainly based on cattle ranching, monoculture agriculture, shrimp farming, and, recently, tourism. The Azuero Peninsula belongs to an area known as the Dry Arch of Panama. According to data from the Electric Transmission Company S.A. (ETESA), temperatures in the region can reach up to 38 °C during the hottest months (April, May, and June). In the District of Mariato, the average annual temperature is 23.8 °C; however, maximum and minimum temperatures of 34 °C and 14 °C, respectively, have been recorded (44 years of data collection). In general, the dry season lasts about four months (December to April) and the rainy season lasts about eight months (April to December). During the dry season, the region experiences low precipitation and low humidity, as well as high levels of solar radiation. The months of September to November are characterized by heavy rainfall.

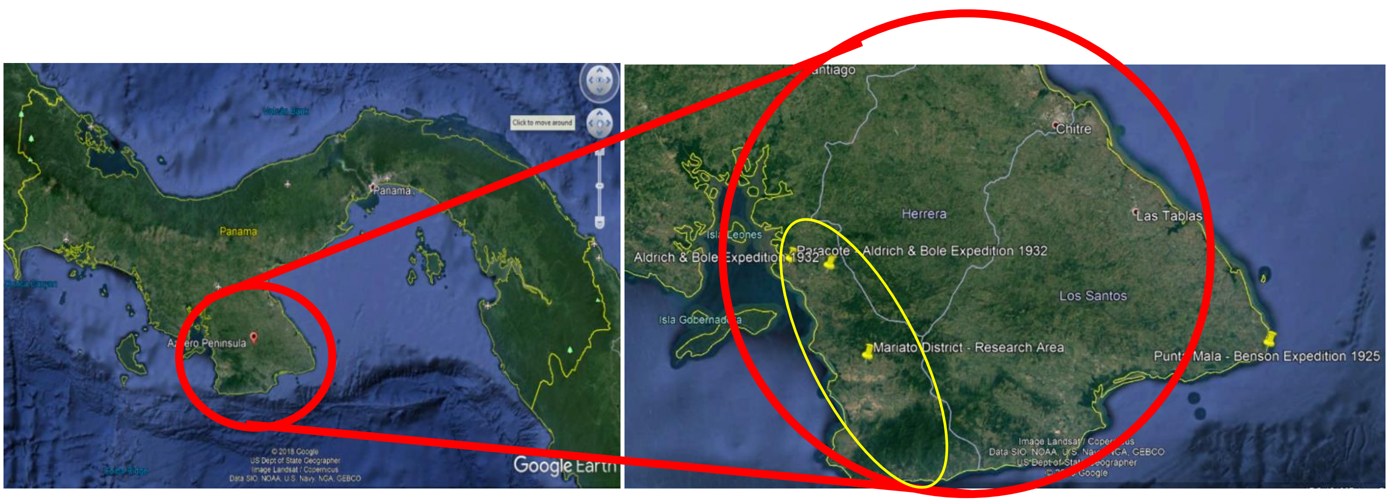
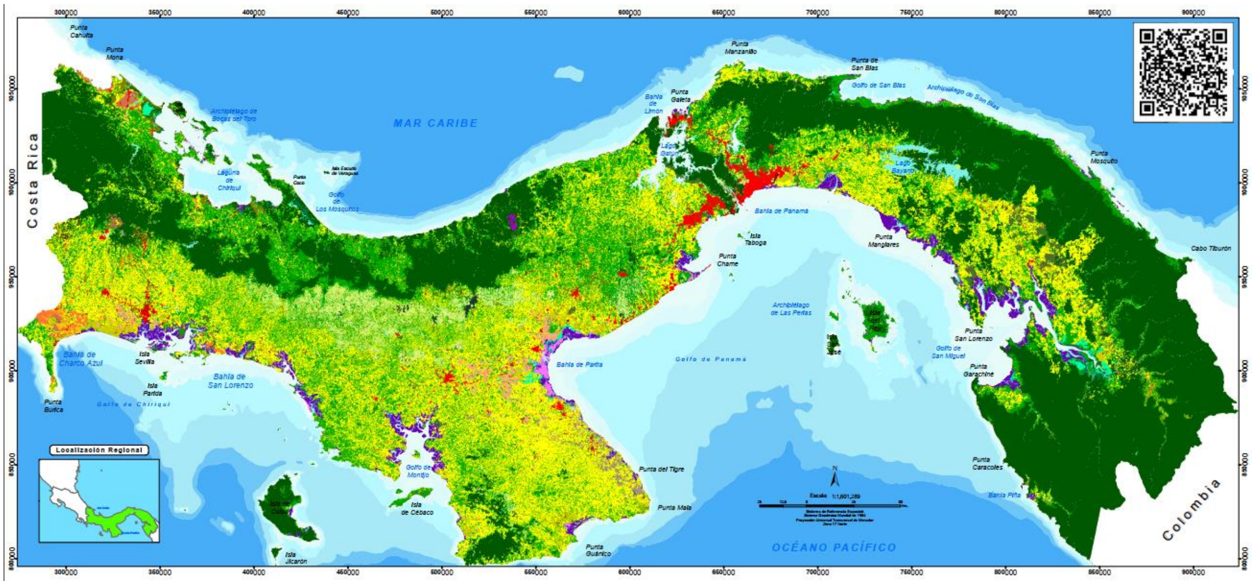


Figure 5.1: Study area in Mariato district, Panama.

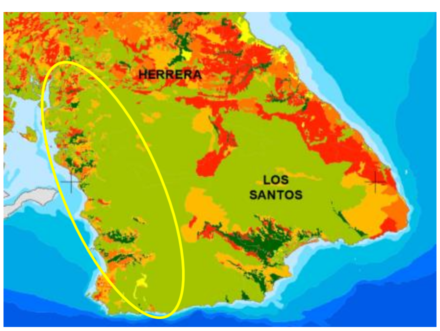
The 2021 Forest cover and land use map states that the Mariato district is dominated mainly by Herbaceous vegetation, shrubbery, and improved pasture (Ministerio de Ambiente, 2022).



	Category	Area (km²)	%		Category	Area (km²)	%		Category	Area (km²)	%
Forest and other wooded land	Mixed broadleaf forest mature	27,491.37	36.50	No Forest	Rocky outcrop and bare soil	49.39	0.07	No Forest	Pineapple	25.99	0.03
	Secondary mixed broadleaf forest	15,970.59	21.20		Beach and natural sand	44.83	0.06		Other annual crop	292.42	0.39
	Mangrove forest	1,837.82	2.44		Coffee	97.49	0.13		Agricultural and livestock production	121.75	0.16
	Ore forest	64.60	0.09		Citrus	30.97	0.04		Pasture	16,288.73	21.62
	Cati forest	33.60	0.04		Oil palm	217.99	0.29		Populated area	1,068.06	1.42
	Raff forest	153.21	0.20		Plantain/banana	127.25	0.17		Infrastructure	321.41	0.43
	Conifer planted forest	88.95	0.12		Other permanent crop	66.69	0.09		Mining	41.02	0.05
	Broadleaf planted forest	665.53	0.88		Rice	805.82	1.07		Aquaculture pond	132.50	0.18
	Stubble and shrubby vegetation	4,867.98	6.46		Sugar cane	350.11	0.46		Salt production	13.72	0.02
	Herbaceous vegetation	1,805.78	2.40		Mixed horticulture	30.70	0.04		Albinas	5.71	0.01
	Low flooded vegetation	273.15	0.36		Corn	267.79	0.36	Water surface	Water surface	1,672.93	2.22

Figure 5.2: Forest cover and land use map of Panama.

Regarding the capacity of the soil for agricultural production, the Rural Land and Water Registry map of Panama (CARTAP, 1965 - 1968) establishes that non-arable soils predominate in the Azuero Peninsula with severe limitations for agriculture, suitable for pastures, forests, and nature reserves. They are highly clayey, acidic, and low in potassium/calcium and organic matter.



Plowable, some limitations in plant selection, requires moderate conservation.
Plowable, severe limitations, in plant selection, require special conservation of both.
Plowable, very severe limitations in plant selection or require careful management.
Not plowable, low risk of erosion, but with other limitations, with qualities for pasture and woodland.
Not plowable, with severe limitations, with qualities for pasture, forest and reserve land.
Not plowable, with very severe limitations, with qualities for pasture, forest and reserve lands.
Not plowable, with limitations that exclude its use for commercial plants production, it can be used for recreation, reserve, water supply and aesthetic appreciation.

Figure 5.3: Land use capacity in Panama.

Methodology

We begin by analyzing the different conceptual maps developed through a participatory process in Chapter 4. Through this analysis, we drag the main indicators (soil quality and productivity) identified in Chapter 4 and identify management practices and principal components of these systems from the study. In the same way, we consider the barriers (degraded soil and climatic influence) reported as crucial elements in the development of the stock-flow model. Understanding the uncertain nature of our model, we perform sensitivity analyses to comprehend how responsive the output is to changes in certain variables. Later we define a series of scenarios, run the model and analyse its results. Finally, we compare the results of the simulations and reach conclusions in line with the objectives and questions of this research work. Our methodology and model seek to motivate the generation of more informative models with a local context focus, facilitating the understanding and decision-making of stakeholders in the smallholder farmer sector.

V.6 Data Sources and Collection

In Chapter 4 a widely tested framework, developed and applied by Elias et al. (2002) was implemented. This framework consists of four significant steps:

1. A listing of stakeholders
2. Their categorization based on their roles
3. Their prioritization according to their attributes
4. Their selection is based on their power and interest

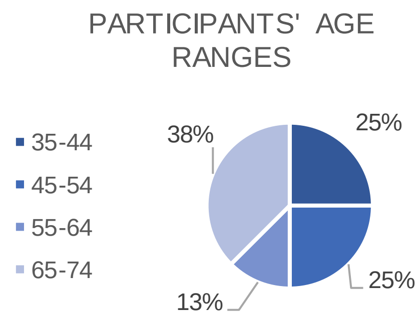
Once the group of stakeholders was identified and invited to participate in the study, they ran a participatory stakeholder process, which served two primary purposes:

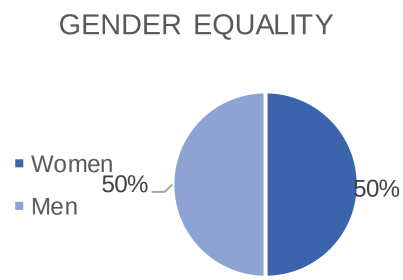
- Gathered opinions about what the community in Mariato thought was a suitable agricultural system for them.
- Guided the research work in terms of potential criteria for the comparison of small-scale agricultural systems

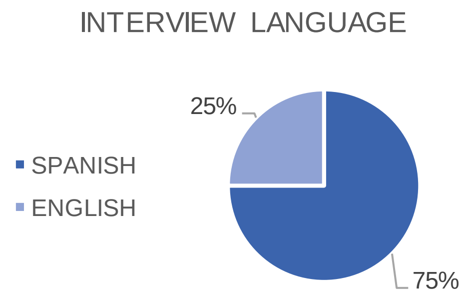
Through the implementation of face-to-face semi-structured interviews, one hour on average, they collected valuable and representative information on the study's objectives. Interviews were tape-recorded and transcribed verbatim. Afterward, the content of the interview transcripts was rigorously analyzed with the implementation of a Computer Aided/Assisted Qualitative Data Analysis Software (CAQDAS). In this case, it was the ATLAS.TI version 8 software. The software interface allowed to identify quotations, which were nothing more than sentences containing critical data for the study. Those quotations were classified in codes. Some codes included barriers or challenges, interviewee motives, strategies, and beliefs.

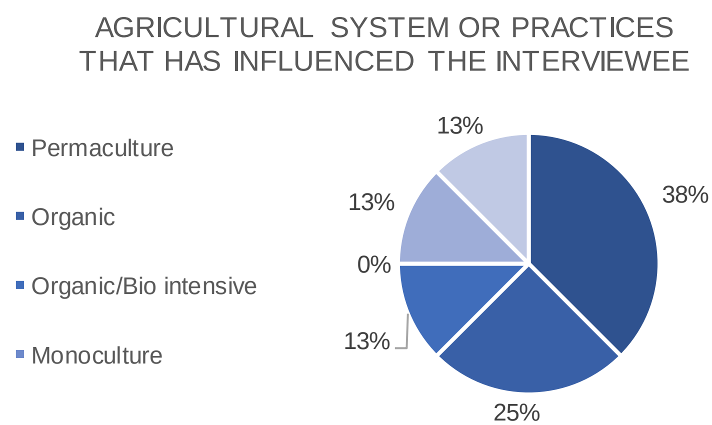
Each sentence of each interview was analyzed. The software provides an interface that allows the researcher to interact with the transcriptions and quickly identify Quotations, which are nothing more than sentences containing critical data for the study. In turn, segments of the quotations are visually classified in Codes. Interviewee barriers, motives, strategies, and beliefs were some codes created.

