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Spatio-temporal modeling of land use competition in small islands through a Water-Energy-Food nexus approach

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Résumé

Les défis environnementaux et intersectoriels auxquels sont confrontées les petites îles exigent une attention particulière à la gestion des utilisations multiples des ressources. Ces défis impliquent, en particulier, la nécessité d'une résilience accrue dans des secteurs spécifiques, en soutenant l'utilisation des ressources locales afin de réduire la dépendance de ces territoires aux ressources extérieures. De plus, les petites îles font face à des pressions démographiques qui entraînent des pressions liées à l'utilisation des terres. Ensemble, ces facteurs créent des impacts imbriqués sur l'utilisation des terres, soulignant ainsi la nécessité d'une approche holistique.

Dans cette thèse, nous proposons une approche qui prend en compte et exploite les interdépendances entre les différentes utilisations des ressources. Nous nous concentrons sur les ressources en eau, en énergie et en alimentation dans le cadre du nexus Eau-Énergie-Alimentation, avec un accent particulier sur l'évaluation de la compétition pour l'utilisation des terres liée à l'utilisation des ressources locales et au développement urbain.

Notre approche consiste, dans un premier temps, à produire des scénarios holistiques qui intègrent les dynamiques de développement urbain, les pratiques agricoles, la production d'électricité à partir de diverses sources d'énergie et les habitudes alimentaires de la population sur l'île. Ces scénarios holistiques sont façonnés par des données qualitatives et quantitatives recueillies à partir d'entretiens terrain et à l'aide de la littérature existante.

Nos contributions se concentrent sur l'amélioration de la résilience du système alimentaire dans les petites îles en identifiant les seuils multidimensionnels liés à l'autonomie alimentaire. L'identification de ces contributions souligne la nécessité de développer un système d'aide à la décision afin de : (1) gérer efficacement les terres agricoles ; (2) planifier le développement urbain ; (3) encourager les changements liés aux habitudes alimentaires ; et (4) mettre en place des politiques visant à minimiser l'empreinte foncière de la production d'électricité.

Nous avons développé un modèle générique qui combine Système d'Information Géographique (SIG) avec un modèle d'optimisation robuste. Nous utilisons Ocelet, un langage de modélisation conçu pour simuler les dynamiques de changement d'utilisation des terres, qui est intégré dans notre modèle intégré. Notre modèle fonctionne comme un outil d'analyse spatiale, facilitant l'identification des parcelles optimales pour le développement urbain ainsi que des zones potentielles pour la production agricole et électrique. De plus, il fournit des projections à moyen terme concernant les impacts des scénarios holistiques sur la production agricole et électrique à l'échelle de l'île. Ainsi, il sert de système d'aide à la décision pertinent pour les parties prenantes à différents niveaux.

Nos résultats sur l'île de La Réunion soulignent l'importance de la conservation des terres en valorisant les ressources locales grâce à des politiques efficaces de gestion de l'utilisation des terres, combinées à des pratiques agricoles alternatives. De plus, les résultats mettent en évidence l'importance de modifier les habitudes alimentaires ainsi que la nécessité d'une planification urbaine territoriale, préconisant la densification des zones urbaines afin de promouvoir l'utilisation de ressources locales.

Mot clés: Nexus Eau-Énergie-Alimentation, Compétition pour l'utilisation des terres, Système d'Information Géographique, Optimisation Robuste, Scénarios holistiques

Abstract

The environmental and cross-sectoral challenges faced by small islands call for careful attention to the management of multiple resource uses. These challenges involve, in particular, the necessity for increased system resilience, supporting the uses of local resources to reduce the islands' dependency on external sources. Additionally, small islands face demographic pressures that lead to land use issues, exacerbated by their spatial constraints. Together, these factors create intertwined impacts on land use, underscoring the need for a holistic approach.

In this thesis, we propose a systemic approach that considers and leverages the dependencies among the uses of multiple resources. We focus on the water, energy, and food resources within the Water-Energy-Food (WEF) nexus framework, with a specific emphasis on assessing land use competition driven by the uses of local resources and urban development.

Our approach consists, first, of producing comprehensive scenarios that incorporate urban development dynamics, agricultural practices, electricity production sources, and the dietary behaviors of the island's population, all shaped by qualitative and quantitative data collected from field interviews and existing literature.

Our contributions focus on enhancing food system resilience in small islands by identifying multidimensional thresholds related to food self-sufficiency, resulting from land use competition between the uses of local WEF resources and urban development. The identification of these contributions underscores the need to develop a decision support system in order to: (1) manage agricultural lands efficiently; (2) plan urban development; (3) encourage shifts in dietary behaviors; and (4) implement policies for minimizing the land footprint of electricity production.

We developed a generic model that combines Geographic Information System (GIS) with robust optimization model. We make use of *Ocelet*, a modeling language designed for simulating the dynamics of land use change, which is incorporated into our integrated model. Our proposed model functions as a spatial analysis tool, facilitating the identification of optimal parcels for urban development as well as potential areas for electricity and agricultural production. Additionally, it provides medium-term projections regarding the impacts of comprehensive scenarios on electricity and agricultural production at the island scale. As such, it serves as a relevant decision support system for stakeholders at various levels.

Our findings on Reunion Island highlight the importance of conserving land by valuing local resources through efficient policies on land use management, coupled with shifts in agricultural practices. Furthermore, the results underscore the importance of shifting dietary behaviors as well as the need for territorial urban planning, advocating for the densification of urban areas to promote the uses of local WEF resources.

Keywords: Water-Energy-Food nexus, Land Use Competition, Geographic Information System, Robust Optimization, Comprehensive Scenarios

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CHAPTER 1

Introduction

1.1 Global context

Small islands are grappling with a diverse range of challenges, many of which are exacerbated by climate change. For instance, sea levels are projected to rise by 0.61–1.10 meters by 2100 if global greenhouse gas emissions are not mitigated (IPCC, 2019). This rising sea level, coupled with increasing coast erosion —intensified by both climate change and the pressures of tourism-driven coastal development— poses a substantial threat to these territories. Additional vulnerabilities include water scarcity, land resource depletion, fragile biodiversity, and challenges in waste management (IPCC, 2022). These compounded vulnerabilities underscore an urgent need for efficient management of resource uses (Batra and Norheim, 2022). In response, several studies have explored the interactions between multiple resource uses to improve management practices. One widely adopted approach is the Water-Energy-Food (WEF) nexus, which examines the interconnections between water, energy, and food. For small islands, this holistic approach highlights land use management as a key element in optimizing the uses of local resources (Lin et al., 2019) (Russeil et al., 2023). Land use management becomes even more crucial given the significant impact of urban growth in these territories (UN, 2015). Consequently, this thesis focuses on land use competition in small islands, examining how multiple resource uses and urban development compete for limited space. Given the challenges of managing the uses of WEF resources in spatially constrained areas, this thesis aims to enhance food system resilience by identifying multidimensional thresholds related to food self-sufficiency, with a specific focus on Reunion Island, a French overseas department. This focus aligns with the French government's goal of achieving food and energy self-sufficiency for its overseas departments and regions by 2030 (CIRAD-AFD, 2021) (ADEME, 2021).

1.2 Problem, challenges, and objectives

In this thesis, which aims to enhance the food system resilience in small island territories, it is essential to develop a modeling approach tailored to the unique characteristics of these regions. This approach must ensure the reproducibility of results and facilitate the articulation of the interconnected uses of multiple resources.

Given the context of land use competition among the uses of WEF resources and urban

development, the primary challenge lies in effectively modeling this competition between various potential land uses. This involves determining the optimal land use(s) for a given parcel, from among all its potential land uses related to electricity production, crop production, and urban development. To address this, a spatio-temporal model must be developed to process and integrate a large set of heterogeneous, context-specific data from multiple sources. The model must handle diverse data types, including population and resource demand projections, with the appropriate time window chosen between short- and long-term projections. Additionally, spatial data, as well as both qualitative and quantitative data, need to be effectively integrated. Efficiently managing these multi-source data sets and ensuring communication between them within a generic model is essential. This requires developing a robust framework capable of handling data integration across different stages of the model. Furthermore, the model must address key questions, such as: (1) Which conditions must a parcel meet to be assigned potential land use(s) as defined in our approach ? (2) How can the optimal land use(s) for a parcel be determined from its potential land uses ? The model must also facilitate the incorporation of various scenarios, shaped by quantitative and qualitative data.

The objective of this thesis is to propose a thematic and methodological framework that serves as a decision support system for stakeholders (specified in Chapter 3). By adopting a systemic approach and building a generic model, the motivation is to provide stakeholders with valuable insights and practical solutions for comprehensively addressing issues related to food system resilience, particularly in the realm of land use management.

In summary, within the context of systemic modeling, the objective is to formulate an exhaustive methodology integrating heterogeneous data collection, constraint specification, and optimization modules to generate insightful scenarios that support food system resilience and offer actionable recommendations for local governance.

1.3 Contributions

The contributions of this thesis stem from a critical analysis of the existing scientific literature, highlighting both the strengths and limitations of existing WEF nexus modeling approaches, particularly regarding land use competition in small islands. As a result, these contributions are outlined in direct relation to the existing body of research. The first contribution relates to the exploration angle of food system resilience.

Contribution 1: We explore food system resilience in small islands by identifying multi-dimensional thresholds related to food self-sufficiency resulting from land use competition between the uses of local WEF resources and urban development.

The second contribution refers to the methodological approach implemented to model land use competition and identify these thresholds. It requires the design of an integrated modeling framework tailored to achieve these objectives.

Contribution 2: We develop an integrated model using a GIS-based model combined with an optimization model, incorporating a wide range of data and constraints specific to the nexus in small islands. A key component of this approach is the incorporation of the *Ocelet* modeling tool, which is specifically used to simulate the dynamics of land use change in order to effectively model land use competition.

Lastly, comprehensive scenarios are designed to assist stakeholders in exploring multiple

future trajectories related to urban development, dietary behaviors, agricultural practices, and electricity production. This leads to the third major contribution:

Contribution 3: We build comprehensive scenarios that account for urban development dynamics, dietary behaviors, agricultural practices, and electricity production sources. Tailored specifically for Reunion Island, these scenarios integrate both qualitative and quantitative data gathered obtained from field interviews and an extensive review of existing literature. They are incorporated into the integrated model, offering a holistic perspective on their combined effects on electricity and crop production.

The identification of these contributions underscores the need to develop a decision support system tailored in order to: (1) manage agricultural lands efficiently, (2) plan urban development, (3) encourage shifts in dietary behaviors, and (4) implement policies for minimizing the land footprint of electricity production. By constructing insightful scenarios, this tool is designed to facilitate informed decision-making.

Figure 1.1 illustrates the flow chart of our decision support system, which is informed by the comprehensive scenarios.

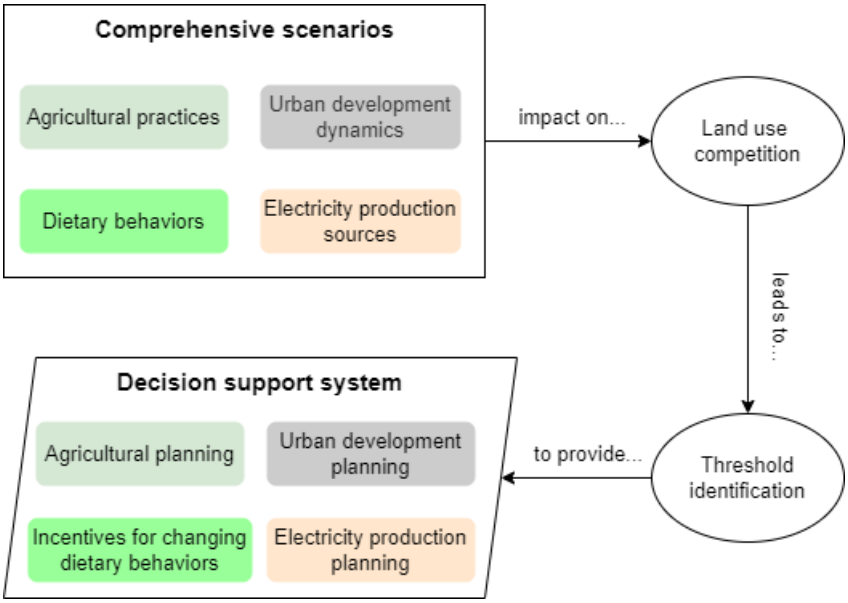


Figure 1.1: Structure of the decision support system.

1.4 Thesis plan

The manuscript is structured as follows:

- **Chapter 2**: This chapter offers an overview of the resilience challenges faced by small islands and reviews relevant literature. It outlines the vulnerabilities of small islands, emphasizing the importance of addressing food system resilience through a systemic approach.
- **Chapter 3**: This chapter outlines the methodology designed to enhance food system resilience, which integrates a generic modeling framework that combines a GIS-based model with an optimization model. This integrated modeling framework is designed to identify multidimensional thresholds related to food self-sufficiency resulting from land use competition, under various comprehensive scenarios.

- **Chapter 4**: In this chapter, the generic methodology is applied to the specific of case of Reunion Island. This chapter examines the island's territorial characteristics, outlines the methodology for scenario production, specifies multi-source data, and presents the main results, providing decision support elements for informed policy implementation.
- **Chapter 5**: This concluding chapter summarizes the key findings of the research and outlines further developments and future work.

1.5 Publications

- Influence of electricity production sources and agricultural practices on the food SSR:

  Romain Authier, Benjamin Pillot, Guillaume Guimbretière, Pablo Corral-Broto, and Carmen Gervet. A Water-Energy-Food Nexus Approach to Assess Land Use Trade-Offs in Small Islands. In: *Proceedings of the 10th International Conference on Geographical Information Systems Theory, Applications and Management*, 2024.
  DOI: 10.5220/0012556900003696

- Influence of dietary behaviors on the food SSR and agricultural land distribution:

  Romain Authier, Benjamin Pillot, Guillaume Guimbretière, Pablo Corral-Broto, and Carmen Gervet. Towards sustainable land management in small islands: a Water-Energy-Food nexus approach. In: *PLOS ONE*, 2024.
  DOI: https://doi.org/10.1371/journal.pone.0310632

- Influence of urban planning scenarios on the food SSR, electricity production, and the location of future urban areas:

  Romain Authier, Benjamin Pillot, Guillaume Guimbretière, Pablo Corral-Broto, and Carmen Gervet. Land Use Optimization in Small Islands: A Water-Energy-Food Nexus Approach. In: *Communications in Computer and Information Science*, 2024. **Accepted**.

- Publication of a "Sustainability Science References" fact sheet:

  Romain Authier, Benjamin Pillot, Guillaume Guimbretière, Pablo Corral-Broto, and Carmen Gervet. Le nexus Eau-Énergie-Alimentation dans les petites îles. In: *Science de la durabilité, comprendre, co-construire, transformer*, 2023. `https://www.ird.fr/sites/ird_fr/files/2023-10/FicheSciDur_Authier_87.pdf`

CHAPTER 2

Related work and thematic context

The geographical isolation and small size of small islands make them heavily reliant on imports, and then vulnerable to external supply disruptions (Ghina, 2003). While international trade remains important, strengthening local systems across multiple sectors has become essential for these isolated territories (Talubo et al., 2022). However, given the fragility of ecosystems in small islands, efforts to support local systems must avoid land use changes that could make them even more vulnerable, such as the conversion of protected natural areas (Ortiz et al., 2023). In that regard, tackling this challenge requires a systemic approach that assesses how the valorization of local resources affects the dynamics of land use change.

2.1 An overview of small island territories

Small islands territories exemplify the intricate challenges stemming from various vulnerabilities and their wide-ranging implications across environmental, social, and economic domains (Purvis et al., 2019). In that regard, small islands offer a valuable case study for analyzing the preservation challenges faced by territories under multiple constraints -especially geographic ones- particularly in light of the current social and ecological situation.

2.1.1 Representing small islands: insights from doughnut theory

The impact of various human activities on climate change has been firmly established through numerous scientific works, notably by the Intergovernmental Panel on Climate Change (IPCC), which aggregates and synthesizes all relevant scientific knowledge on this phenomenon. Besides, awareness of the impacts of these human activities on environmental systems has led to the formulation of Sustainable Development Goals (SDGs) (UN, 2015). Among the deterioration to different environmental systems and ecosystems induced by these human activities are adverse impacts on water availability, food production, health and well-being, cities, settlements, and infrastructure, as well as observed changes in biodiversity and ecosystems (IPCC, 2023). In particular, over-exploitation of natural resources can result in ecosystem fragility due to excessive consumption and related production, use of fossil fuels, and the high environmental footprint associated with the uses of resources (Amer et al., 2024). In particular, the past 50 years have witnessed massive extraction of natural resources related to infrastructure development worldwide and high levels of material consumption,

especially in upper-middle and high-income countries. Indeed, there has been an increase in the extraction of natural resources, particularly in high-income countries that use six times more resources and seem to generate ten times the climate impacts compared to low-income countries (UN, 2024). These socio-economic disparities underscore the importance of addressing basic human needs through the use of natural resources within the framework of greater **social justice**, while ensuring environmental preservation (Deldrève et al., 2021).

Definition 1 ***Social justice*** *refers to "the equality of rights for all peoples and the possibility for all human beings, without discrimination, to benefit from economic and social progress worldwide" (UN, 2023).*

In this regard, our planet can be characterized by boundaries corresponding to different ecological limits resulting from the exploitation of natural resources and intense economic activity, as well as boundaries reflecting the level of social justice. These ecological and social boundaries refer to limits beyond which the SDGs cannot be met (UN, 2015). This theoretical framework was formalized by Kate Raworth, an economist at the University of Oxford, providing a visualization known as the "doughnut" theory as illustrated in Figure 2.1 (Raworth, 2018).

In this representation, we have the definition of inner boundaries (the foundation) and outer boundaries (the ceiling) determined respectively by social and ecological foundations, with these foundations resting on 9 ecological indicators and 12 social indicators. This doughnut theory aims to be particularly structuring and systemic by questioning how population needs are met, at what ecological and social cost, i.e., whether there is an overshoot in the ecological ceiling or a shortfall in the social foundation while meeting people's needs. Within this framework, addressing the growing human needs must focus on inspecting production practices to ensure ecological preservation and foster social justice.

This approach is particularly well-suited to small islands, as their geographical isolation make them akin to small-scale planets. By integrating multiple resources -such as water, energy, and food (the social foundation)- this approach provides a systemic understanding of the significance of interconnections within isolated territories. It also emphasizes the challenges and multi-sector vulnerabilities these regions face, offering insights that can subsequently be applied on a larger scale.

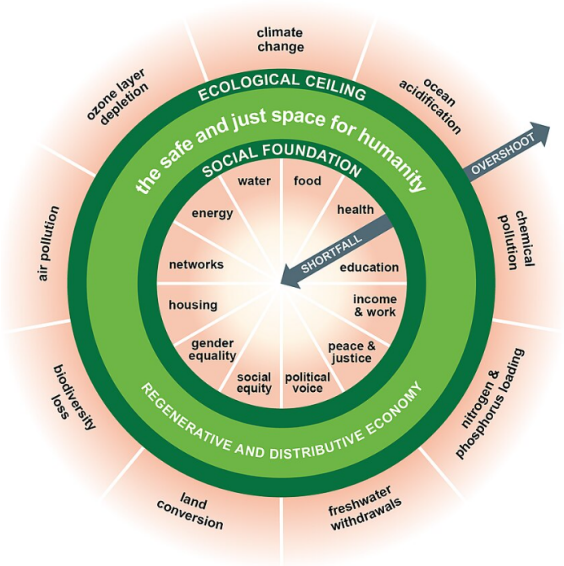


Figure 2.1: The doughnut theory (Raworth, 2018).

2.1.2 Multi-sector vulnerabilities

Small islands, defined as territories surrounded by water, with a small surface area and limited resources, are characterized by strong economic, climatic and demographic vulnerabilities (IPCC, 2022). More precisely, small islands face significant environmental issues, including land fragility and biodiversity loss. These issues are largely due to their geographical isolation, exposure to natural hazards, and pressures from human activity (Scandurra et al., 2018). In addition, these islands present a great vulnerability to climate change. In particular, small islands face critical challenges from sea level rise and coastal flooding. According to the IPCC, under a Representative Concentration Pathway (RCP) 4.5 scenario —an intermediate scenario for the reduction of greenhouse gas emission— a significant number of small islands are projected to experience coastal flooding. In some cases, over 50 % of the population on these islands could be affected, as illustrated in Figure 2.2 (IPCC, 2022).

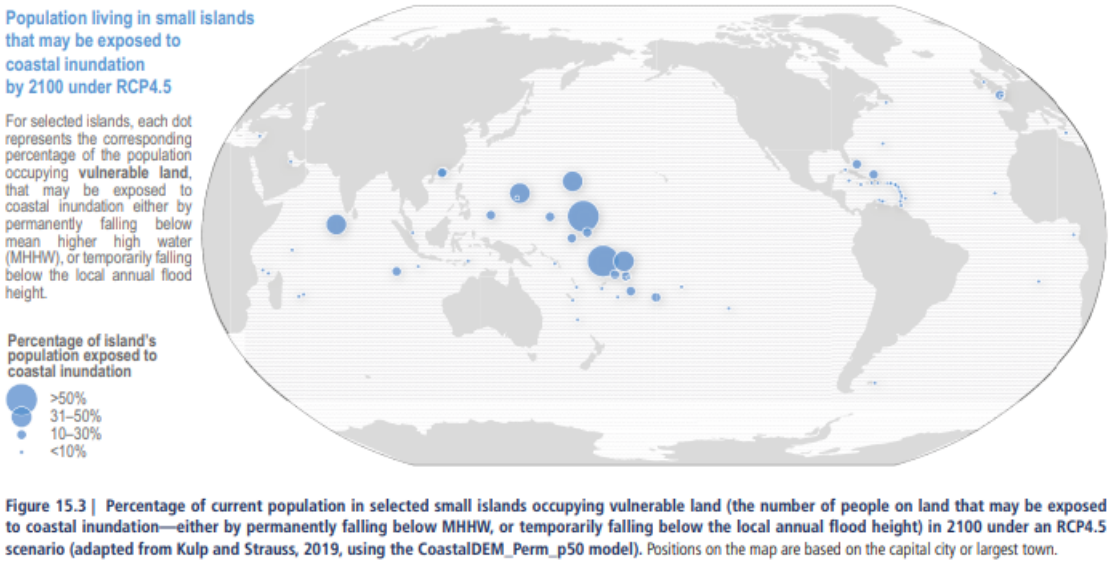


Figure 15.3 | Percentage of current population in selected small islands occupying vulnerable land (the number of people on land that may be exposed to coastal inundation—either by permanently falling below MHHW, or temporarily falling below the local annual flood height) in 2100 under an RCP4.5 scenario (adapted from Kulp and Strauss, 2019, using the CoastalDEM_Perm_p50 model). Positions on the map are based on the capital city or largest town.