This methodology enabled us to quantify the data and achieve the following results. A total of 11 semi-structured interviews were carried out, and eight of the eleven interviews were conducted with farmers or early adopters from the Mariato Community.


PARTICIPANTS' AGE RANGES
35-44
45-54
55-64
65-74
38%
25%
25%
13%


GENDER EQUALITY
Women
Men
50%
50%


INTERVIEW LANGUAGE
SPANISH
ENGLISH
25%
75%


AGRICULTURAL SYSTEM OR PRACTICES THAT HAS INFLUENCED THE INTERVIEWEE
Permaculture
Organic
Organic/Bio intensive
Monoculture
13%
38%
13%
0%
13%
25%

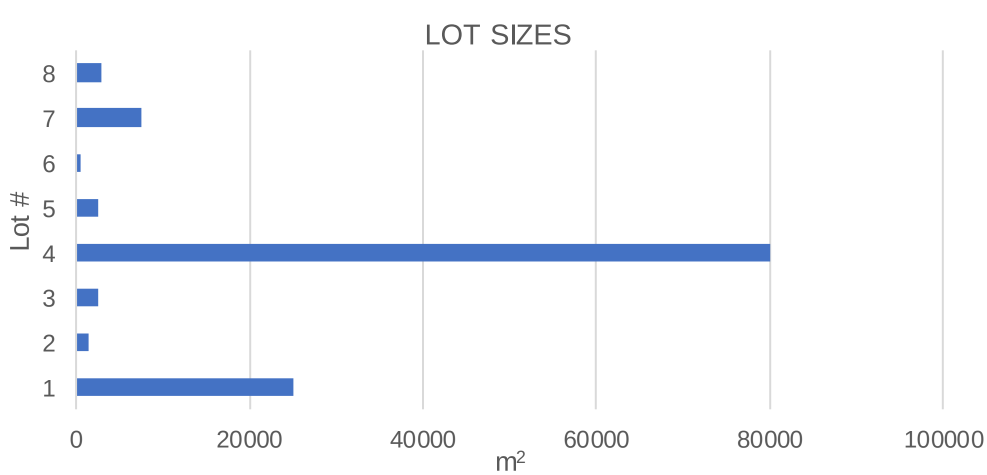

LOT SIZES
Lot #
8
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Figure 5.4. Demographic and related data on farming systems

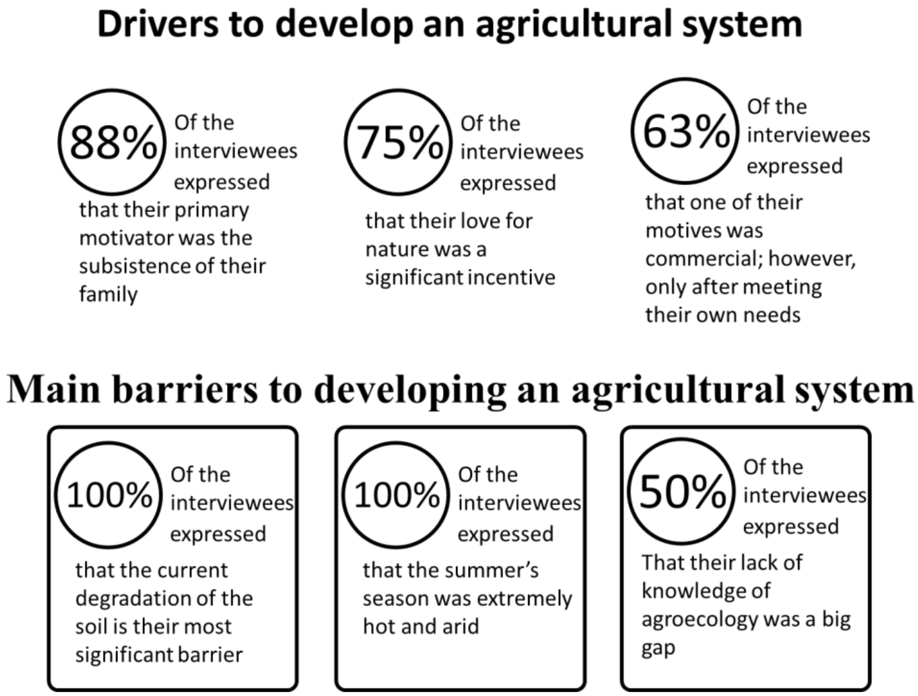

Figure 5.5. Barriers and drivers extracted from the qualitative analysis

V.7 Model Scope and Boundaries

According to Sterman (2000), a modeling process begins by identifying the system which will be modeled. Once the system is identified, the next step is to develop a clear statement of the problem and define the model's boundaries (Sterman 2000). The model's scope has to be as comprehensive as the question or concern to be solved. Endogenous and exogenous variables need to be identified to define the boundaries of the model. Endogenous variables are within the model's scope and can change during the simulations. It means any variable part of a feedback loop or affected by a variable within a feedback loop (Ford 2010). Meanwhile, exogenous variables are outside the model boundaries and do not change with the simulation. Exogenous variables are usually called the inputs to a model(Ford 2010). Our model's scope is depicted in figure 5.6. Endogenous variables are located in the inner ring a, and the exogenous variables in the outer ring. Not all variables are included in the Bull's eye diagram, and its purpose is simply to communicate the scope and focus of our model. Excluded variables, as their name indicates, are those that would not be included in the modeling because they are not essential to answer the objectives and questions that promoted the development of the model in the first instance.

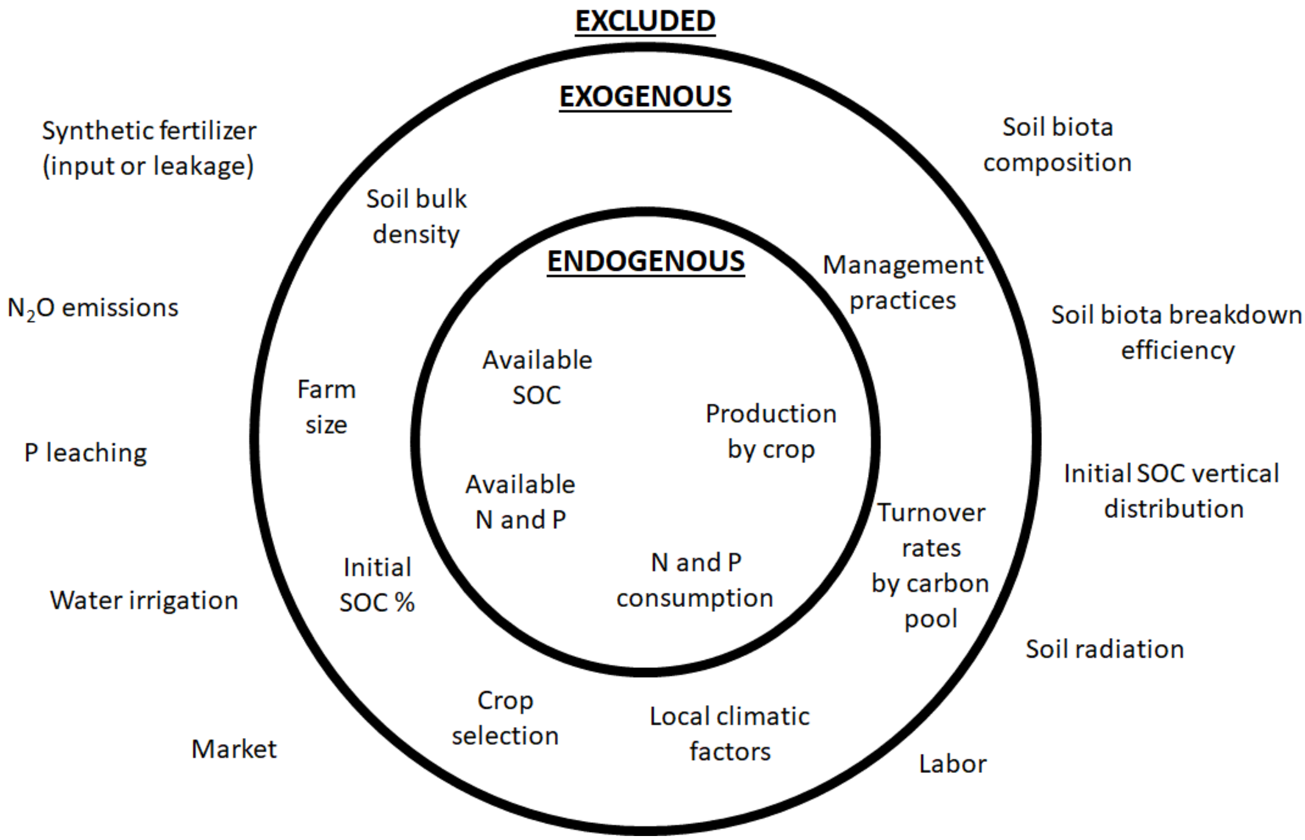

Figure 5.6. A bull's-eye diagram illustrating how the model works.

V.8 Model Structure and Description

This model has been developed to serve principally two audiences 1) small farmers with intermediate experience and 2) people interested in starting a small-scale farming system. Knowing in advance that some of these early adopters of small-scale agricultural systems lack the necessary knowledge (agriculture, ecology, and planning) to start this activity, we implemented STELLA Architect software which provides an interface that allows easy visualization of the components (flows, stocks, and feedbacks) of a system. This object-oriented graphic simulation modeling environment was developed by isee (https://www.iseesystems.com/). Our initial premise four using STELLA Architect was that if the components of a small-scale agricultural system could be captured, it would be more intuitive to understand its complexity. There are other advantages in developing our model in Stella architect, which are listed as follows:

1) It has been proposed by experts in SDM as software with top online technical support and detailed and well-illustrated explanations (Ford 2014).

2) The models developed in Stella can easily be converted into Vensim by following a series of straightforward steps (Vensim Ventana Systems Inc., 2015)

3) Stella has a 30-day free trial (ISEE Systems Inc., 2023) that would allow stakeholders to run the model from their home community. In addition, other software such as Vensim (Vensim Ventana Systems Inc. 2015)and Powersim (Powersim Inc., 2023) also have free trials.

The only software-specific limitation we could detect is that the cost of licensing this software is considerably high. In that case, the stakeholder should look for similar emerging versions of SDM software free of charge.

Among the model specifications, we have a time step or "delta time" of one month, which means the amount of time between calculations in the model simulations. The total simulation length is 50 years. The model also consists of a friendlier interface where users can enter data on the initial conditions of the land at their discretion. Below we outline and briefly explain the different sections of which the model is composed and their respective objectives.

The model encompasses four sections identified in figure 5.7:

Section 1 – Allows users to select the initial parameters required to start the modeling process, including farm size, bulk density, and initial SOC %. This segment also introduces residual biomass that is generated during harvests.

Section 2 – Simulates the soil's organic matter turnover process. The simulation is based on the three carbon pools proposed by the scientific literature. Where one pool corresponds to the organic matter that can be decomposed in days to months, known as Labile, the second corresponds to the organic matter that decomposes in months to decades, known as intermedium or slow pool, and the third is where carbon is more stable with turnover rates ranging from decades to thousands of years and is known as recalcitrant.

Section 3 – Emulates potential production depending on soil nutrients requirements. A crop production per hectare is estimate based on available nitrogen and phosphorus and crop nutrients requirements. N and P availability is estimated based on the stock of SOC at the time of the computation.

Section 4 –Takes the potentially producible stock of crops based on the availability of nutrients and a yield influenced by climatic factors (temperature, relative humidity, and precipitation) and calculates the production per hectare in the different crop cycles.

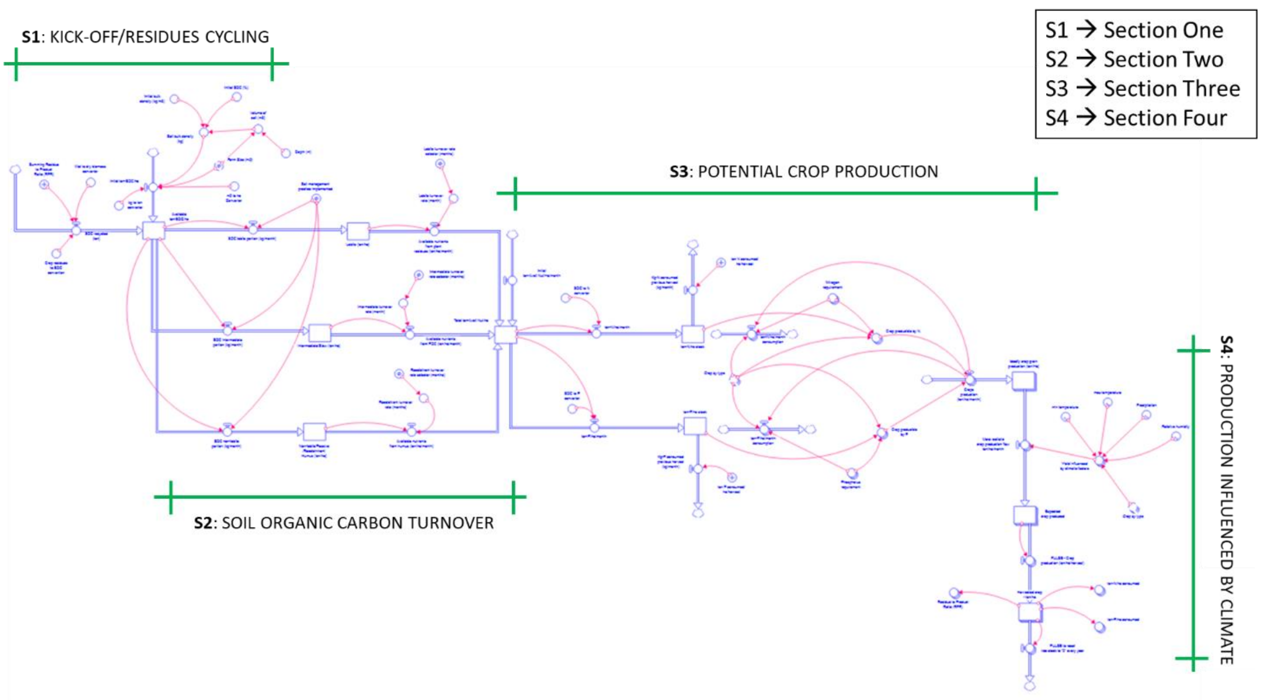

Figure 5.7. Diagram of the stock and flow model identifying its sections.

V.8.1 Management practices

The interface provides a slider that allows the user to analyze the impact of tilling symbolized as the number "1" in the interface or not tilling practices on the system symbolized by the number "0.". Tillage is an agricultural management practice that consists of tracing furrows either with manual tools in the case of small-scale agricultural systems or with the use of mechanized and even automated plows in the case of conventional agriculture. The depth of tilling can range from 12 cm to over 30 cm. Generally, the manual practice of tillage only involves the tracing of furrows. However, in industrial and agricultural practices, it involves plowing, which consists of turning and crushing the dirt with force to reveal the soil below the topsoil. Although small farmers generally make decisions based holistically and not on individual management practices, scientific studies examine the effect of tillage as an independent practice (Haddaway, Hedlund et al. 2017). In addition, scientific literature suggests that these practices have a more significant influence on the distribution of soil organic carbon in the three different pools and, in turn, how it influences the availability of nutrients (N and P), thus reducing the need for external inputs such as synthetic fertilizers. For instance, Haddaway et al. (2017) concluded through a meta-analysis of related studies that No-Till compared to High-intensity-till increases SOC concentrations in the upper part of the soil, improve the activity of the biota, therefore lower turnover rates, in addition to increasing the resilience of these agricultural systems to extreme weather conditions (Haddaway et al. 2017).

V.8.2 Description of state variables and equations

Table 5.1. A description of the main equations of the stock and flow model.

Type	Variable label	Equation	Units	Definition
Stock	Available SOC	"Total_t-Avail_Nut/ha/month"(t - dt) + ("Available_nutrients_from_humus_(t/ha/month)" + "Available_nutrients_from_POC_(t/ha/month)" + "Available_nutrients_from_plant_residues_(t/ha/month)" - "t-N/ha/month" - "t-P/ha/month" - Other_SOC_nutrients_and_elements) * dt	t/ha/ month	Based on this SOC stock, nitrogen and phosphorus are calculated using a proxy from the scientific literature (WAAA, 2018).
Stock	Crop production	"Crop_produced_annually_influenced_by_climate_t/ha"[Crop_types](t - dt) + ("More_realistic_crop_production_flow_t/ha/a"[Crop_types]) * dt	t/ha/ a	The stock of crops produced, whose calculation considers the influence of climatic factors (precipitation, relative humidity, and temperature)
Stock	Ideal crop production	"Ideally_crop_grain_production_(t/ha/month)"[Crop_types](t - dt) + ("Crops_production_(t/ha/month)"[Crop_types] - Crop_monthly_production_influenced_by_climate[Crop_types]) * dt	t/ha/ month	The stock of crops produced only based on nitrogen and phosphorus requirement compliance
Stock	Available nitrogen	"t-N/ha/month_stock"(t - dt) + ("t-N/ha/month" - "t-N_consumed_previous_harvest_(kg/ha/month)") * dt	t/ha/ month	The stock of nitrogen available to produce crops
Stock	Available phosphorus	"t-P/ha/month_stock"(t - dt) + ("t-P/ha/month" - "t-P_consumed_previous_harvest_(kg/ha/month)") * dt	t/ha/month	The stock of phosphorus available to produce crops
Flow	SOC from biomass residues recycled	IF Management_practice_2=1 THEN ("Residue_to_Product_Ratio_(RPR)"[Corn]*Crop_residues_to_SOC_convertion*Wet_to_dry_biomass_converter[Corn]+"Residue_to_Product_Ratio_(RPR)"[Cassava]*Crop_residues_to_SOC_convertion*Wet_to_dry_biomass_converter[Cassava]+"Residue_to_Product_Ratio_(RPR)"[Yam]*Crop_residues_to_SOC_convertion*Wet_to_dry_biomass_converter[Yam]+"Residue_to_Product_Ratio_(RPR)"[Rice]*Crop_residues_to_SOC_convertion*Wet_to_dry_biomass_converter[Rice]) ELSE 0	t/ha/ month	SOC flow re-entering the system that comes from the residual biomass of the previous year's harvest.
Flow	Initial SOC	PULSE("t-SOC/ha", 1, 0)	t/ha/ month	The initial content of SOC is calculated, considering the bulk density, depth of 10 cm, and the SOC%.

Table 5.1. (continued)

Type	Variable label	Equation	Units	Definition
Flow	External_SOC_ input	IF External_biomass=0 THEN (IF "Farm_Size_(m2)"=0 THEN 0 ELSE PULSE("Annual_aggregated_Dry_biomass_t/ha"/("Farm_Size_(m2)"/10000*Crop_residues_to_SOC_convertion) , 18, 12)) ELSE 0	t/ha/ month	This is the annual input of SOC which is calculated considering the tons of dry biomass added annually from external sources.
Converter	Corn yield influenced by climatic factors	25.902 − 0.641 minimum temperature − 0.306 maximum temperature − 0.001 relative humidity + 0.001 rainfall	t/ha	Linear regression model to calculate the yield of this crop, taking into account climatic factors. (Dwamena et al., 2022)
Converter	Cassava yield influenced by climatic factors	3.227 minimum temperature − 3.382 maximum temperature + 1.219 relative humidity − 0.001 rainfall	t/ha	Linear regression model to calculate the yield of this crop, taking into account climatic factors. (Dwamena et al., 2022)
Converter	Yam yield influenced by climatic factors	0.830 minimum temperature − 1.262 maximum temperature + 0.385 relative humidity + 0.002 rainfall	t/ha	Linear regression model to calculate the yield of this crop, taking into account climatic factors. (Dwamena et al., 2022)
Converter	Rice yield influenced by climatic factors	15.6224 + 2.0805 lnTemp** + 2.0755 lnRH*** + 0.0573 lnRainfall)	t/ha	Linear regression model to calculate the yield of this crop, considering climatic factors. (Chowdhury & Hossain, 2011)

V.8.3 Model parameters

Table 5.2. A description of the main parameters of the stock and flow model.

Variable label	Units	Model's default values and ranges	References
Crop_residues_to_SOC_ ratio		1.4 - 2.5	(Pribyl 2010)
Initial_bulk_density	g/cm3	1.1 – 1.6	(WAAA 2018)
Initial_SOC	%	0 - 7	(The University of Western Australia 2022)
Turnover rates	month		(WAAA 2018)

Table 5.2. (continued)

Variable label	Units	Model's default values and ranges	References
Labile pool fraction	%		(Chan 2008)
Intermedium pool fraction	%		(Chan 2008)
Recalcitrant pool fraction	%		(Chan 2008)
max_temperature (average)	℃		(Empresa de Transmisión Eléctrica 2022)
min_temperature (average)	℃		(Empresa de Transmisión Eléctrica 2022)
Precipitation (average)	mm		(Empresa de Transmisión Eléctrica 2022)
Relative humidity (average)	%		(Empresa de Transmisión Eléctrica 2022)
Nitrogen_requirement [Corn]	kg/ha	79 – 132	(Dreyfus et al. 1987)
Nitrogen_requirement [Cassava]	kg/ha	99 – 153	(Phien and Vinh 2007)
Nitrogen_requirement [Yam]	kg/ha	50 - 100	(Hgaza, Diby et al. 2012)
Nitrogen_requirement [Rice]	kg/ha	74 – 84	(Dreyfus et al. 1987)
Phosphorus_requirement [Corn]	kg/ha	20 - 40	(Van der Eijk, Janssen et al. 2006)
Phosphorus_requirement [Cassava]	kg/ha	57 - 113	(Phien et al. 2007)
Phosphorus_requirement [Yam]	kg/ha	70 - 80	(Hgaza et al. 2012)

Table 5.2. (continued)

Variable label	Units	Model's default values and ranges	References
Phosphorus_requirement [Rice]	kg/ha	17 - 25	(De Datta et al. 1990)
Residue_to_Product_Ratio_(RPR)[Corn]		2.27	(Lye and Bilsborrow 2013)
Residue_to_Product_Ratio_(RPR)"[Cassava]		0.31	(Lye et al. 2013)
Residue_to_Product_Ratio_(RPR)"[Yam]		0.31	(Lye et al. 2013)
Residue_to_Product_Ratio_(RPR)"[Rice]		2.01	(Lye et al. 2013)
SOC_to_N_proxy		0.1	(WAAA, 2018)
SOC_to_P_proxy		0.015	(WAAA, 2018)
Wet_to_dry_biomass_converter		0.78 - 0.88	(Intergovernmental Panel on Climate Change 1996)

V.8.4 Farm model scenarios

Small-scale farming systems tend to be highly diverse in plants (perennials and annuals), animals (insects, birds, and mammals), and crops (Altieri et al., 2012; Food and Agriculture Organization 2017; Morel et al., 2017). Diversity generates high complexity in a model if care is not taken to define a scope consistent with the questions sought to be answered and to carry out the corresponding analyzes to identify which are the relevant variables in the model and which can be excluded. In this investigative work, in addition to defining a relevant scope and carrying out the corresponding sensitivity analysis, we implemented scenarios to simplify the simulations further and facilitate the management and understanding of the results by the stakeholders. In the same line of thought, the model allows analyzing up to four crops simultaneously to reduce the generation of complex interactions between many elements in the model. These four crops respond to crops identified by the community, small farmers, and the authorities as a fundamental component of the regional Basic Food Basket. Besides these four agricultural products are highly consumed throughout the country. One of the traditional main plates of Panama and for many the main dish is the "Sancocho" the products selected for our model make up more than 50% of the components of this traditional dish. The Sancocho is always accompanied by a plate of rice that is commonly poured into the soup when it is eaten.

V.9 Results and Discussion

V.9.1 Building model confidence

There are two important aspects when looking to build confidence in an SDM, testing and validation. The first refers to the acceptance or rejection of the model based on how well the trends produced by the model reflect the behavior of a simplified version of a real environmental system of interest (Barlas, 1996). While the second refers to the process of building confidence in the usefulness and soundness of the model (Barlas 1996). Ford (2010) proposes concrete tests to build confidence in a model. Since this is a very rudimentary version of a process-based model that is not predictive nor represents a farming system, it makes no sense to carry out the verification and validation process of the model. However, in order to verify the functionality of the model, we have applied a series of exercises recommended by Ford (2010) that include:

- Sensitivity Analysis - SDM often reveal that the uncertainties in many parameters do not significantly affect the results. However, some parameter values may be crucial, which means that small changes in their estimates can lead to significant changes in the results (Ford 2010).