Figure 2.2: Percentage of current population in selected small islands occupying vulnerable land in 2100 under an RCP 4.5 scenario (IPCC, 2022).

Furthermore, these territories are characterized by energy vulnerabilities, through their dependence on fossil fuel imports, leading to greater exposure to any economic disruption such as rising energy prices or supply shortages (Genave et al., 2020), food vulnerabilities with high dependence on food imports (Teng, 2020) and land vulnerabilities due to biophysical, socio-economic and demographic factors (Birch-Thomsen et al., 2010). Indeed, due to significant territorial constraints, land use management represents a major challenge for these islands, where preserving natural spaces is essential, especially in the context of demographic growth (Noda et al., 2019).

Besides, small islands are highly dependent on international trade (imports and exports) (Julca and Paddison, 2010). Notably, most small island economies exhibit substantial trade deficits, with tourism serving as a primary export sector, while imports predominantly consist of food, oil, and other essential commodities. Since 2000, these economies collectively have consistently maintained trade deficits 2–3 times higher than the median of developing countries, as illustrated in Figure 2.3. While tourism exports are highly vulnerable to fluctuations and economic downturns in developed nations, the demand for imports in many small island economies remains relatively inflexible. This is especially true in economies that depend heavily on importing food, oil, and other essential goods. In fact, food imports alone account for over 15 % of total merchandise imports in many small island economies, which

is double the international average. Moreover, tourism significantly drives the demand for food and oil imports in these economies, meaning that global travel restrictions can lead to decline in imports. Nevertheless, disruptions in global food production and supply chains could result in heightened food price inflation for many small island economies (UN, 2020). Therefore, reducing reliance on imports is crucial for mitigating vulnerability to external disruptions or shocks.

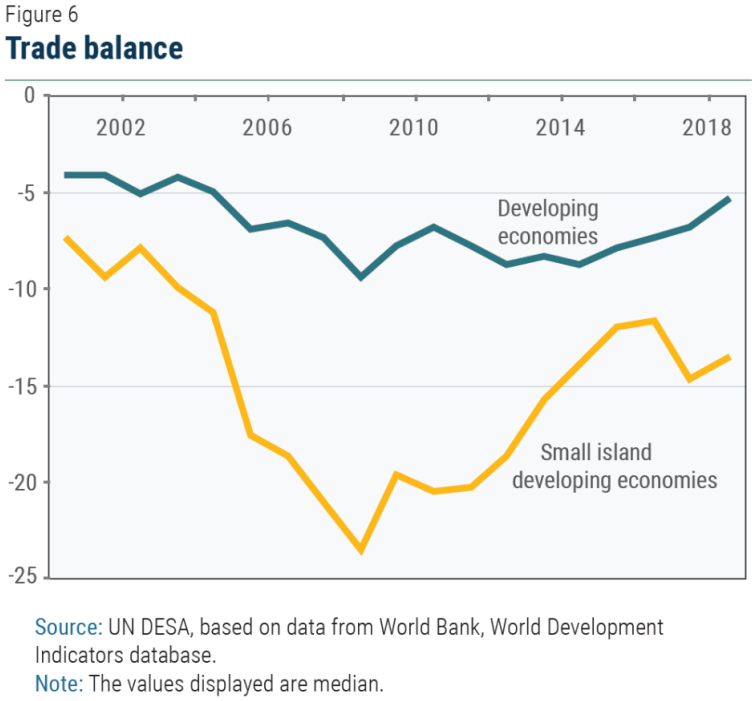


Figure 2.3: Trade balance (UN, 2020).

These vulnerabilities, unique to the island context, underscore the need to introduce the concept of **system resilience** specifically for small island territories.

2.1.3 System resilience in small islands

Definition 2 ***System resilience*** *is the ability of a system to "anticipate, reduce, accommodate, or recover from the effects of a hazardous event or trend in a timely and efficient manner" (IPCC, 2014).*

The need for enhanced system resilience in small island territories is underscored by their vulnerability to external shocks, such as the COVID-19 pandemic and subsequent border closures (Foley et al., 2022), the effects of climate change on international trade (Jones and Olken, 2010), and international conflicts that disrupt exports (Krpec and Hodulak, 2019). While the goal is not to sever international trade ties, it is crucial to strengthen resilience against these extreme events and ensure the ecological preservation of these territories. This specifically entails supporting the use of local resources (Kim et al., 2015), particularly in the food and energy sectors (Guell et al., 2022) (Weir and Kumar, 2020). Nevertheless, particular attention must be given to land use management, especially when maximizing the uses of local resources in these spatially constrained territories (Samara et al., 2015).

In this context of spatial constraints, Figures 2.4a and 2.4b illustrate the levels of resilience in the food and energy sectors in terms of dependence on resource imports and their impact on **land use competition**.

Definition 3 ***Land use competition*** *refers to the competing demands for limited land, where multiple uses —such as agriculture, housing, or electricity production— contend for limited space, creating conflicts over how land should be allocated.*

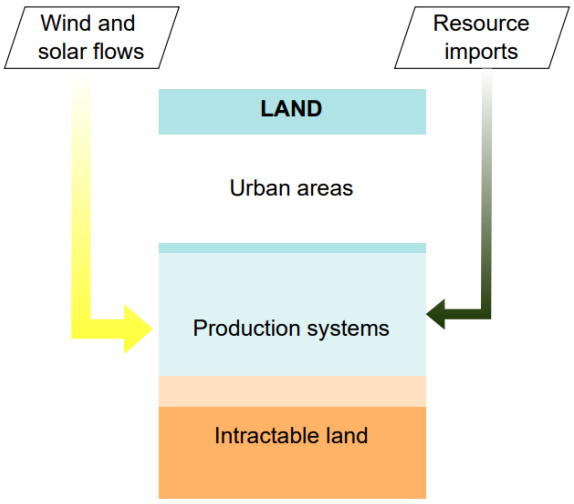
The *Production systems* block reflects the **land footprint** associated with the uses of food and energy resources, such as electricity production and agricultural production.

Definition 4 *In our approach, the* ***land footprint*** *of a production system refer to the amount of land required to support it.*

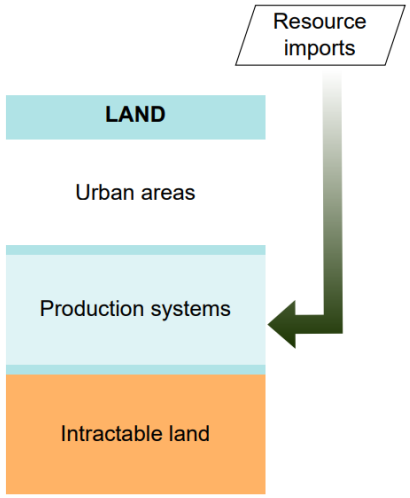
The *Urban areas* block represents the land footprint of urban areas, while the *Intractable land* component denotes protected natural areas that cannot be converted to other uses. Land footprint levels are represented by the size of the rectangles. Figure 2.4a illustrates that enhancing resilience in the food and energy sectors by reducing dependence on resources imports may require significant land resources. This is especially true for electricity production using **intermittent Renewable Energy Sources** (RES) like wind and solar, which rely on land-intensive technologies such as wind turbines and ground-mounted photovoltaic (PV) systems (Trainor et al., 2016).

Definition 5 ***Intermittent Renewable Energy Sources*** *(RES) refer to renewable energy sources that are intermittent in nature, meaning they are highly variable and less predictable (Poncelet et al., 2016).*

Regarding food production, increased land pressure arises from developing subsistence farming to reduce reliance on food imports. This demonstrates that without careful land use planning, efforts to boost resilience in specific systems could significantly increase the land footprint of production systems, potentially encroaching on *Intractable land*. Conversely, as shown in Figure 2.4b, reliance on imports can alleviate land pressure. For instance, importing food can free up agricultural land for other uses. Likewise, the land footprint of electricity production systems is reduced when relying on imported fossil fuels like coal and oil (Trainor et al., 2016).



(a) Highly resilient in terms of resource imports.



(b) Weakly resilient in terms of resource imports.

Figure 2.4: Degrees of food and energy system resilience in terms of resource imports.

In brief, while addressing resilience challenges is crucial in small islands, it raises the question: what could be the implications on land use ? It requires a thorough understanding of the interconnections between resource uses and their combined impacts on land use. However, taking into account all the possible interactions between resource uses and ecosystems from a modeling perspective is a task that can only be approximated. Given the objectives of this thesis, setting priorities is necessary. Therefore, we focus on examining the Water-Energy-Food (WEF) nexus.

2.2 The Water-Energy-Food nexus

Food, energy, and water are intricately linked, a relationship referred to as the nexus, which denotes the connections between two or more sectors. This framework encompasses interactions such as water-energy, energy-food, food-water, and food-energy-water (Lotfi et al., 2020). Figure 2.5 provides an overview of the main interactions between the uses of these resources.

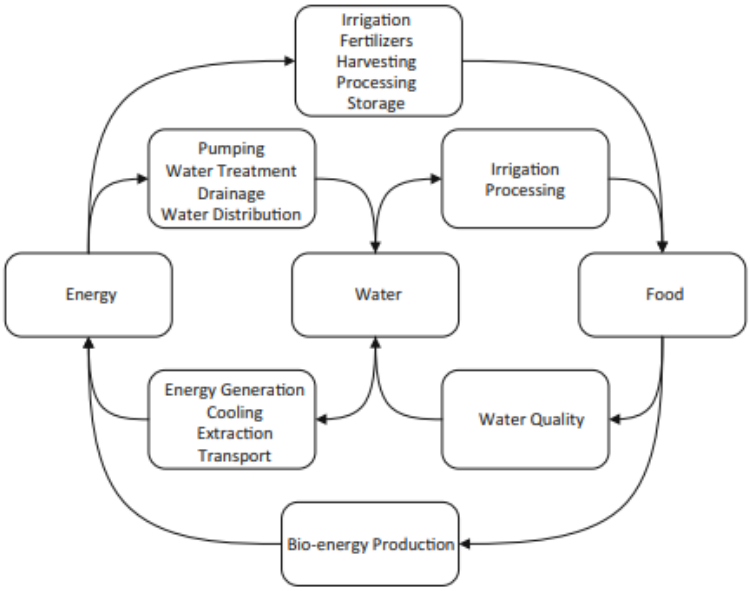


Figure 2.5: Interconnections within the WEF Nexus (Lotfi et al., 2020).

The WEF nexus analysis delves into the synergies, trade-offs, and potential conflicts that arise from the multiple uses of natural resources. This holistic approach provides a foundation for integrated management strategies, aligning with key SDGs (Lalawmpuii and Rai, 2023) (Herrera-Franco et al., 2023). In small islands contexts, the nexus approach's relevance is demonstrated by the nexus impact on the dynamics of land use change (Lin et al., 2019) (Russeil et al., 2023). Indeed, poor management of resource uses within the WEF nexus can result in adverse consequences for agricultural, natural and protected areas, and urban areas. Furthermore, supported by extensive literature across various geographical scales, the WEF nexus is more accessible compared to other nexus approaches.

2.2.1 The balance of resource uses under human-driven factors

Interest in studying the interconnections among food, energy, and water within the WEF nexus is growing, particularly in light of constraints such as climate change, demographic growth, and urban development, which intensify competition for the uses of these resources

(Lotfi et al., 2020). Indeed, external factors influence the demand for resources (Reinhard et al., 2017), as illustrated in Figure 2.6. Specifically:

- Increased energy demand in residential and transport sectors is directly linked to urban growth and infrastructure development. Economic growth can also lead to a rise in overall electricity demand (Zhao et al., 2023).
- Rising water demand is driven by demographic growth and urban development dynamics (Heidari et al., 2021). Specifically, (He et al., 2021) examined water scarcity under different scenarios of demand and demographic growth up to 2050.
- Demographic growth and rising household incomes are key factors influencing food demand (Van Dijk et al., 2021).

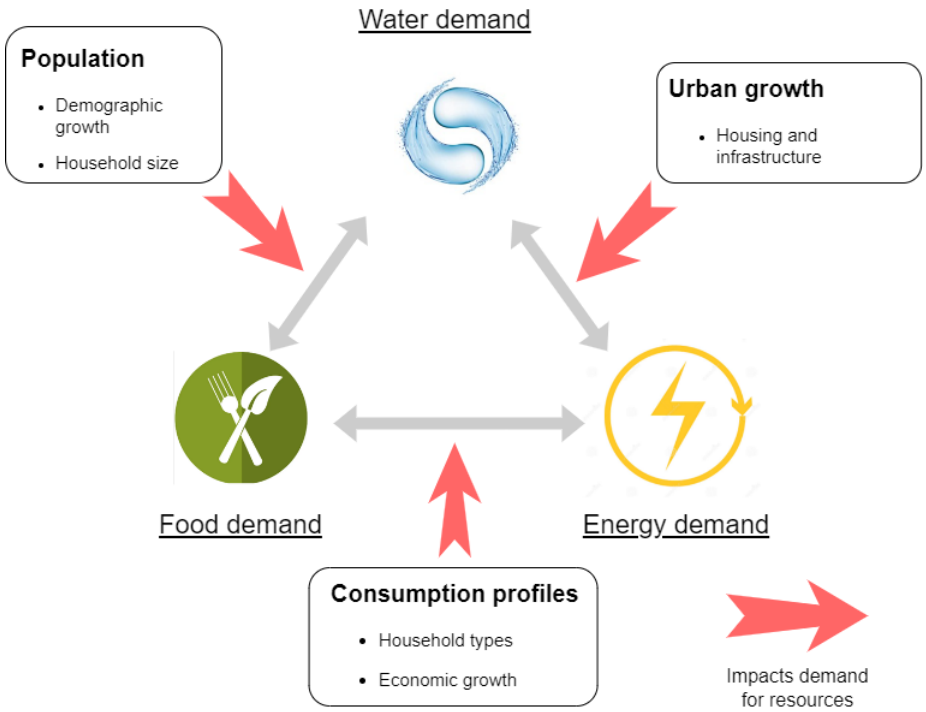


Figure 2.6: Impacts of human-driven factors on the demand for WEF resources. Adapted from (Reinhard et al., 2017).

Furthermore, understanding the impacts of land use changes on resource uses is essential (Wolde et al., 2021). Demographic growth can increase variability in water, energy, and food availability, making ongoing land use changes a potential threat to the uses of water and energy resources, and possibly affecting future food supply. Conversely, the uses of WEF resources can also influence land use changes, particularly through land suitability criteria for food and energy production (Keson et al., 2023). This includes selecting optimal areas based on factors such as water and energy consumption to identify suitable locations for food crop cultivation (Azzam et al., 2023).

The complex interactions within the WEF nexus, combined with the impact of human-driven factors on resource uses, has fostered scientific literature. Research, conducted at various geographical scales, has yielded a wide range of findings.

2.2.2 An overview of existing literature

Various hypotheses and scenarios are employed to model interactions within the nexus, with choices tailored to the study's objectives and the geographical scale of the research. By nature, modeling is an abstraction of reality, requiring decisions about approximations, computational feasibility, and the availability of data, whether real or simulated.

At the world scale, the study by (Asghar et al., 2020) examines key challenges in managing WEF resource uses. It reviews waste management practices and identifies crisis related to resource scarcity, while also proposing solutions to address declining availability and accessibility. On the same scale, the study conducted by (Van Vuuren et al., 2019) presents a set of scenarios to explore the interactions between land, energy, and water, as well as their impacts on greenhouse gas emissions and land use. This research employs a combination of two **Integrated Assessment Models** (IAMs) to examine the interlinkages within the nexus domains.

Definition 6 ***Integrated Assessment Models*** *(IAMs) are in essence "computer simulations that represent complex interactions and feedbacks on a long time scale between the socioeconomic system (including climate policies) and the natural system, which are explicitly designed to inform climate policy-making" (Van Vuuren et al., 2011) (Parson and Fisher-Vanden, 1997).*

Another modeling approach proposed by (Akbari-Dibavar and Mohammadi-Ivatloo, 2020) consists in an optimal planning of the WEF nexus through a stochastic **optimization model**.

Definition 7 *An* ***optimization model*** *is defined as a decision tool designed to find the best feasible solution to a problem, in which a function has to be maximized or minimized (called the objective function) via the variable values subjected to some constraints (Ding et al., 2020).*

This decision support model is an extension of the model proposed by (Zhang and Vesselinov, 2017) in deterministic form. Optimization consists in minimizing economic costs (electricity production costs, fixed and variable costs associated with power plants, water consumption costs, food production costs) and environmental costs (greenhouse gases emission costs) considering a 15-year planning horizon. Results present an optimal electricity production for each type of fuel (here coal and natural gas), as well as specific considerations regarding water use (ground or surface water) and optimal food production. Lastly, the identification of trade-offs between water and bioenergy, analyzed by (Gerbens-Leenes et al., 2009), emphasizes the importance of choosing countries that produce bioenergy in the most water-efficient way and selecting agricultural residues for less water-intensive production.

At the national scale, (Gulati et al., 2013) propose a systemic approach to study food security issues in South Africa. This study highlights the reciprocal influences of energy and water prices on food prices, as well as the influence of water and energy systems on food quality, availability, and affordability. It also provides a set of practical solutions for improving food security, taking into account its interactions with other resources. (Shannak and Vittorio, 2020) developed a spatio-temporal decision support tool to assess energy requirements in Saudi Arabia's agricultural sector. This provides policymakers with valuable insights into the energy inputs that most significantly impact food production and identifies the factors contributing to rising energy consumption over time and across regions. A web-based **Geographic Information System** (GIS) application was specifically designed to

enable users to select study sites directly on a map.

Definition 8 *A **Geographic Information System** (GIS) is defined as a technology that integrates computer-based mapping with database functionalities "for capturing, analyzing, modeling spatial data, and finally providing insights in a spatial dimension as basis for management decisions" (Böhner et al., 2014).*

Based on input data for a specific agricultural crop, the system calculates the corresponding water, land, and energy requirements. To support this, a land use suitability map for agriculture is generated using multiple factors. This decision support system offers a comprehensive view of the interactions between food, energy, and water at the crop level across various spatial locations, helping to optimize the use of these resources. More specifically, several studies have focused on bioenergy within the nexus framework. For example, (Benites Lazaro et al., 2021) explored the use of bioenergy and its impact on natural resource availability and food security in Brazil. (Munoz Castillo et al., 2019) examine the water-land nexus of bioenergy production in Brazil. It quantifies how land and water use for bioethanol production varies across states, highlighting both the trade-offs and synergies involved, as well as the associated environmental impacts.

At the local scale, methodological approaches vary and are often presented as decision support systems. For instance, (Sánchez-Zarco et al., 2021) developed a multi-objective optimization model to evaluate the security of WEF resources in the Monterrey Metropolitan Area (in Mexico). The optimization model aims to minimize economic costs related to the nexus, freshwater consumption, and greenhouse gas emissions in designing energy and water distribution networks. By adjusting the objective function, stakeholders can identify optimal trade-offs for resource security. Another decision support model presented by (Nie et al., 2019) consists in finding the optimal combinations of agricultural crops based on various objectives, such as maximizing profit and yield while minimizing water, energy consumption, and CO_2 emissions. This model, applied to Yucheng Station (China), illustrates the land use competition between different crops and offers valuable insights for optimal crop rotation through a multi-objective **MINLP optimization** approach.

Definition 9 ***Mixed-integer nonlinear programming** (MINLP) is the area of optimization that addresses "optimization problems with nonlinearities in the objective and/or constraints as well as continuous and integer variables" (Sahinidis, 2019).*

At the island scale, (Rodríguez-Urrego et al., 2022) provide a decision support system through scenarios' production to analyze future trends in energy consumption and greenhouse gas emissions on the island of Tenerife (Spain). This analysis incorporates projections of demand for water and energy resources alongside demographic, economic and climatic variables. Two distinct scenarios for 2050 are proposed: one is a maintained trend scenario, characterized by underdeveloped renewable energies, while the other is an ecology-aware scenario featuring an electricity mix composed entirely of 100 % renewable energy. This study highlights the island's dependency on imports, driven by the anticipated increase in water and energy demand under each scenario. The approach developed by (Winters et al., 2022) integrates all three dimensions of the WEF nexus to assess the sustainability of food, water, and energy resources across the Caribbean Small Island Developing States (SIDS) using a range of indicators. This study incorporates diverse datasets, such as climate projections and demographic growth estimates for 2050. The comprehensive analysis offers a holistic perspective on the region's sustainability challenges while highlighting the unique characteristics of each Caribbean SIDS. In their study on Kinmen island, (Chen et al., 2020)

define risk as the potential negative outcomes arising from an imbalance between the supply and demand of WEF resources. The research underscores how industrial and household consumption significantly heightens these risks, particularly in the context of demographic growth and industrial development, using a **material flow analysis**.