- Face Validity - You verify if the model structure and parameters make sense. This test relies on the understanding of the system to judge the structure (Ford 2010).

- Extreme behaviour - the model is submitted to a stability test in which an extreme change is introduced, and the model's response is evaluated whether it goes towards the "run away behavior" or if it manages to return and stay in the Span of Control (Ford 2010).

V.9.2 Sensitivity analysis

Sensitivity analysis is a critical step in the modeling process, especially when working with SDM which contain highly uncertain parameters. The sensitivity analysis is a necessary activity that adds to the efforts to develop the reliability of the simulated results and verify the robustness of the model's behavior in the face of changes in the values of the parameters. Our model's parameters are based on expert judgment, while others are drawn from peer review articles or gray literature. Therefore, the estimates could be highly uncertain. However, the uncertainty should not dictate the inclusion or not of a parameter in the model (Ford 2010). On the other hand, some of the model parameters are crucial; that is, small changes in their estimates can generate considerable differences in the simulation results (Ford 2010). We ran the sensitivity analysis within the Stella Architect tool.

Precipitation, dry matter input and SOC transformation rates are among the parameters we identified as crucial in our model. We determine these variables by the method proposed as "Sampling" by (Ford 2010), in which a control panel is created in the initial stages of model development. This panel is composed of sliders to which different uncertainty ranges are assigned. The developer experiments with the different variables of the model and, in this way, identifies which variables generate the most significant impact on the results. Table 5.3 shows the parameters and assumptions established for this scenario.

V.9.2.1 Sensitivity analysis A

Table 5.3. Simulation parameters used for Sensitivity Analysis A.

			TURNOVER RATE*	**CONSTANTS**				
MANAGEMENT	Till	No Till	Medium	Initial SOC % (medium)	Farm Size (ha)	Initial bulk density (g/cm^3)	Simulation time length (month)	Annual aggregated dry biomass (t/ha)
CROP SELECTION								
Rice		X	X	1.5	2	1.5	50	5

The model simulation results are displayed in figure 5.8. The figure 5.8 (a) shows the results of the sensitivity analysis of the production of rice (monoculture) influenced by changes in precipitation. Rice production tends to increase as rainfall increases (100 mm, 575 mm, 1050 mm, and 1525 mm). However, there is a breaking point where the increase in precipitation impacts production negatively. Figure 5.8 (b) shows the drop in production when precipitation reaches 2000 mm, coinciding with a behavior of a natural system where extreme climate impacts (slides, erosion, loss of nutrients) negatively impact crop production.

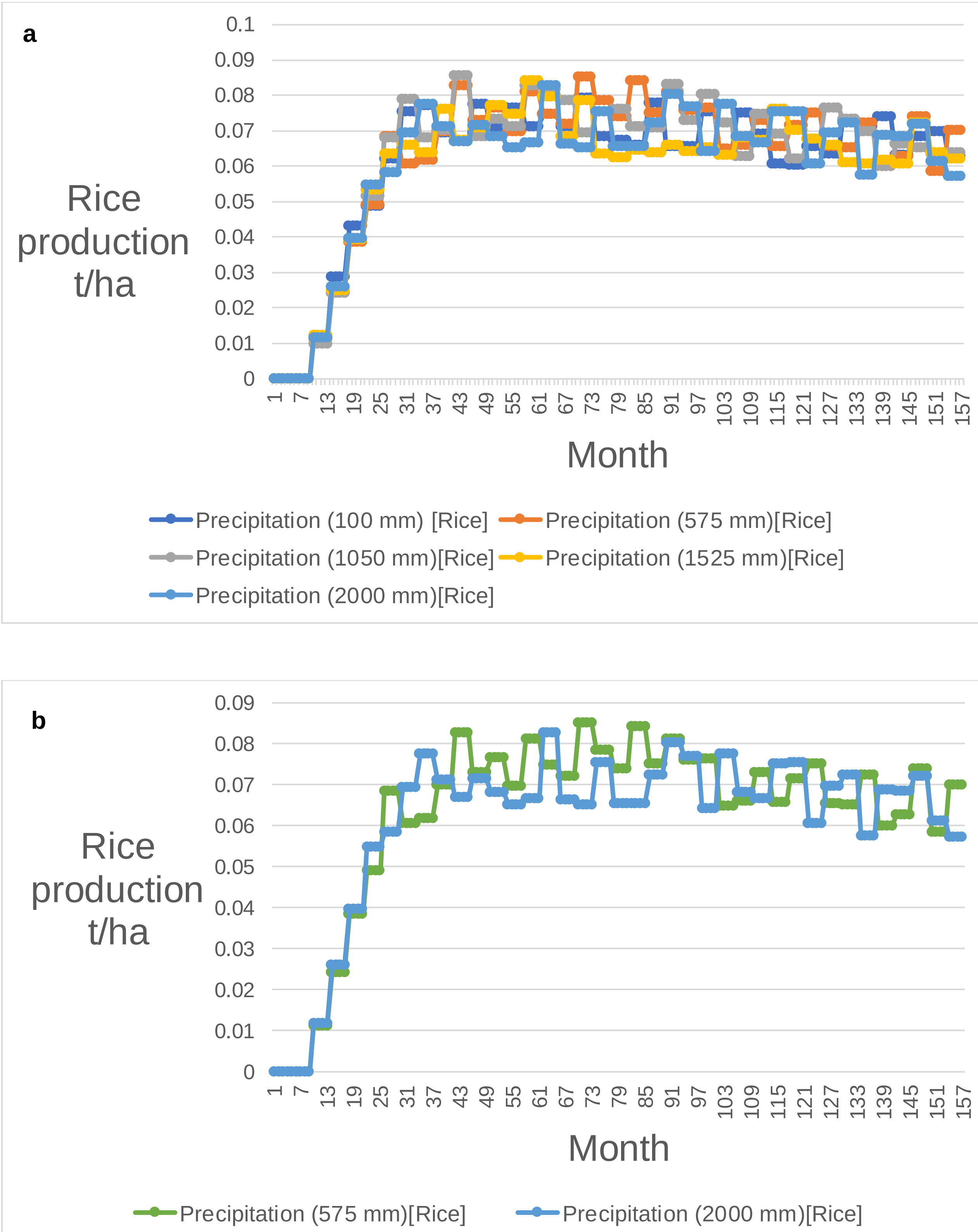

Figure 5.8. Sensitivity analysis results of the production of rice (monoculture) influenced by changes in precipitation.

V.9.2.2 Sensitivity analysis B

In this scenario, it is assumed that the total area of the farm is dedicated to corn production. The dry matter input was identified in our initial screening as an influential variable in the results of the model simulations. Therefore, in this scenario, we evaluate the variable's impact on the system's production. For this, we conduct a sensitivity analysis that tests different magnitudes of dry matter (t/ha/a) input (from 2000 to 14000 t per year), and its influence on production is analyzed. Table 5.4 shows the parameters and assumptions established for this scenario.

Table 5.4. Simulation parameters used for Sensitivity Analysis B.

			TURNOVER RATE*	**CONSTANTS**				
MANAGEMENT	Till	No Till	Medium	Initial SOC % (low)	Farm Size (ha)	Initial bulk density (g/cm^3)	Simulation time length (month)	Annual aggregated dry biomass (t/ha)
CROP SELECTION								
Corn		X	X	1.5	2	1.5	50	5

The sensitivity analysis results show that the dry matter input variable has a considerable influence on the system's production. As the input of dry matter increases progressively, the production also increases until a moment arrives in which the production begins to stabilize. The way the model has been built, there is a production limit per hectare that is independent of the number of available nutrients. Figure 5.9 shows an equilibrium trend once this maximum yield is reached.

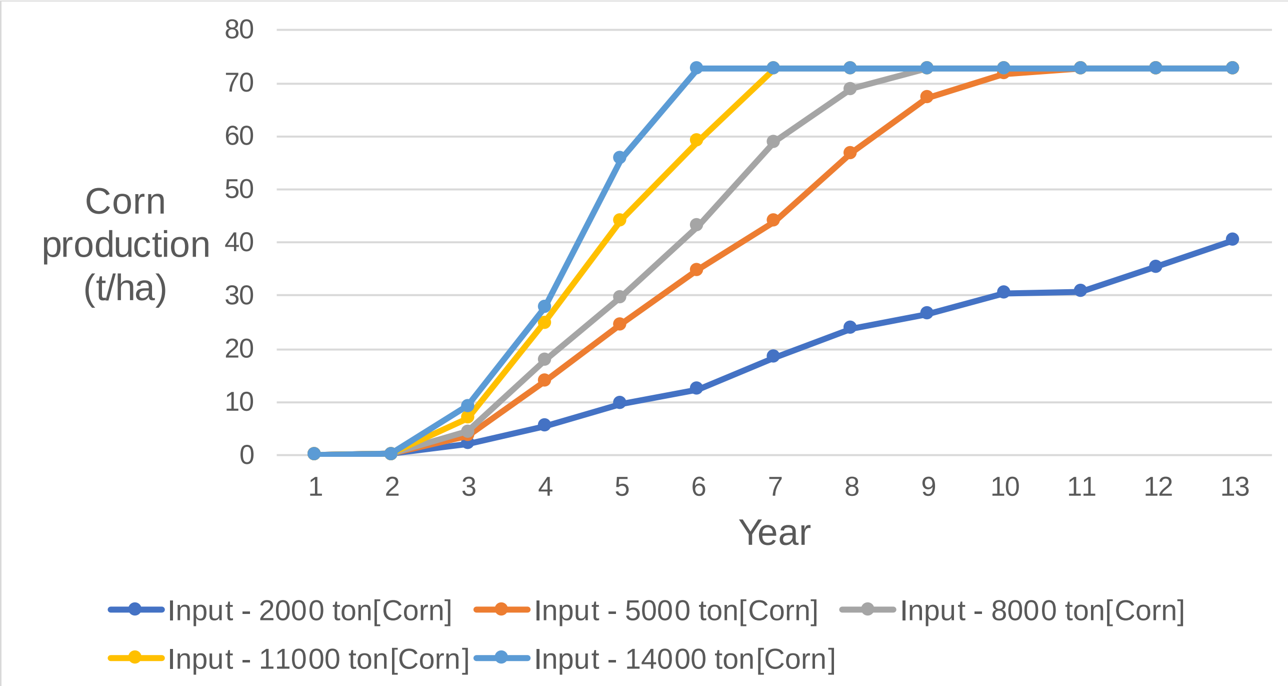

Figure 5.9. Sensitivity analysis results of maize cumulative production (monoculture) influenced by annual dry matter inputs to the system.

V.9.2.3 Sensitivity analysis C

In this scenario, it is assumed that the total area of the farm is dedicated to cassava production. The residue to product ratio (RPR) input was identified in our initial screening as an influential variable in the results of the model simulations. Therefore, in this scenario, we evaluate the variable's impact on the system's production. For this, we conduct a sensitivity analysis that tests different magnitudes of RPR input (from 0 to 2.5), and its influence on production is analyzed. Table 5.5 shows the parameters and assumptions established for this scenario.

Table 5.5. Simulation parameters used for Sensitivity Analysis C.

			TURNOVER RATE*	**CONSTANTS**				
MANAGEMENT	Till	No Till	Fast	Initial SOC % (low)	Farm Size (ha)	Initial bulk density (g/cm^3)	Simulation time length (month)	Annual aggregated dry biomass (t/ha)
CROP SELECTION								
Cassava		X	X	2	2	1.5	50	5

The sensitivity analysis results show that the RPR input variable has a considerable influence on the system's production. The higher the RPR in the different crops, the greater the generation of nutrients will be; therefore, a higher production for a longer time is estimated. Literature suggests that corn and rice have higher RPRs (between 2 and 3 approximately) (Lye et al. 2013). Compared to the RPRs of cassava and yam, which reach between 0.36 and 0.5 approximately (Lye et al. 2013). However, the RPR fluctuates depending on the yield and many other factors (Fischer, Prieler et al. 2010). Figure 5.10 shows how the progressive increase of the RPR of cassava crops induces increases in crop production, respectively.