Definition 10 ***Material flow analysis*** *is an analytical tool used to quantify the flows and stocks of materials within a well-defined system over specific spatial and temporal boundaries (Escobar and Laibach, 2021).*

(Lin et al., 2019) developed a user-friendly nexus platform based on GIS in Taiwan. This tool is based on a life cycle assessment approach to analyze the interconnections between WEF resources, allowing for the quantification of environmental impacts over different time horizons. By integrating land use data as input, the platform generates various outputs such as impact distribution maps and land use allocation maps. A key aspect of the tool is its focus on preserving agricultural lands for food security. This study allows for the exploration of how enhancing food security influences the dynamics of land use change, and examines the trade-offs between bioenergy production, food supply, and environmental benefits. Finally, (Russeil et al., 2023) conducted a spatio-temporal modeling to analyze the drivers of change affecting food and energy self-sufficiency through semi-directive interviews in Reunion island. Land use maps are generated for 2035, based on different land use scenarios. This article provides a clear understanding of the trends associated with food and energy self-sufficiency over time, and highlights the challenges related to land availability on small islands, which the development of local food production and energy projects. Land use competition between urban development and the uses of food and energy resources is also evaluated.

In summary, to our knowledge, many approaches tackle parts of the problem we want to address, with different focus of studies and operating at different scales. At the world scale, studies of the WEF nexus offer a holistic perspective on the associated issues, taking into account both economic and environmental factors. However, these global approaches often overlook the spatial dimension and land use constraints specific to the nexus, making them less applicable to small island contexts. At the national and local scales, some research does incorporate geographical data and territorial specificities. Nevertheless, we do not find the examination of land use competition between resource uses. At the island scale, existing literature falls short of addressing system resilience in terms of land use competition driven by the uses of local resources. In essence, literature on the WEF nexus underscores the importance of the scale of study. Especially at the island scale, these studies must be framed within the context of land use competition, where land use is significantly influenced by the policies in place. Therefore, special attention must be given to the increasing competition for lands that provide ecosystem services, ensuring that specific land uses do not result in environmental degradation or destabilization of resource uses (Smith et al., 2010).

We saw that integrating the concept of resilience requires a deep understanding of the complex interactions between resource uses. A comprehensive and systemic approach is therefore essential, particularly when assessing the diverse impacts on land use. In that sense, it is also crucial to evaluate the effects of urban growth on resource uses and land use changes in small islands.

2.3 Modeling urban growth in small islands

Small islands must grapple with issues related to urban growth (UN, 2015), whose main drivers are demographic growth and economic development (Mahtta et al., 2022). It can negatively impact land use, through urban sprawl, particularly by encroaching on agricultural areas (Karakayacı and Karakayacı, 2019). Modeling is an effective means for assessing the impacts of urban planning on the dynamics of land use change, providing valuable insights into urban development trends under various policy scenarios (Tajbakhsh et al., 2016). In that regard, **spatial modeling** can be employed to model spatial dynamics, thereby supporting more effective land use planning.

Definition 11 ***Spatial models*** *are defined "as simplified representations of reality that include spatial and other relevant non-spatial quantitative and qualitative data" (Miller et al., 2018).*

2.3.1 A review of some methodological approaches

Spatial modeling of the dynamics of land use change, driven by urban growth, often employs **agent-based models** and **cellular automata** (CA) (Chakraborty et al., 2022).

Definition 12 ***Agent-based models*** *simulate the interactions between multiple autonomous agents and their environment, including neighboring agents and surrounding conditions. Each agent operates according to a set of rules, assessing its situation relative to its surroundings and making decisions based on this assessment. Thus, agents are entities capable of adaptation and learning from experience (James and Bradshaw, 2023).*

Definition 13 *The principle of* ***cellular automata*** *(CA) revolves around dividing space into numerous cells, each characterized by an initial state that evolves iteratively based on the states of neighboring cells and predefined transition rules. Initially, the system undergoes despatialization into a grid of cells with a finite number of states. Subsequently, a type of neighborhood is established among the cells. Lastly, a set of initial conditions is defined, and transition rules are applied to simulate the state of a cell transitioning from time t to time t+1 based on its interactions with neighboring cells (Kari, 2005).*

A fundamental distinction between agent-based models and CA lies in the static nature of the cells in the latter, whereas agents in the former are mobile and capable of interacting with other agent types (Degenne and Lo Seen, 2016). When agent-based models are integrated with GIS, they can incorporate various factors influencing the dynamics of urban development. For instance, the proximity of students' residences (agents) to universities, metro stations, or grocery stores can determine settlement patterns (Malik and Abdalla, 2017). Additionally, studies may account for factors such as proximity to infrastructure and land costs for various agents, including governmental bodies, private enterprises, and both local and non-local populations (Alghais and Pullar, 2018).

Similarly, integrating CA with GIS proves highly effective for analyzing the dynamics of land use change (Pratomoatmojo, 2018) and are extensively employed to simulate such changes (Van Soesbergen, 2016). Many CA models have been coupled with a probabilistic approach, such as Markov chains, allowing for the control of the time variable through

transition probabilities from one cell state to another. This method is illustrated in Figure 2.7 for a specific model of land use change. This hybrid approach is commonly preferred for projecting land use changes (Houet and Hubert-Moy, 2006) (Jafarpour Ghalehteimouri et al., 2022).

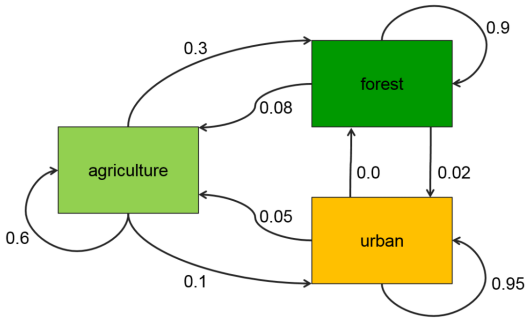


Figure 2.7: A Markov chain model for land use change (Wallentin, 2024).

Other combined approaches to modeling land use change driven by urban growth have been explored. For instance, the integration of CA with agent-based model was investigated by (Kumar et al., 2021), while (Liu et al., 2020) delved into analyzing the interaction between **system dynamics** (SD), CA, and agent-based model.

Definition 14 ***System dynamics*** *(SD) is an approach used to understand the non-linear behavior of complex systems over time by modeling stocks, flows, and internal feedback loops (Currie et al., 2018).*

Numerous studies have also analyzed the influence of different land use planning (Kim et al., 2020) and agricultural management scenarios (Gago-Silva et al., 2017) on land use change. For example, (Liang et al., 2018) explored these land use scenarios using a combination of SD and CA, whereas (Rimal et al., 2019) and (Lu et al., 2018) used a CA/Markov chain approach. Additionally, (Kim and Newman, 2020) developed a **neural network** to study urban growth.

Definition 15 *A* ***neural network*** *is a computational model inspired by the human brain, composed of interconnected nodes that process information through weighted connections across multiple layers. This architecture enables tasks such as pattern recognition and decision-making (West and Bhattacharya, 2016).*

At the scale of a small island, various models have been used to simulate urban growth under different scenarios. In Reunion Island, (Lajoie and Hagen-Zanker, 2007) employed a CA model, while (Lagabrielle et al., 2010) used a multi-agent model to explore various land use scenarios. Developing these multi-agent models requires close collaboration between scientists and urban planners to design accurate scenarios. Additionally, (Rousseaux and Judge, 2017) introduced an agent-based model that simulates household satisfaction based on social and spatial parameters, relying on extensive preliminary studies, including field surveys.

An overview of some urban growth models is provided in Table 2.1.

Table 2.1: Overview of some urban growth models.

Model	Description
SLEUTH	Probabilistic CA model developed to project urban growth and land use changes. This model incorporates four growth types that determine the probability of a cell becoming urbanized: spontaneous new growth, diffusive or new spreading center growth, edge growth and road-influenced growth (Chaudhuri and Clarke, 2013).
FLUS	A SD model and CA model are interactively coupled in the FLUS model. The SD model projects future urban growth demands, while the CA model simulates the spatial patterns of land use based on these projections. The FLUS model, which incorporates this integration, uses various data inputs, including land use data, socioeconomic data, topography, road networks, facility locations, and planning data (Liang et al., 2018).
Metronamica	CA that integrates a stochastic transition mechanism, where cell state changes based on a transition potential. This potential is influenced by factors such as neighborhood effects, initial existing land use, geographical location, physical suitability, accessibility, and random disturbances (Lajoie and Hagen-Zanker, 2007).
CLUE	Generic modeling framework that simulates land use change by quantifying the biophysical and human drivers influencing land use conversion. It consists of three distinct modules: (1) *a regional biophysical update* module that simulates the effects of factors such as land use history; (2) *a regional land use objectives* module that defines land use requirements based on biophysical and human factors; and (3) *a local land use allocation* module for executing land use changes (Veldkamp and Fresco, 1996).

2.3.2 The Ocelet approach

Among the multiple modeling tools used to investigate the dynamics of land use change, the *Ocelet* programming language stands out for its relevance. It offers a high level of expressiveness due to its domain-specific nature, setting it apart from both CA and agent-based models. Its uniqueness lies in its focus on interactions, particularly spatial ones, and its ability to describe all types of interactions (spatial, functional, social, hierarchical) within a model using a unified concept: the interaction graph (Castets, 2015). In Figure 2.8, a schematic depiction illustrates the various types of relationships that can be modeled within a typical rural landscape, where a single entity may engage in multiple relationships (Degenne and Lo Seen, 2016).

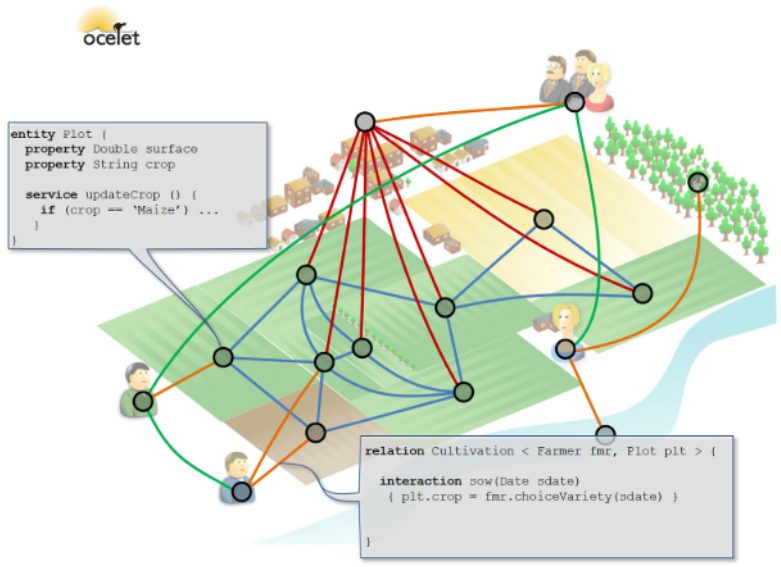


Figure 2.8: Schematic diagram showing landscape elements in interaction (Degenne and Lo Seen, 2016).