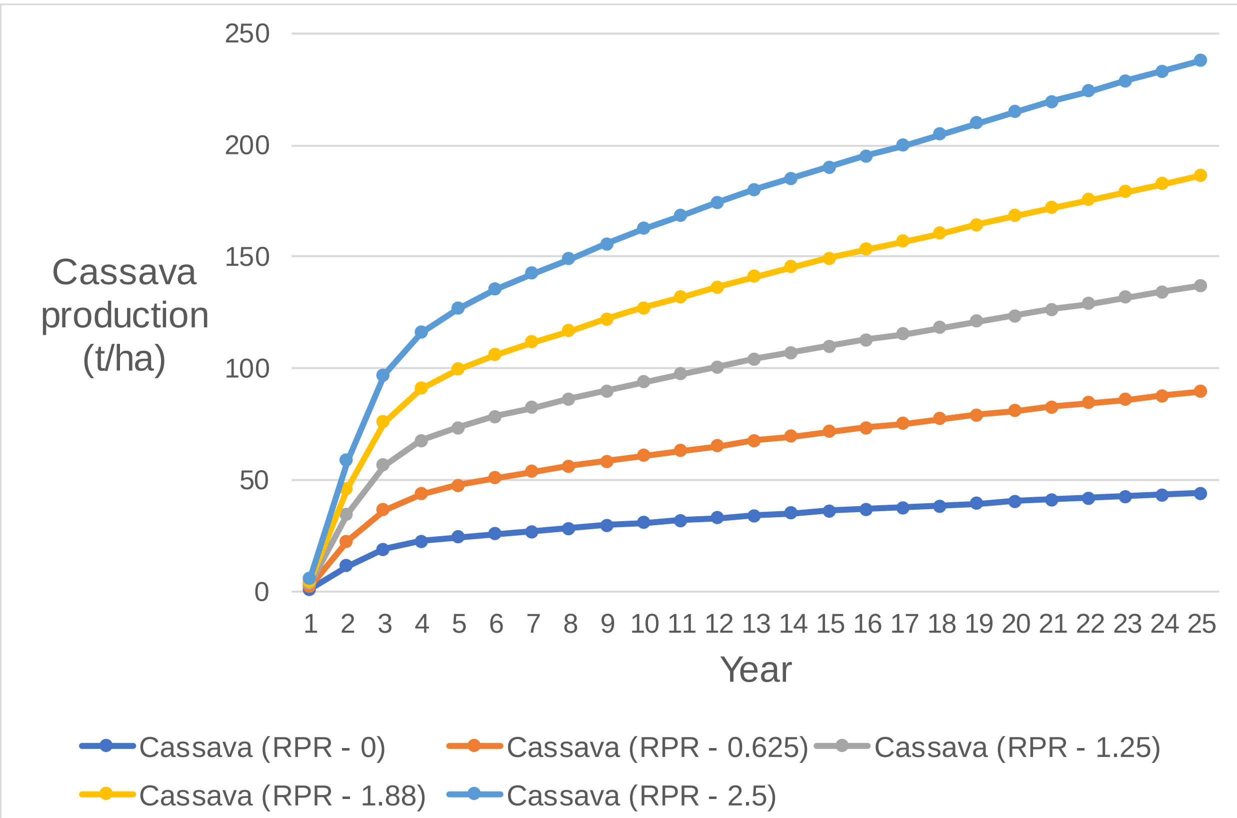

Figure 5.10. Sensitivity analysis results of cassava production (monoculture) influenced by changes in the residue-to-product ratio.

V.9.3 Stability test

The extreme behavior test simulates abrupt drainage of the total content of the stock of available nutrients in month 120 (year 10). For this, we added a flow (figure 5.11) that drains 1000 t/ha of organic matter during the simulation period. This immediately creates a situation of stress in the system that causes a precipitous drop in production. However, figure 5.12 shows how the system begins to seek equilibrium once the disturbance has passed.

This disturbance is generated by the following formula:
PULSE(1000, 120, 0)

Table 5.6. Stability test parameters..

			TURNOVER RATE*	**CONSTANTS**				
MANAGEMENT	Till	No Till	Medium	Initial SOC % (low)	Farm Size (ha)	Initial bulk density (g/cm^3)	Simulation time length (month)	Annual aggregated dry biomass (t/ha)
CROP SELECTION								
Yam & Rice		X	X	1.5	2	1.5	50	5

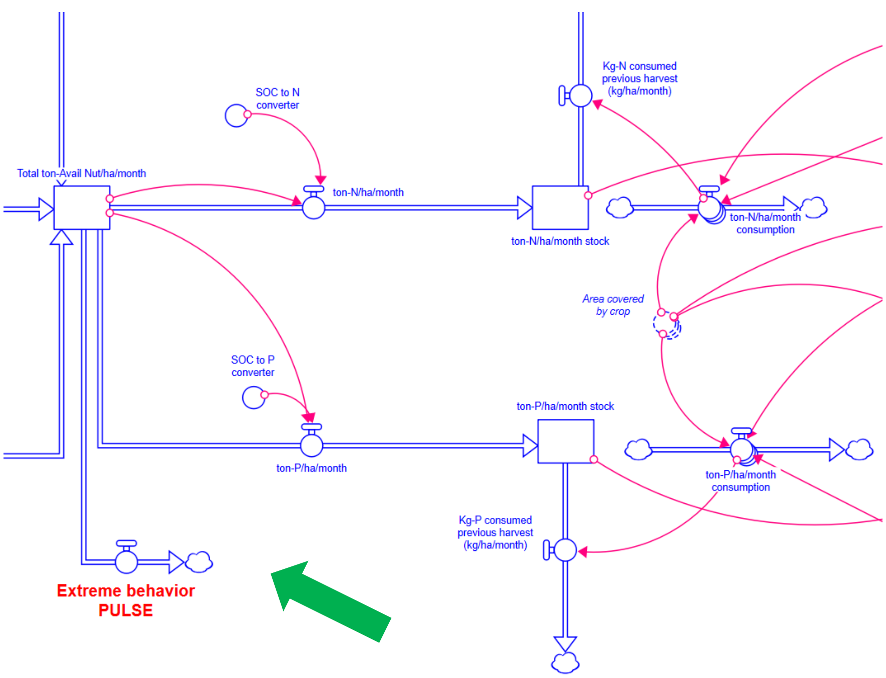

Figure 5.11. The extreme behavior flow in the stock and flow model is displayed.

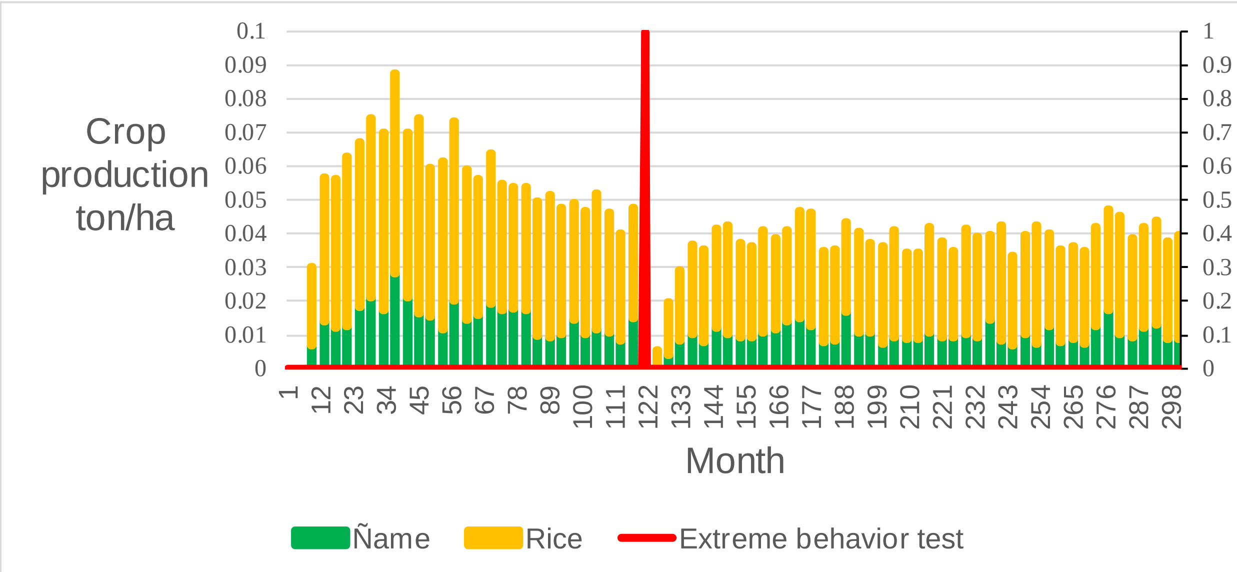

Figure 5.12. Visualization of the effect that the disturbance has on the system.

V.9.3.1 Scenario A: Comparison of monoculture systems of each crop using annual production as an indicator.

In Chapter IV, qualitative work, 88% of the interviewees established that their most significant motivator for starting a small-scale agricultural system was to provide the necessary food for their family's subsistence. Moreover, in our definition of ecological sustainability, a small-scale farming system can sustain production over time. This comparison intends to visualize the different tendencies that emerge from the simulations and to analyze whether the systems can maintain a relatively constant production over time under typical climatic conditions of the region. Table 5.7, then reveals the conditions under which the simulations and comparisons will be carried out.

Table 5.7. Simulation parameters used in scenario A.

			TURNOVER RATE*	PARAMETERS					
MANAGEMENT	Till	No Till	Slow	Initial SOC % (very low)	Farm Size (ha)	Initial bulk density (g/cm^3)	Simulation time length (month)	Annual aggregated dry biomass (t/ha)	Crop residue to SOC factor
CROP SELECTION									
Rice (100%)		X	X	1	1	1.1	10	2	1.95
Rice (50%) and Cassava (50%)		X	X	1	1	1.1	10	2	1.95
All crops (25% each)		X	X	1	1	1.1	10	2	1.95

	Nitrogen requirement (kg/ha)	Phosphorus requirement (kg/ha)	RPR value
Corn	132	40	2.27
Cassava	153	113	0.31
Yam	100	80	0.31
Rice	84	25	2.01

We created an extreme scenario where the initial content of SOC in the soil is very low. In addition, the turnover rates were established as slow as the model allows us to put even pressure on the development of nutrients throughout the simulation. All this is with the idea of identifying which systems are more sustainable based on production over time.

Figure 5.13 shows us that the *Rice (100%)* and *All crops (each at 25% of the total area)* scenarios are the ones that generate the best yields. One of the factors that may have influenced these results is that corn and rice present the highest RPR values , according to the literature. Therefore, in the scenarios that involve these two crops, the generation of residual biomass will be more significant. Our model calculates N and P using proxies derived from scientific literature that are based on the amount of SOC present. As a result, the higher the SOC stock, the greater the availability of nitrogen and phosphorus.. Panama's rice consumption per capita is estimated at 70.2 kg/a (0.0702 t/a) (Ministerio de Desarrollo Agropecuario 2020). Considering a family of 4 members of two adults and two minors, and we assume that minors consume 50% of an adult, this gives us a consumption per family of 0.2106 t/a. Figure 5.14 shows that even the lowest yield scenario (50% rice, 50% cassava) would provide the minimum annual rice requirement for a family of 4 members.

As it is not a complete or validated model, the values will not resemble the reality of these small-scale agricultural systems. For example, Oldfield et al. (2020), through a greenhouse experiment, compared soil organic matter (SOM) between 1% and 9% by applying different management treatments (irrigation and fertilization at different rates). They concluded that once a concentration of 5% SOM was reached, Wheat production began to decline, suggesting that more SOM does not necessarily improve productivity (Oldfield, Wood et al. 2020). This is the type of feedback required to be included in this model, and due to time limitations, lack of a multidisciplinary team and resources were not possible. Since our model lacks this balancing feedback, crop yield continues to increase disproportionately to numbers that differ from the reality of this type of system. However, our work suggests a mechanism to make these comparisons in the future using integrations of stock and flow models with process-based models.