Ocelet has frequently been used to assess the impact of various scenarios involving human actions. For instance, it has been applied to study cropland expansion in Burkina Faso by 2040 (Jahel et al., 2018) and to simulate different urban development scenarios in Reunion Island with the cooperation of multiple stakeholders, ranging from uncontrolled to planned urban growth (Lestrelin et al., 2017). Additionally, (Augusseau et al., 2018) and (David et al., 2013) examined urban development dynamics in western Reunion, engaging numerous local stakeholders.

In summary, these approaches of urban growth modeling provide valuable insights into the diverse modeling tools put in place to simulate urban growth across different scales and involving various stakeholders. However, there is a lack of studies exploring urban growth scenarios within the framework of the WEF nexus in small islands territories. As a result, urban growth modeling and WEF nexus approaches can be combined to address challenges related to system resilience more comprehensively and systemically. **Food system resilience** can serve as a case study within this framework of system-specific resilience.

Definition 16 *A **food system** refers to all elements and activities involved in food production and consumption (OECD, 2021).*

2.4 Food system resilience: key concepts

Definition 17 ***Food system resilience** is defined as the "capacity over time of a food system and its units at multiple levels, to provide sufficient, appropriate and accessible food to all, in the face of various and even unforeseen disturbances" (Tendall et al., 2015).*

This definition highlights the importance of the time dimension in resilience. It emphasizes the core objective of food systems: to provide food that is sufficient, appropriate, and accessible to all. "Sufficient" refers to both the sufficient quantity and nutritional quality of

food, while "appropriate" encompasses cultural, technical, and nutritional suitability. "Accessible" means ensuring that food is both physically and economically accessible. Maintaining this functional goal during periods of disturbance introduces a fourth dimension: stability. These components collectively define the four pillars of **food security** (Tendall et al., 2015), as represented in Figure 2.9.

Definition 18 *The widely accepted definition of* ***food security*** *was introduced in the FAO's 2001 annual report (Peng and Berry, 2019), defining it as "a situation that exists when all people, at all times, have physical, social and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life." (FAO, 2001). This definition was last updated during the 2009 World Summit on Food Security, where a fourth dimension –stability– was added to reflect the short-term ability of food systems to withstand both natural and human-made shocks (Peng and Berry, 2019).*

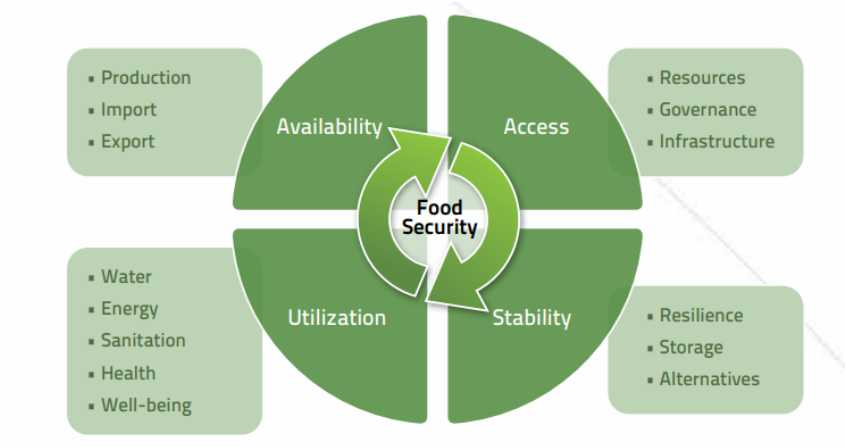


Figure 2.9: The components of food security (Sadeg and Al-Samarrai, 2020).

The correlation between supporting food security and enhancing food system resilience is depicted in Figure 2.10, which highlights the behavior of food system resilience over time, divided into distinct phases (Simonovic and Peck, 2013): (1) robustness, or the capacity to resist disturbances before any food security is lost (Anderies et al., 2013); (2) redundancy, the degree to which system elements are replaceable, which enhances the ability to absorb shocks and minimize food insecurity; (3) flexibility and reactivity, referring to how quickly the food system can recover lost food security; (4) resourcefulness and adaptability, which determine how much of the lost food security is restored (Tendall et al., 2015).

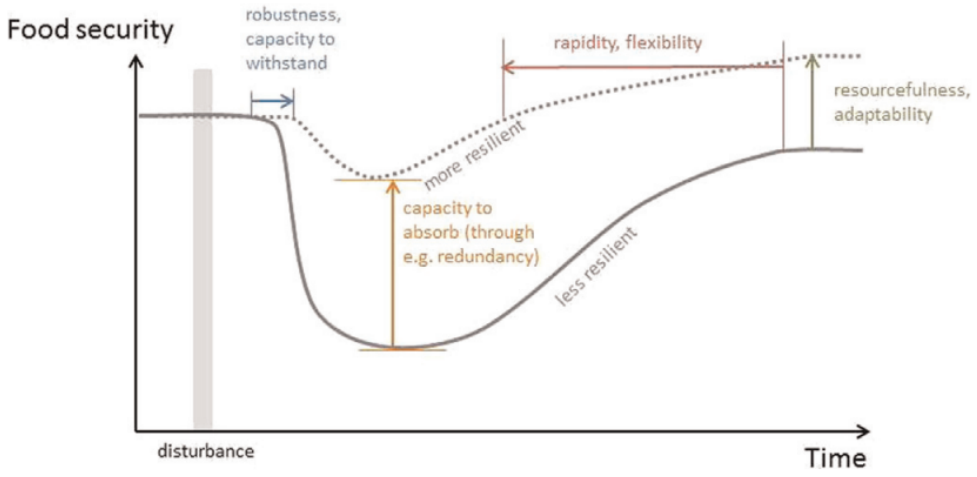
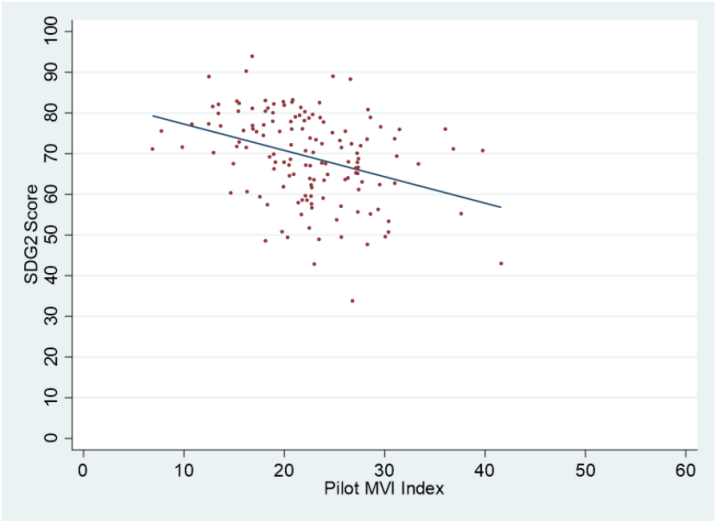


Figure 2.10: Food system resilience, as the capacity to provide food security over time and despite disturbances, can be broken down into various components (Tendall et al., 2015).

Enhancing food security by increasing food system resilience becomes a critical challenge, particularly for highly vulnerable territories like small islands. Indeed, as depicted in Figure 2.11, there is a clear correlation between territorial vulnerability and the achievement of food security. The y-axis represents SDG 2 "zero hunger", indicating the level of food security, while the x-axis displays the Multidimensional Vulnerability Index (MVI), which measures a country's vulnerability through 18 indicators across economic, structural development, and environmental dimensions (UN, 2021). This figure shows that countries with higher vulnerability levels struggle more to achieve higher levels of food security, as it is threatened by economic, demographic, and climatic factors (IPCC, 2019). Environmental issues also play a role, including the extensive use of fertilizers to increase food production (Penuelas et al., 2023) and the presence of microplastics in seafood, which pose potential health risks to humans (Unuofin and Igwaran, 2023).



[1] The Pilot MVI is an index which aims at measuring the degree of *structural* vulnerability of a country. It is made up of 18 indicators selected to capture vulnerability of Small Island Developing States (SIDS) specifically. These indicators are allocated across three categories: economic vulnerabilities, structural development vulnerabilities, and environmental vulnerabilities. See Sachs et al. (2021a).

Figure 2.11: Pilot MVI vs SDG2 – Zero Hunger (UN, 2021).

In summary, enhancing food security in small islands is a major challenge that can be addressed by strengthening food system resilience, as food system resilience reflects the capacity to ensure food security. Therefore, the emphasis should be on building a more resilient food system to bolster food security. With this in mind, we choose to focus on the term "food system resilience" rather than "food security" throughout the manuscript. Thus, the core of the thesis is framed around enhancing food system resilience. However, we do not seek to address every aspect of food system resilience, as not all dimensions contribute to increased land use competition. Instead, we concentrate specifically on food sufficiency, a key pillar of food system resilience (Rikkonen et al., 2023).

2.4.1 The concept of food self-sufficiency

The term food self-sufficiency has been defined in various ways, with multiple interpretations available on the subject (Clapp, 2017). We give a definition of **food self-sufficiency** below:

Definition 19 ***Food self-sufficiency*** *refers to "domestic food production that is equal to or exceeds 100 % of a country's food consumption" (Clapp, 2017).*

In this definition, trade is not excluded, as food self-sufficiency is defined by the ratio of food produced to food consumed at the domestic level. Therefore, even self-sufficient countries may engage in agricultural specialization trade with other countries. The key point is that food self-sufficient countries produce enough food to meet or surpass their domestic consumption. A key indicator that reflects this understanding is the **Self-Sufficiency Ratio** (SSR).

Definition 20 *The* ***food Self-Sufficiency Ratio*** *(SSR) is defined as "the percentage of food consumed within a country that is produced domestically" (FAO, 2015).*

This ratio-based approach to food self-sufficiency is widely used in several studies at both national and regional scale (Soltani et al., 2020) (Van Oort et al., 2015). Food self-sufficiency can also be evaluated through the measure of **Dietary Energy Production** (DEP).

Definition 21 *The* ***Dietary Energy Production*** *(DEP) is an indicator that evaluates a country's ability to produce sufficient calories from its own food sources to meet dietary needs (Porkka et al., 2013).*

A country is considered self-sufficient if it produces over 2500 kcal per capita per day, as this limit is generally deemed adequate for a healthy diet (Porkka et al., 2013). This approach is frequently utilized in nutrition studies and dietary assessments to evaluate energy intake, both nationally (Schramski et al., 2019) and globally (Porkka et al., 2013).

2.5 Summary

Given the significant vulnerabilities faced by small islands, we emphasized the need to focus on system resilience. Enhancing resilience in these regions requires a holistic approach, with the WEF nexus being particularly relevant. While a rich body of literature has emerged, it has not addressed resilience challenges in terms of land use competition driven by the uses of local resources.

This thesis is framed around this nexus, highlighting the dynamics of land use change that arise from the interactions among its components. To further refine this approach, we saw the importance of considering the impact of urban growth on resource uses and land use change, particularly within the context of spatial restrictions and demographic pressures. More specifically, this thesis aims to connect this comprehensive approach with the objective of fostering food system resilience through the support of the **food self-sufficiency process**.

Definition 22 *The term* ***food self-sufficiency process*** *captures the ongoing trajectory towards food self-sufficiency.*

To address this objective, we developed a decision support model. The overall thematic and methodological approach that led to the model's construction, along with its ability to generate valuable insights for stakeholders, is described in the following chapter.