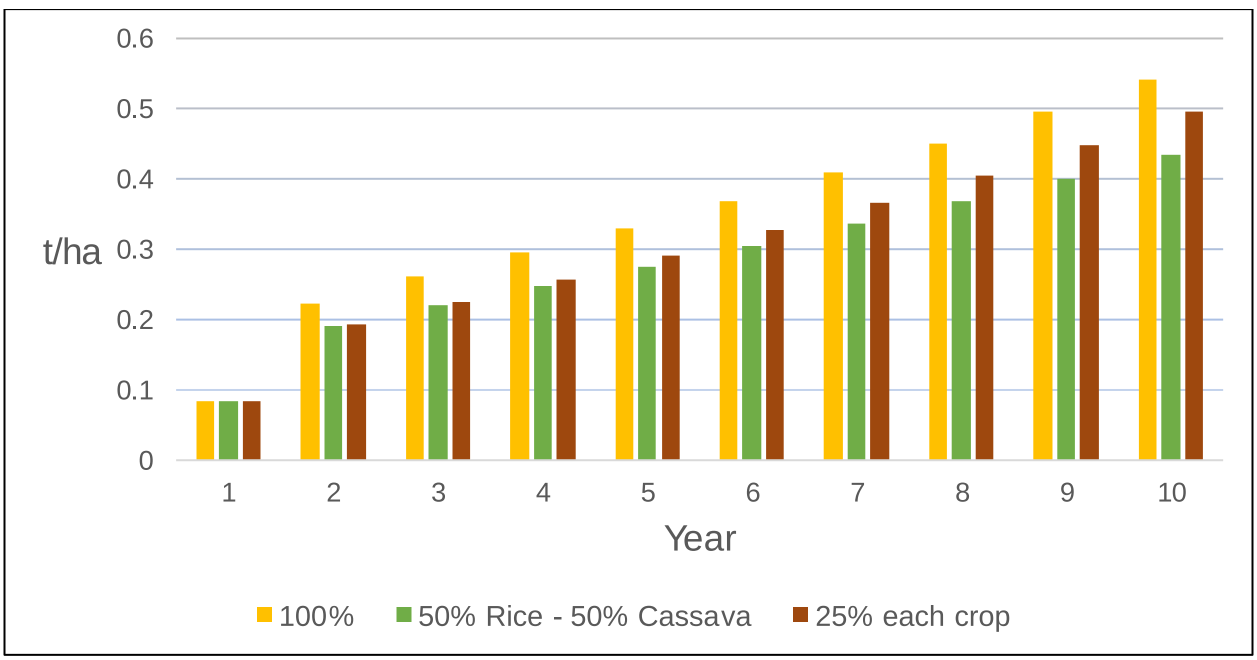

Figure 5.13. Performance of three agricultural systems using annual yield

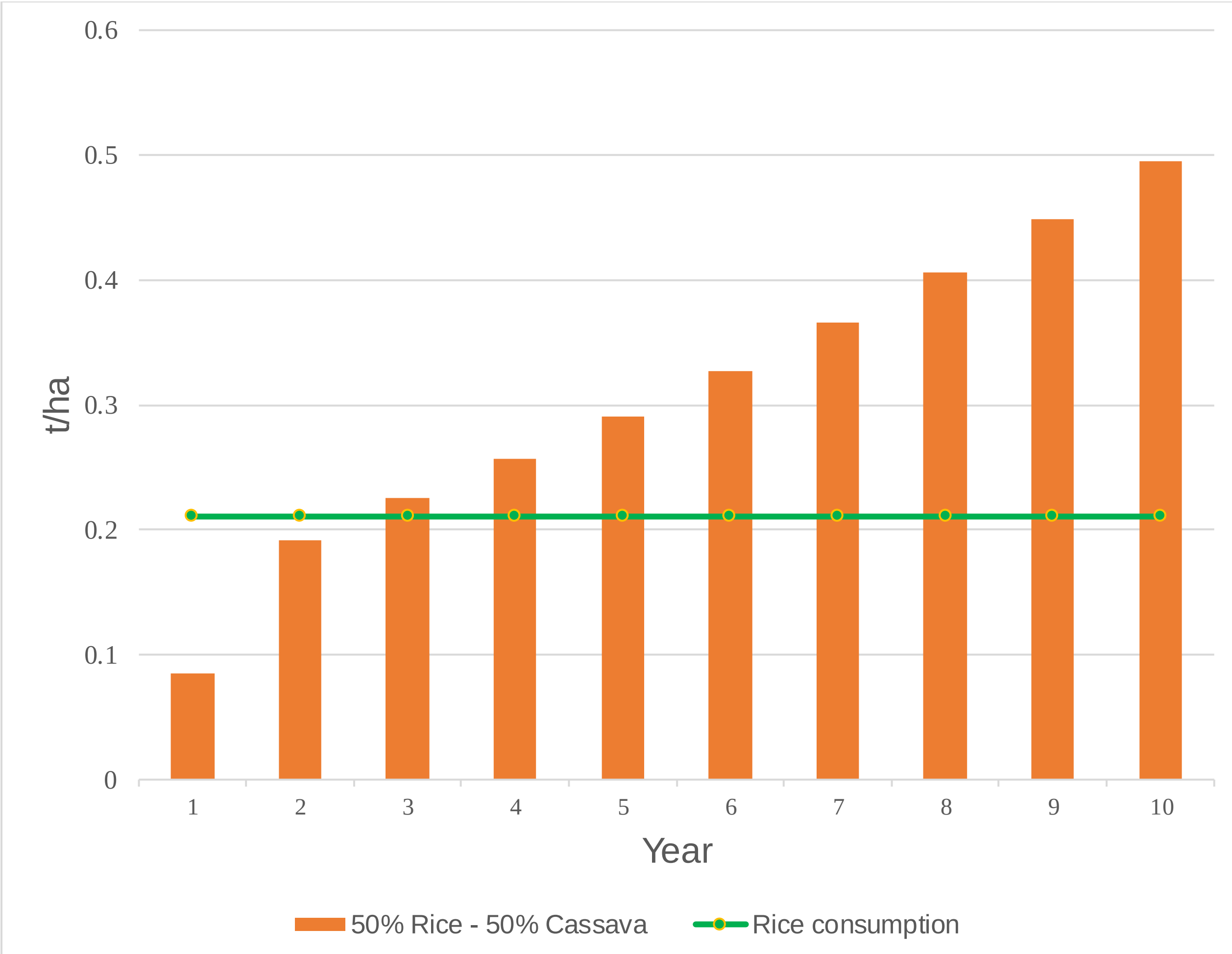

Figure 5.14. Performance of two agricultural systems using the subsistence indicator

V.9.3.2 Scenario B: Comparison of monoculture systems against diverse agricultural systems using nutrient availability as a base of comparison.

In our definition of sustainability outlined in Chapter 1, soil quality is one of the leading indicators to compare ecological sustainability. As reported in Chapter 4, 100% of the interviewees stated that the high degradation of the soil was one of their most significant barriers. This exercise intends to use the availability of SOC (t/ha) as the basis for comparing the different systems.

Table 5.8, then reveals the conditions under which the simulations and comparisons will be carried out.

Table 5.8. Simulation parameters used in scenario B.

			TURNOVER RATE*	**PARAMETERS**					
MANAGEMENT	Til l	No Till	Slow	Initial SOC % (very low)	Farm Size (ha)	Initial bulk density (g/cm^3)	Simulation time length (month)	Annual aggregated dry biomass (t/ha)	Crop residue to SOC factor
CROP SELECTION									
Cassava (100%)		X	X	1	1	1.1	15	2	1.95
Cassava (50%) and Corn (50%)		X	X	1	1	1.1	15	2	1.95
All crops (25% each)		X	X	1	1	1.1	15	2	1.95

	Nitrogen requirement (kg/ha)	Phosphorus requirement (kg/ha)	RPR value
Corn	132	40	2.27
Cassava	153	113	0.31
Yam	100	80	0.31
Rice	84	25	2.01

Figure 5.15 proposed a way to compare soil quality by using SOC (t/ha) as an indicator of the comparison. According to the results of our model system, All crops (25% each) would be the ones that would accumulate the most significant amount of SOC over time. We established 19.5 t/ha as an indicator of a minimum acceptable SOC% to sustain productivity. The 19.5 t/ha comes from the following formula:

SOC% = SOC / (BD*Depth*100)

Soil organic carbon: SOC (t/ha)

Bulk density: BD (g/cm3)

Depth (cm)

19.5 t/ha is the amount of SOC required to reach a minimum of 3% of SOC, which is the recommended minimum to sustain production over time (The University of Western Australia 2022) in soil with a BD of 1.1 (g/cm3) and a Depth of 10 cm we obtain 19.5 t/ha.

Figure 5.15 shows us that within 15 years, none of the systems could reach the minimum required to maintain adequate production. As it is not a complete or validated model, the values will not resemble the reality of these small-scale agricultural systems. However, our work suggests a mechanism to make these comparisons in the future using integrations of stock and flow models with process-based models.

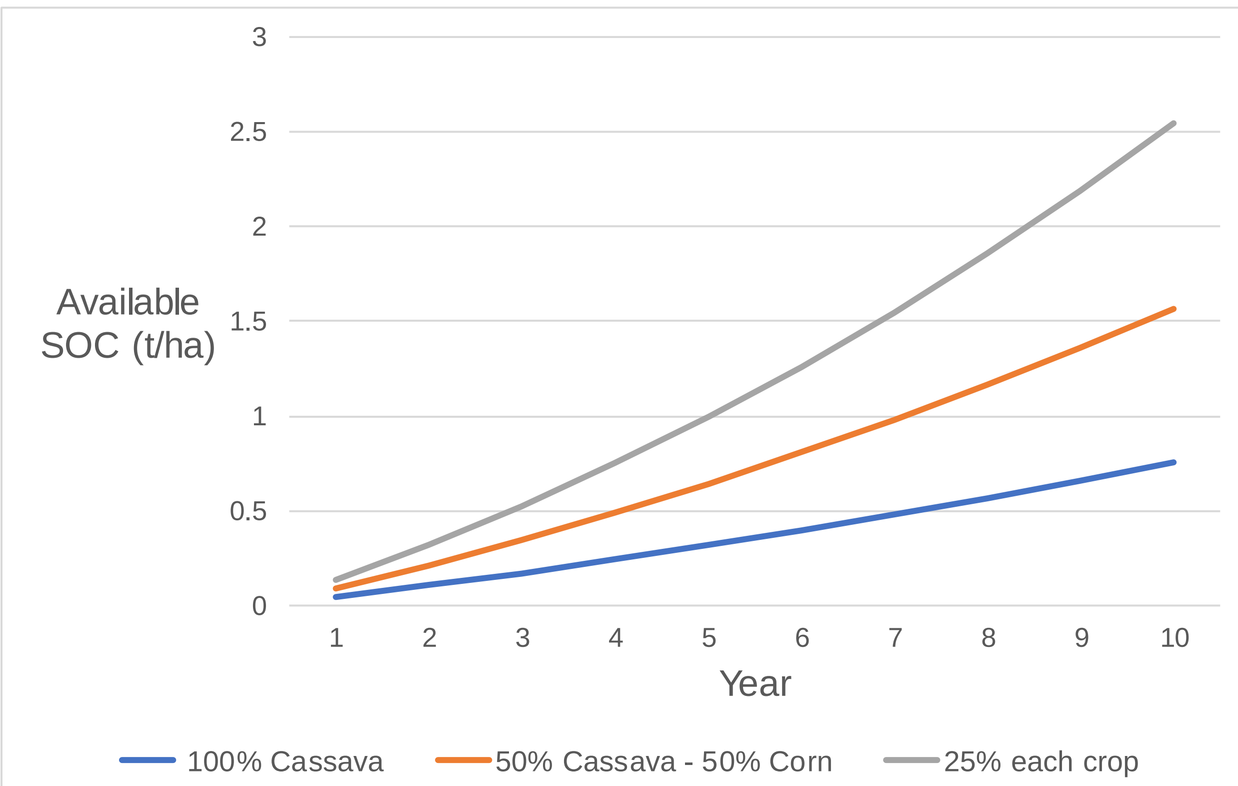

Figure 5.15. Performance of three agricultural systems using the SOC availability indicator

V.9.4 Model Interface Structure Proposal

Stella Architect provides an intuitive interface that allows users to interact with the model and select the initial parameters of the modeling process. Figure 5.16 shows a scenario selected by a user where three crops are chosen, two of which cover 25% of the land area each, and the third crop covers 50% of the land area.. The interface allows the user to choose countless scenarios based on farm size, initial % of Soil Organic Carbon (SOC), management practices, and organic matter turnover rates for three different soil pools. Our interface proposal separates those variables that a farmer or agriculture early adopter manages because he is the one who knows what scale of a project he can develop and has at least an early notion of the system he would like to undertake. We have called this section of the interface "farmer panel." While the other section of the interface includes variables that require more technical knowledge (crop nutrient requirements, soil microbiology, and historical climatic data of the region, among others) and has been labelled as "extensionist or expert panel."

Users can select scenarios relevant to the system and the combination of crops they seek to develop. Users can simulate numerous conditions that apply to them and understand the impact that those conditions have on different components of the system. The tool will generate different trends that allow stakeholders to visualize changes for instances, on the availability of fundamental nutrients such as nitrogen and phosphorus under different soil carbon pool turnover rates. The tool also allows users to visualize crop production (monoculture or polyculture) trends through time under climatic factors (temperature, precipitation, and relative humidity) in different crop cycles, among others.