CHAPTER 3

Our thematic and methodological approach

Our thematic and methodological approach is designed to offer actionable insights that support decision-making around food system resilience in small islands. Central to this is the establishment of a spatio-temporal modeling framework aimed at developing a decision support system for stakeholders (identified in section 3.3). This framework is specifically tailored to highlight land use competition and identify critical **multidimensional thresholds related to food self-sufficiency**, while accounting for the unique territorial characteristics of small islands within a WEF nexus approach.

Definition 23 *We define* ***multidimensional thresholds related to food self-sufficiency*** *as critical limits beyond which land use competition induces the non-satisfaction of constraints related to balancing electricity production and demand, as well as the inability to meet housing needs. These thresholds are considered multi-dimensional, as they are shaped by a range of factors including dietary behaviors, agricultural practices, electricity production sources, and urban development dynamics.*

The methodology is intentionally crafted to be holistic and generalizable, making it applicable across various small islands that share common characteristics and vulnerabilities. Given the complex interplay between the WEF nexus and urban growth, the approach necessitates precise modeling of the connections between the uses of local resources and urban development, as well as their associated constraints. The modeling approach must be flexible, allowing users to adjust input parameters to suit the specific contexts of different small islands, thereby ensuring its replicability across similar regions. It should also support the implementation of **scenarios**.

Definition 24 *We define a* ***scenario*** *as a combination of finely-tuned parameters used as inputs to a model, designed to explore potential future outcomes.*

3.1 A thematic framework for exploring food system resilience

A conceptual model is designed to illustrate our contributions related to food system resilience (see Contribution 1 in Chapter 1), as shown in Figure 3.1. It highlights demographic growth and economic development as primary drivers influencing changes within the WEF nexus (Rodríguez-Urrego et al., 2022) (UNESCO, 2021). Urban growth, driven by both economic development and demographic growth, alters land use through urban sprawl and increases the demand for resources, assuming a constant resource consumption per capita. Consequently, this heightened demand necessitates a corresponding increase in resource supply to meet growing needs. When production relies heavily on resource imports, it results in a precarious food system (FAO, 2018). Conversely, the intensive use of local resources to satisfy the demand can strengthen land use competition, a phenomenon already exacerbated by urban sprawl. This competition can further limit the uses of local resources (mutual influences) due to the spatial constraints of small islands, leading to the identification of critical thresholds. Then, the discourse on food system resilience in small islands is framed by identifying the multidimensional thresholds related to food self-sufficiency resulting from land use competition between the uses of local resources and urban development.

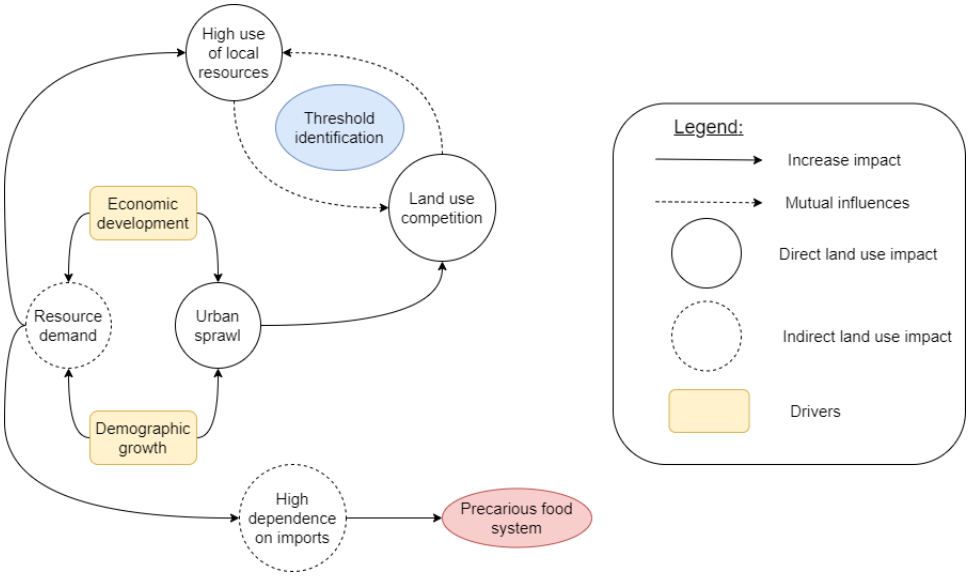


Figure 3.1: Conceptual model for exploring food system resilience.

To provide stakeholders with a decision support system for supporting food system resilience in small islands, we focus on developing various **comprehensive scenarios**.

Definition 25 ***Comprehensive scenarios*** *are scenarios that encompass various urban development dynamics, dietary behaviors, agricultural practices, and electricity production sources.*

3.2 Towards the production of comprehensive scenarios

Comprehensive scenarios are designed to combine both demand-side and supply-side approaches, drawing on online literature and field interviews to establish a deeper connection with the local context. The methodology for conducting field interviews is detailed

in Chapter 4. While traditional scenarios typically focus on consumer demand orientation (*demand-side approach*) (Temme et al., 2020), the integration of production means (*supply-side approach*) (Kain et al., 2010) into our approach enables a more detailed depiction of the interconnected uses of resources. Indeed, *demand-side approaches* can be challenging to target and direct towards the means of production. These approaches can therefore be seen as complementary to (rather than replacing) *supply-side approaches*. The comprehensive scenarios are designed to bring insights into the dynamics of land use change by encompassing each component of the WEF nexus and urban growth that drives land use change in small islands. Specifically, we focus on the following components: electricity production sources, agricultural practices, dietary behaviors and urban development dynamics. We exclude the water component from the scenarios as water treatment facilities are typically located in already developed areas or industrial zones, which limits their impact on the dynamics of land use change (Talat, 2021).

3.2.1 Electricity production sources

The land footprint of electricity production varies with the share of intermittent RES. Specifically, production systems utilizing RES, such as wind and solar, generally require more land than those relying on traditional fossil fuels, like coal and oil, which have a smaller land footprint (Trainor et al., 2016).

3.2.2 Agricultural practices

We consider **crop diversification** and **subsistence farming** as agricultural practices.

Definition 26 ***Crop diversification*** *is considered as "an attempt to increase the diversity of crops through, e.g. crop rotation, multiple cropping or intercropping, compared to specialized farming with the aim to improve the productivity, stability and delivery of ecosystem services" (Hufnagel et al., 2020).*

Definition 27 ***Subsistence farming*** *is related to agricultural activity focused on producing food primarily for consumption by the farming household (Lidzhegu and Kabanda, 2022). In our approach, we consider scenarios that incorporate subsistence farming at the island scale to address a portion of the population's food needs.*

3.2.3 Dietary behaviors

With the aim of strengthening food system resilience by supporting the food self-sufficiency process, we consider that dietary behaviors influence agricultural land use. The dietary behaviors we consider are as follows:

- **Prevalent dietary behavior:** Refers to the diet predominantly adopted by the population.
- **Emerging dietary behaviors:** Refers to emerging behaviors driven by various factors, including climate and economic conditions (Pais et al., 2021).

3.2.4 Urban development dynamics

In our approach, urban sprawl is driven by demographic growth and economic development and evaluated by taking into account (1) an urban development surface per new household, and (2) an urban development surface for non-residential areas, such as economic and production zones. The following three types of urban planning are investigated as part of our scenarii:

- **Highly planned:** Reflects policymakers' efforts to regulate urban development within existing urban areas through high densification rates.
- **Continuity planning:** Mirrors the current level of urban densification. It entails the conversion of agricultural parcels into urban parcels to accommodate the housing needs of the growing population, as well as expanding economic and production zones.
- **Unplanned:** Represents uncontrolled urban development with no measures to limit urban sprawl. It involves significant ecological impacts, including the conversion of a substantial portion of agricultural parcels to accommodate urban growth.

Details of the comprehensive scenarios are summarized in Figure 3.2.

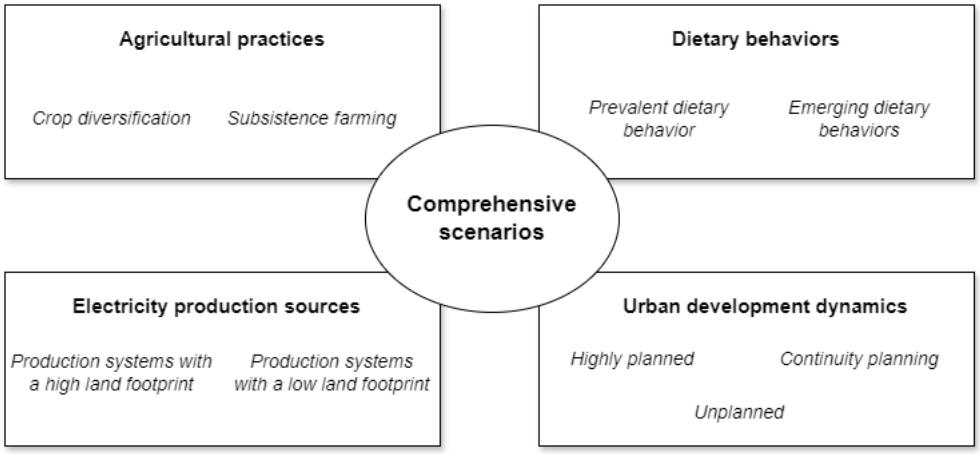


Figure 3.2: Specifications of the comprehensive scenarios.

Having established a conceptual framework for studying food system resilience, it is important to identify the key stakeholders targeted in our approach.

3.3 Targeted stakeholders

This model is designed to assist both policymakers and other key parties involved in urban planning, land management for crop and electricity production, and the promotion of specific dietary behaviors.

Table 3.1: Targeted stakeholders.

Urban planning	**Municipal leaders** responsible for local urban development can use the model to integrate urban plans, enabling them to visualize and manage the distribution of future urban areas in order to minimize the conversion of agricultural areas.
Promotion of specific dietary behaviors	**Civil society**, such as citizen groups and associations, can leverage the findings to promote incentives and initiatives aimed at encouraging specific dietary behaviors that support the food self-sufficiency process.
Agricultural planning	**Citizen associations** can draw on the results for supporting local initiatives and advocating for short supply chains, alongside **government authorities** for shaping agricultural policies towards subsistence farming.
Electricity production planning	**Policymakers** can use the findings for shaping national energy policies by promoting electricity production systems with a low surface footprint.

3.4 Design of an integrated modeling framework

3.4.1 Methodological challenges

The main goal of this thesis is to develop and analyze the outputs of an **integrated model** that fulfills several key objectives: (i) address land use competition between the uses of local resources and urban development, and (ii) identify multidimensional thresholds related to food self-sufficiency.

Definition 28 *An **integrated model** combines multiple models into a unified system, leveraging the interconnections among different components (Jørgensen and Swannack, 2019).*

Within the context of systemic modeling, the objective is to formulate an exhaustive methodology. The key methodological challenges we identified to support food system resilience in small islands through comprehensive scenarios are as follows:

(a) Data integration: This involves the integration of multi-source data through geographical data that enables the characterization of specific features of the territory, both qualitative and quantitative data for shaping comprehensive scenarios, and projected data (resource demand, population projections...) for a future horizon 2035. The 2035 horizon was chosen because it balances short- and medium-term impacts, making it more actionable for policy decisions (Reed et al., 2009).