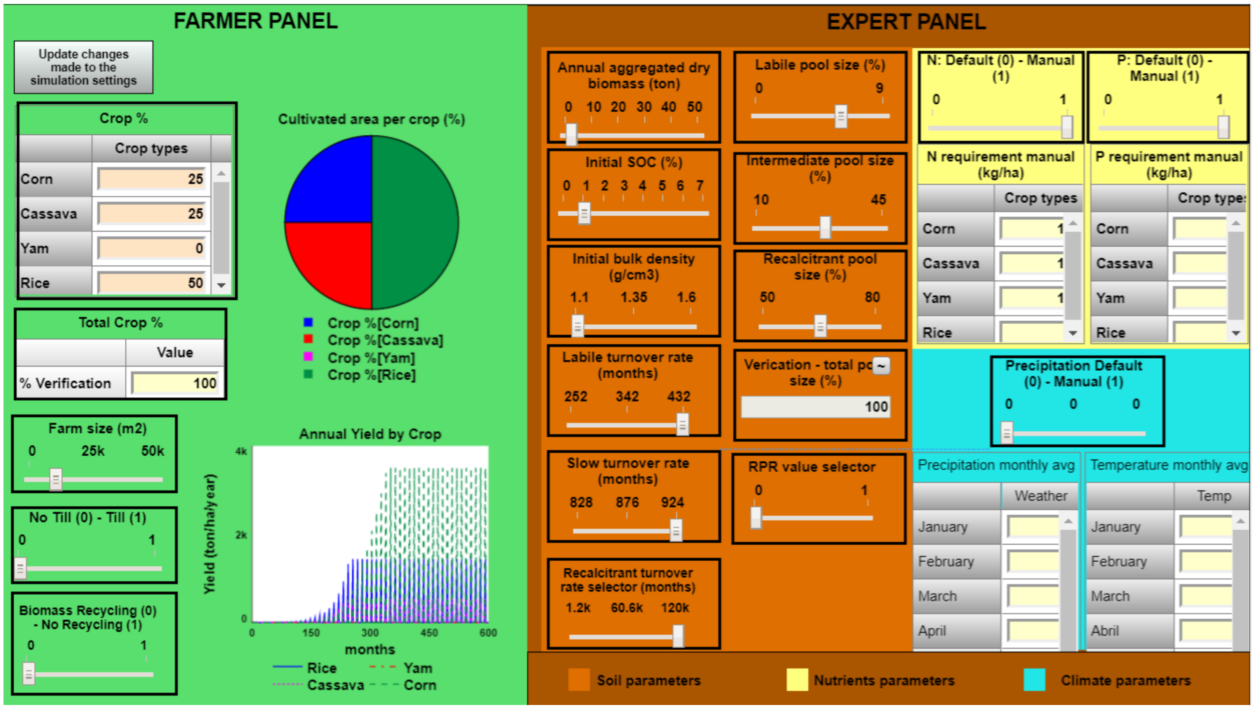

Figure 5.16. Interface proposal for integrating stock and flow models with process models

V.9.5 Model Integration

The scope of this research work does not include attempts to integrate process models for natural resource management, as this requires many resources and a multidisciplinary technical team. However, recent cases demonstrate that the successful integration of process-based models from multiple disciplines with even SDM in natural resource management is possible. For example, Inam et al. (2017) successfully integrated the physical model (SAHYSMOD), which is used to simulate soil salinity and water movement within the crop root zone, transition zone, and aquifer, with an SDM developed by a rigorous participatory method of stakeholders and supported by other tools such as Excel and Python. With this, Inam et al. (2017) tested soil salinity management scenarios and proposed relevant policies for this issue in Pakistan (Inam, Adamowski et al. 2017). Another successful example was that of Parsons et al. (2011), who integrated a crop system model with a livestock model to assess biophysical and economic influences on farming practices in the tropics. Parsons et al. (2011) used Vensim to develop a dynamic stock-flow model to evaluate sheep production and manure generated. Furthermore, this livestock model was integrated with the widely known crop simulation software Agricultural Production Systems Simulator (APSIM), with which they simulated weather patterns, crop production, and soil dynamics. As a result, the integration of these models successfully represented the complexity of the interactions between crops and livestock (Parsons, Nicholson et al. 2011).

Based on the indicators (production, soil quality, and management practices) identified in Chapter 4, a complete version of the stock-flow model developed in Stella Architect and proposed in this study could be integrated with the DNDC model. In conversations via email with the Stella Architect technical team, they told us that integration with other models is possible when you build a stand-alone model in Stella and then use import/export feature to connect with the other models (B. Bahaddin, personal communication, october 31 2022). Other ways to link these models is by using tools such as Excel and Python as suggested by INAM et al. (2017). Finally, Parsons et al. (2011) integrated their model developed in Vensim (Ventana Systems Inc) with the Agricultural Production Systems Simulator (APSIM) that simulates biophysical processes in farming systems with a particular focus on yield estimation and prediction of long-term consequences of farming practices on soil quality. For this integration, Parsons et al. (2011) used the VENLINK module (CSIRO et al. 2007), which is a modeling package designed by Ventana Systems Inc and allows the integration of various modules through a “plug-in-pull-out” approach. In VENSIM, as in Stella Architect, it is also required to create a stand-alone model, and while it is being developed, it is crucial to identify which variables will be used in Vensim and which will be passed to APSIM and vice versa.

Both STELLA architect and DNDC simulate on daily or yearly intervals which facilitates communication and enables dynamic integration feedback. DNDC could accurately predict crop growth, soil temperature, soil carbon dynamics, nitrogen leaching, and emissions of trace gases (N2O), nitric oxide (NO), dinitrogen (N2), and ammonia (NH3), amongst others). For example, DNDC could simulate the changes in the three carbon pools of section 2 of the stock and flow. The DNDC model can also predict crop growth and total crop production, one of the leading indicators identified in Chapter 4. Finally, DNDC could simulate with great precision the cycles of carbon and nitrogen that were endogenous variables identified in the scope of the stock-flow model.

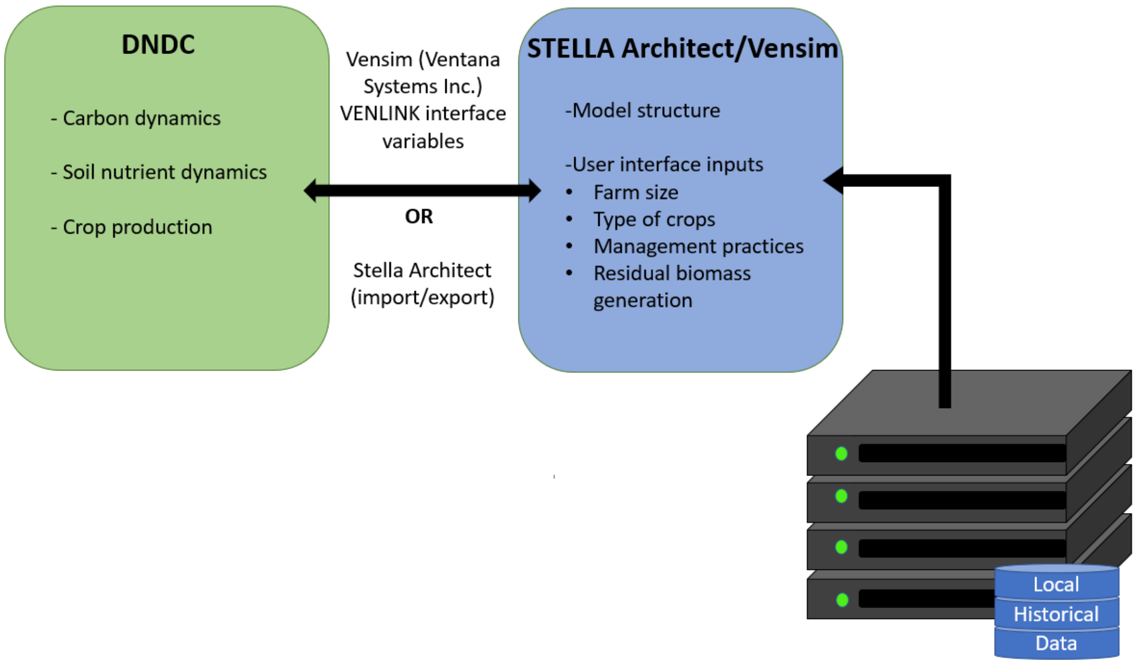

Figure 5.17. Visual representation of the proposed integration

V.10 Research Impact

- The paper presents a methodology for depicting critical components of small agricultural systems within a local context. Additionally, I developed an intuitive way to visualize the components, interactions, and feedback in small-scale agricultural systems to facilitate stakeholder understanding.

- Incorporating a stock and flow model with a process-based model provides end users (farmers, stakeholders, and extensionists) with an innovative method of analyzing different scenarios and impacts of influencing variables in a small-scale production system without incurring higher costs. A tool like this would facilitate the decision-making process for small farmers in rural areas of the tropics in order to accelerate their transition from conventional agricultural practices to more environmentally friendly ones.

- A successful implementation/adaptation of this methodology will provide the scientific community with the opportunity to develop tools that will facilitate the adoption of more sustainable and progressive agricultural systems through inclusive and participatory practices in the tropics.

V.11 Conclusions

This investigative work presents different products listed below: 1) a methodology for developing small-scale agriculture models according to the local context. An essential aspect of the methodology is the early involvement of the main actors (farmers, community leaders, and government representatives, amongst others). This level of participation is achieved through an inclusive stakeholder selection and analysis led by Roberto Forte (2020), described in Chapter IV. We also refer to the conceptual models developed by Roberto Forte (2020), also described in Chapter IV. The conceptual models resulted from a participatory process that implemented causal loop diagrams to identify the main components, interactions, and feedback of small-scale agricultural systems in this rural community in Panama. 2) With these critical elements in mind, we proceeded to structure a stock and flow model that allowed us to propose a novel way of comparing the sustainability of different small-scale farming systems, using as guide indicators that emerged from the qualitative study depicted in Chapter IV. The limitations of time and resources did not allow us to validate the model. However, it materializes the idea of putting end users such as farmers, stakeholders, and extension workers in the early stages of developing this tool. In addition, the model also served as an operational foundation for the user-friendly interface we proposed in this research. 3) An interface that seeks to promote the discussion of how to close the gap between the technicality and robustness of the well-known agricultural process-based models (DNDC, RothC, and CropSyst, amongst others) and the need for them to be accessible, practical and manageable for critical users in the transformation of the conventional and small-scale agricultural sectors towards sustainability.

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CHAPTER VI: **General Discussion and Recommendation for Future Research**

VI.1 A systematic review of the literature related to permaculture.

We conducted a systematic literature review of the term permaculture in three languages (Spanish, English, and French) in response to arguments from experts that permaculture lacks acceptance in the scientific community. A variety of tools and methods were used to evaluate the acceptance of these practices in the scientific community, including bibliometric analysis, qualitative content analysis, H-index, and citation counts. During our literature review, we consulted both white and gray literature published between 1905 and 2020. Our analysis shows a growing trend in the development of literature on the term permaculture since 2009. Additionally, our analysis reveals that most of the peer-reviewed literature related to permaculture is of a scientific and technical nature. Lastly, we conclude that renowned researchers are increasingly involved in publications on the concept of permaculture according to our H-index analysis.

There are many potential audiences that can benefit from this systematic literature review, as will be explained below.

- Institutes of permaculture research and education worldwide. It may be beneficial to them to contrast their understanding of the evolution of the term based on practice and case studies with the results of this research paper that examines the history of the permaculture concept and its evolution.
- Smallholder farmers and community leaders. This research provides a foundation and guide for understanding the conglomerate of literature (white and grey) developed around permaculture.
- Instructors in the field of permaculture. In this document, a rigorous and methodological analysis of the history and acceptance of the term is provided that can be included in their certification courses.

This systematic literature review can be updated and expanded in the future to other languages in which permaculture literature is developed, such as Portuguese and German. In order to determine whether the growth in white and gray literature related to permaculture is in response to the development of literature in specific fields of science or society in general, further analysis should be undertaken. A study of the acceptance of permaculture practices in a broader scientific community would require a different approach, such as a study of the "technical paradigm."

VI.2 Implementing causal loop diagrams in the early stages of a smallholder's participatory process.

In this manuscript, we have combined inclusive participatory processes with system dynamics tools such as CLDs and loop polarity analysis to identify and visualize the drivers and barriers associated with the development of small-scale agricultural systems. Additionally, the methodology facilitated the understanding of the relationships between the components of these small but complex agricultural systems. The participatory process in the field began just three weeks prior to the pandemic (COVID-19) and all of the chaos, mobility, and resource constraints it unleashed.

According to our initial plan (pre-pandemic), semi-structured interviews would be used to accomplish three objectives:

1) Validate, adapt, and confirm the stakeholder analysis results prior to the participatory process.
2) To identify the barriers and motivators for developing a small-scale farming system in the region among selected stakeholders.
3) Develop individual CLDs with each of the smallholders of the three selected farming systems in accordance with the recommendations made by the group of selected local stakeholders.

Upon completing semi-structured interviews, transcription and analysis, and the generation of individual CLDs, focus groups were planned to validate the results obtained from semi-structured interviews and conceptual models developed for the three systems visited. Moreover, our initial goal was to conduct 15-20 semi-structured interviews. However, due to the pandemic outbreak, we were only able to conduct 11 interviews. Mobility limitations and censorship of face-to-face group meetings forced us to eliminate the focus group component. Despite the reduction in the number of semi-structured interviews, the rigor of our methodology has not been compromised since we adhere to the replication and redundancy principles proposed by Marshall et al. (2013) and the saturation proposed by Thompson (2010).

Having to adapt our methodology at the last minute and carry out our research during times of great uncertainty resulted in the following biggest learnings:

1) Semi-structured interviews have significant potential in times of uncertainty, for the following reasons:
a) The use of open questions over closed ones reduces the influence of investigator criteria on data generation and collection. In addition, it allows the interviewee to freely express their knowledge and beliefs. When this type of process is conducted in groups, a person's willingness to share knowledge can be limited by psychological or emotional factors. This can also be limited by existing power relations between the participants. A number of meetings were conducted via digital means with stakeholders in order to validate the results of the participatory process as well as the concept maps.

b) While transcription of the data is a time-consuming process, the actual collection takes only a few minutes (30 - 60 minutes per interview). I conducted 11 interviews (seven before and four after mobility limitations were enforced in the country). After I had collected the data from the first seven interviews, I was able to analyze the data at my own pace, regardless of the chaos that was occurring at the time. Having access to the data discussed at the time, I was able to verify at any time that the conclusions I drew from the participatory process were consistent with those expressed by the interviewees.

The findings of this thesis will open up new avenues for research in small-scale agricultural systems. The field of system dynamics modeling could benefit from the development of more advanced and user-friendly open-access tools to build these models, as currently the best tools are restricted by the mandatory use of licensed software or packages that are too expensive for a resource-constrained stakeholder. The field of participatory modeling could be further advanced (a) by promoting the development of web-based models that allow traditionally marginalized stakeholders to access these tools from computers in community centers (b) there is a high rate of cell phone penetration in Panama, with an estimated 1.4 cell phones per person, which makes it an ideal place for the development of cellphone-based applications for small-scale agricultural systems (c) by developing offline collaboration technologies to facilitate use in areas with poor internet connectivity.

VI.3 A novel methodology to promote the discussion on the integration of agricultural process-based models with more accessible and easy-to-use tools.

It is the purpose of this manuscript to encourage the development of robust, yet accessible and user-friendly tools targeted specifically at smallholders in the tropics. In small but highly complex agricultural systems, our methodology demonstrated great potential in identifying and visualizing the various components and their interconnections. Additionally, it encourages the use of robust tools, such as process-based models, in conjunction with more user-friendly tools for the development of customized computational tools for small-scale agriculture.

An uncalibrated and highly simplified version of a crop production model is presented in this manuscript, which may be applied to small-scale farming systems. The model serves its purpose by providing a proposal for comparing the ecological sustainability of small-scale agricultural systems. There are, however, several opportunities for further advancement in this area. Below is a list of a few of them:

1) Based on the definition provided in chapter 1, we simplified the comparison of the sustainability of these systems from an ecological perspective. However, future studies should consider other aspects of the sustainability framework, such as financial and sociopolitical factors.

2) Integrating environmental, sociopolitical, and financial aspects into the model increases its complexity and lack of data, especially for socioeconomic factors. It is recommended that the integrated model be subjected to an uncertainty and sensitivity analysis in order to address this issue. A comprehensive review of the literature and interviews with interested parties are recommended to assign standard deviations to highly uncertain exogenous conditions model parameters.

3) A spatial mapping application, such as ArcGIS, could be integrated into the participatory model framework, allowing various demographic data sets to be integrated into a single system and, therefore, showing changes over time through policy maps.

4) There is considerable potential for integrating system dynamic models with process-based models. Nevertheless, simulating dynamic interactions between social, environmental, and economic factors is a complex undertaking. Future integration of these models with machine learning tools may prove to be an effective method for capturing complex interactions between components of small-scale farming systems.

CHAPTER VII: **Summary and Conclusions**

This thesis begins with two literature reviews in chapters 2 and 3. Chapter 2 presents a general literature review of agroecology's state of the art and delves into the term smallholder and its link in the literature with other terms, such as family farming. The second is a systematic literature review on Permaculture in three different languages (English, French, and Spanish). The primary purpose of this literature review was to analyze the term's evolution through time and its acceptance in the scientific community. After dwelling on the state-of-the-art of the most popular small-scale agroecological systems, our following approach was to propose methodologies for developing models that would allow the comparison of the ecological sustainability of these farming systems over time. We propose integrating system dynamic modeling (CLDs, and stock and flow models) with process-based models (such as DNDC, CENTURY, and RothC). For this, a participatory process with the interested parties of the region was planned. Stakeholders in the study area were classified based on their roles, power, attributes, and interest through stakeholder analysis. Potential actors (Ministry of Agricultural Development, farmers, community leaders, MIDA Rural Planning Directorate, among others) were contacted to carry out semi-structured interviews of an hour on average. We used ATLAS TI software to analyze each sentence of the interviews and thus identify the main components of agricultural systems, along with the barriers and motivations that hinder or encourage the development of these types of systems in the region. With this in-depth analysis of the transcripts and subsequent feedback via digital media (due to the COVID pandemic), CLDs were generated that captured local (demographic factors), ecological (system components and interactions), and agricultural (management practices and cropping patterns) details. The CLDs proved to be a resource with great potential, especially in times of limited mobility and challenges, such as limitations in stakeholder experience, financial resources, and availability of time for stakeholder engagement.

With the integration of these CLDs, three conceptual models were generated that were the foundation for the developed stock and flow model. Chapter 5 presents the structure of the stock and flow model. Submodules are created based on the information extracted from the participatory process. The submodules are linked to each other through feedback. For example, the submodules encompassed: a fraction of cultivated area, crop types, SOC turnover, nitrogen and phosphorus requirements, climate, and crop yield. All models are linked together, and sensitivity, structural and extreme behavior tests were run. Due to time and resource constraints, the model must be fully verified and validated. Therefore, the results obtained in scenarios A and B do not represent a small-scale agricultural system in the region and are, therefore, not predictive. Although the model is incomplete, its development process serves as a novel methodology for developing tools that enhance stakeholders' decision-making on the design of small-scale agricultural systems. Chapter 5 also proposed integrating tools such as Stella Architect or Vensim, traditionally used in developing system dynamics models with more rigorous and predictive such as process-based models (DNDC, RothC, CropSyst, CENTURY, among others). This integration seeks to integrate the robustness and precision of the process-based models with the user-friendly structures and interfaces of the system dynamic modeling tools. This way, tools for understanding and simulating small-scale farming systems can be generated, taking traditionally marginalized users (farmers, community leaders, and extension agents) into consideration in the early stages of designing these computational tools.

The conclusions of this thesis are described below based on the results achieved in chapters 3 to 5.

VII.1 Conclusion 1. Systematic literary review in three languages related to permaculture.
A systematic, rigorous, and detailed literary review was successfully carried out in three languages (English, Spanish and French). It took into consideration literature from all over the world. It evaluated the concepts associated with permaculture in 418 publications (peer-reviewed and non-peer-reviewed). The main objective of this bibliographic review was to evaluate the acceptance of the permaculture concept in the scientific community over time. Several methodologies were implemented to answer this question, including bibliometric and content analysis, H-index analysis, and citation counting. Below we listed the most relevant conclusions of this proposed methodology:

- Soil, agriculture, design, sustainability, and food terms have been associated with the permaculture concept over time. In comparison, the terms community, urban gardening, change, and movement have emerged in the last two decades.

- Permaculture is a concept whose interest continues to grow in all kinds of literature, including scientific and academic.

- The term permaculture continues to evolve and adapt to the new challenges posed by the degradation of natural resources and climate change.

- The permaculture concept, since its inception, has been associated with a set of agricultural-technical practices. However, its philosophical aspect began to emerge in the 2000s and shows a general growth trend.

- The permaculture concept is gradually becoming a scientific discipline, attracting the attention of internationally recognized groups of scientists.

VII.2 Conclusion 2. Implementation of CLDs in stakeholders' participatory processes for the development and greater acceptance of small-scale agricultural system dynamics models.

The participatory process began with a list of more than 20 potential stakeholders (local farmers, experts, local government, national government, and NGOs, among others). Through conversations with members of the community and as the interviews were carried out, the list was adapted. The final list of stakeholders is achieved through a stakeholder analysis process based on role, power, interest and attributes. In total, 11 semi-structured interviews with stakeholders were conducted. It should be noted that the COVID pandemic and the extreme mobility limitations in Panama began when we were still collecting data in the field. Hence the pandemic considerably influenced the number of interviews completed. Through an exhaustive analysis of the transcripts of the recordings (both in English and Spanish), concept maps were developed with the help of CLDs, for three small-scale agricultural systems in the region. Subsequently, meetings were held with most of the interviewees through digital means (due to all kinds of limitations resulting from the pandemic) to receive feedback on the CLDs generated.

Based on the results of this study, the following conclusions were drawn:

- The use of semi-structured interviews combined with computer-aided qualitative data analysis software (ATLAS TI) for generating concept maps in times of limited mobility (pandemic) has excellent potential.

- The participatory process made it possible to understand the barriers and motivators that hinder or encourage the development of these agricultural systems in the Mariato community.

- CLDs have proven to be successful, practical, and straightforward for stakeholders when addressing complex problems related to small-scale farming systems components.

- Including stakeholders from different economic or socio-political sectors allowed the concept maps to be multi-dimensional. This approach provided advantages over one-dimensional approaches.

- The loop polarity analysis indicated that the most significant variables influencing the system's ecological sustainability were total production, regenerative practices, and soil quality.

- Most stakeholders suggested that using inorganic fertilizers in the early stages of the agricultural system is necessary. Similarly, stakeholders agree that prolonged use of inorganic fertilizers can have legacy effects on crops.

VII.3 Conclusion 3. Stock and flow and process-based model integration proposal to compare the ecological sustainability of small-scale agricultural systems.

Based on the conceptual maps developed in Chapter 4, through the combination of a participatory process, qualitative analysis in ATLAS TI, and CLDs loop polarity analysis, a system dynamics model (stock and flow) is developed. The results of Chapter 4 illustrate the main components of the small-scale farming systems studied in the local context and the most relevant indicators for stakeholders in the study region. The stock and flow model comprised four sections (Initiation/recycling of biomass, SOC turnover, potential crop production, and final yield estimation influenced by climatic factors). With this model, a methodology was proposed for comparing the ecological sustainability of small-scale agricultural systems based on indicators arising from a participatory process in the community of Mariato in Panama. Due to time and resource constraints, the model could not be fully verified or validated. Hence, its results are not aimed to be predictive, nor do they represent the performance of a small-scale farming system in the area. However, this model materializes a methodology for comparing small-scale agricultural systems based on meaningful indicators for the community under study.

Chapter 5 also proposes integrating dynamic system models with more robust and predictive models, such as process-based models. All this is with the idea of promoting discussion on the development of accurate and user-friendly predictive tools in line with the technological needs of the smallholder sector in tropical areas. Chapter 5 shows the great potential of system dynamic model tools such as Stella Architect and Vensim to facilitate the handling of models that seek to simulate the dynamics of small-scale agricultural systems. One of the strengths of this type of tool is its ability to generate a user-friendly interface that can even be organized based on the type of user (farmer, community leader, or expert) or the type of parameters (soil, climate, geospatial, and crop types, among others). Finally, Chapter 5 proposes ways to integrate tools such as Vensim and Stella Architect with process-based models widely used in the agricultural sector, such as DNDC, RothC, and CropSyst.