(b) Specification of spatio-temporal constraints: This entails defining heterogeneous spatio-temporal constraints, accounting for each component of the WEF nexus and urban growth that drives land use changes.

(c) Scenario implementation: This involves examining multiple combinations of electricity production sources, dietary behaviors, agricultural practices and urban development dynamics and analyzing the outcomes.

(d) Threshold identification: This focuses on identifying multidimensional thresholds related to food self-sufficiency.

3.4.2 Model description

The problem we are modeling can be specified as follows: Find the optimal land uses for each parcel by 2035, that ensure 1) the satisfaction of heterogeneous constraints, 2) and the maximization of a food SSR, 3) according to different comprehensive scenarios and the data at hand.

Important remark: *In our approach, we do not consider a food SSR exceeding 100 %, as our goal is to identify multidimensional thresholds related to food self-sufficiency. The aim is to determine the maximum achievable ratio to meet the population's food needs.*

To tackle the management of spatio-temporal data, the introduction of heterogeneous constraints, and an objective function related to the food SSR, we present a GIS-based model combined with an optimization model as a decision support system. The overall structure of the model is presented in Figure 3.3.

First, the allocation model takes as input various geographical data and allocates **potential land uses** for each parcel, based on geographical constraints that each parcel must satisfy.

Definition 29 *The **potential land uses** for a parcel refer to its ability to shift from its existing land use to alternative land uses.*

The allocation model returns a map of potential land uses, which is then converted through a pre-processing step into a set of parcel attributes (e.g., surface area, crop yields...). This set of parcel attributes, together with projections data on population and resource demand, are used as inputs for the optimization model. At each time step, the model generates a map of optimal land uses, with an annual time step based on population projections.

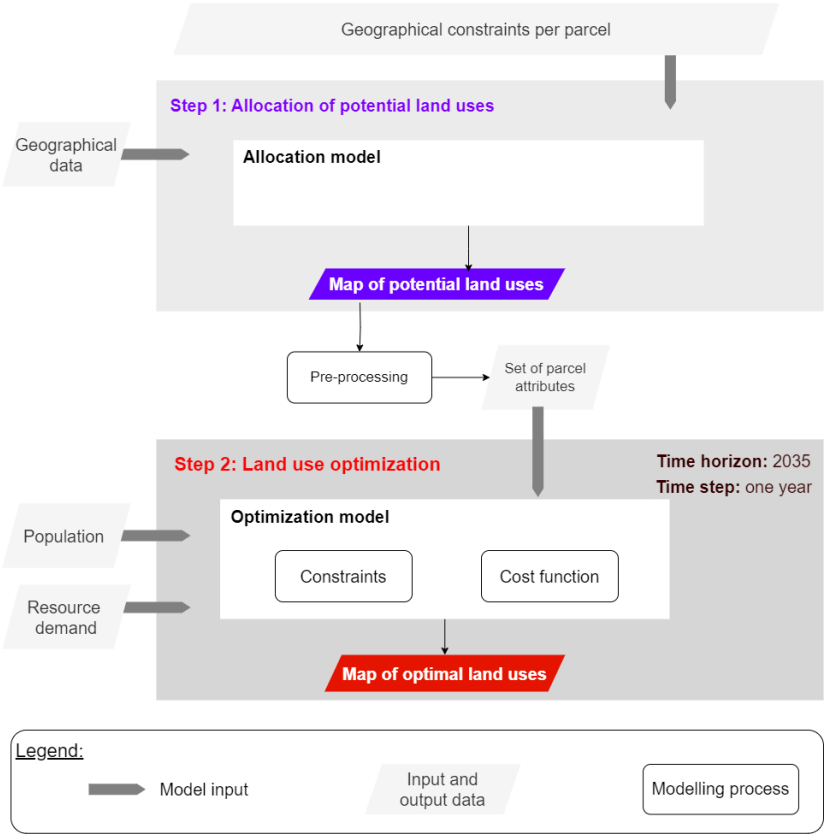


Figure 3.3: Overall structure of the integrated model.

3.5 Allocation of potential land uses

The initial stage in the allocation of potential land uses before going into the model involves (1) deciding how the territory will be divided into manageable units for analysis, (2) defining the range of potential land uses, (3) specifying constraints to allocate potential land uses for each parcel, and (4) incorporating comprehensive scenarios into the constraints.

In our approach, we have selected **cadastral parcels** for spatial partitioning.

Definition 30 *A **cadastral parcel** is considered as "a single area of Earth surface, under homogeneous real property rights and unique ownership" (European Commission, 2015).*

The primary advantage of using this partitioning is the precision and legal recognition of property boundaries, which facilitates more accurate and relevant land use planning and decision-making.

We define potential land uses according to each component of the WEF nexus and urban growth that drives land use change in small islands (as outlined in section 3.2). As a result, three distinct potential land uses are defined: (i) crop production, (ii) urban development, and (iii) electricity production.

3.5.1 Specifications of geographical constraints

The allocation of potential land uses for each parcel is based on a constraint-based filtering step. This process will filter out inconsistent potentials, leading to those that

satisfy all constraints for each parcel. Following interviews (see Chapter 4) and studies carried out, we consider the following geographical constraints, that reflect at the island scale, the dynamics between land characteristics and known land use.

1) Land use type: The proposed approach suggests that some parcels have the potential to undergo transition from their existing land use to another or to multiple land uses, taking into account concomitant land uses. That is the case for agricultural parcels, which have the flexibility to either remain in agricultural use or undergo transition to urban in response to urban growth. They may also undergo transition to electricity production in response to the development of new electricity production systems, as depicted in Figure 3.4. To maintain simplicity and accuracy in this thesis, **agrivoltaism** has been excluded from the range of potential land uses for agricultural parcels.

Definition 31 ***Agrivoltaism*** *refers to the simultaneous use of agricultural production and solar PV systems on the same area (Dinesh and Pearce, 2016).*

The exclusion is due to the complexity of defining a shading limit that negatively impacts crop yields. Such limit can vary significantly depending on the crop type, location, and specific agrivoltaic system employed. As a result, quantifying yield variations under an agrivoltaic system is particularly challenging (Widmer et al., 2024).

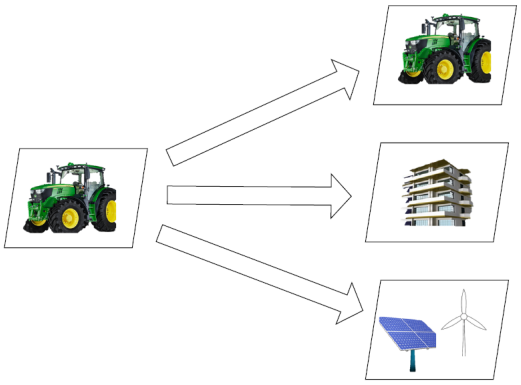


Figure 3.4: Potential land uses for an agricultural parcel.

Regarding urban parcels, we consider that they can remain urban or undergo transition to dual-use, becoming both urban and electricity-producing parcels, as shown in Figure 3.5. This includes possibilities such as solar self-consumption, which minimizes the impact on land use change compared to ground-mounted PV systems. For the scope of reliable data projections, the model excludes urban agriculture, which involves food production within urban areas (Opitz et al., 2016). The exclusion is due to several challenges: urban areas are densely populated with limited available space, making it difficult to allocate land for agriculture without conflicting with other urban uses (Martellozzo et al., 2014). Additionally, buildings and dense construction in urban areas can significantly limit sunlight exposure, which is crucial for plant growth (Johnson et al., 2015).

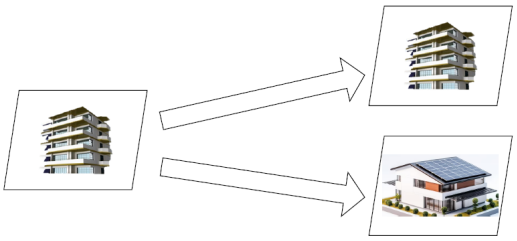


Figure 3.5: Potential land uses for an urban parcel.

In contrast, natural and protected areas lack the flexibility to undergo transition, as their status prevents any changes. These areas are vital for preserving biodiversity and ecosystems. Therefore, it is crucial to protect these spaces from anthropogenic pressures by excluding them from the dynamics of land use change (UNEP-WCMC, 2016).

2) Topography: Topographic constraints are essential considerations in crop production, as variations in topography significantly impact soil properties and crop productivity (Rabia et al., 2022). Topography also plays a crucial role in determining site suitability, serving as a key criterion for selecting appropriate locations (Makungwe et al., 2021). In the context of electricity production, topographic features are essential for identifying suitable sites for ground-mounted PV installations (Nebey et al., 2020). Additionally, topographic constraints are carefully considered in the selection of urban development areas (Lajoie and Hagen-Zanker, 2007).

3) Neighborhood relations between parcels: When allocating a potential for urban development to a parcel, it is important to consider factors such as the proximity of parcels to existing urban areas (Lajoie and Hagen-Zanker, 2007). However, we do not consider other neighborhood relations, such as proximity to commercial zones or roads. Indeed, we argue that a simplified modeling approach, based a few robust assumptions, is sufficient for modeling urban growth within the nexus framework. Given the objective of delineating urban development areas that directly compete with parcels designated for crop and electricity production, we do not delve into the complex interactions among multiple stakeholders and facilities typically found in agent-based models. Instead, we focus on accurately delineating areas with multiple potential land uses. For the allocation of other potential land uses, neighborhood relations between parcels are considered less critical and are therefore excluded from the model.

4) Crop water requirements: Crop water requirements are crucial for crop development, agronomic viability, and yield enhancement (Hussain et al., 2023). In this context, future crop production will occur in irrigated areas or regions with sufficient rainfall to meet these water requirements. Although various climate factors -such as temperature, humidity, and wind speed- can influence crop water requirements (FAO, 1998), for simplicity, crop water requirements per hectare are assumed to remain constant over time.

5) Parcel surface area: A constraint on minimum surface area is implemented to exclude parcels that are too small to support electricity production systems. Conversely, there is no maximum surface area defined, allowing for flexibility in accommodating larger projects (Pillot et al., 2020). For crop production, a minimum area requirement (in hectares) can be established based on factors such as farm size and crop type (Peltonen-Sainio et al., 2020).

By specifying the set of geographical constraints, we require the collection of the cor-

responding set of geographical data **layers**: *cadastral parcels, land use, topography, rainfall and irrigated perimeters.*

Definition 32 *A **layer** is "a reference to a collection of geographic data that can be accessed and displayed in a map. Each layer references a file or service data source. The data source contains either vector data (points, lines, polygons and attributes) or raster data (images)" (Esri Developer, 2024).*

In the context of spatial modeling, accurately spatializing energy and food resources at the scale of a small island is crucial. This process involves integrating geographical data on crop yields, which provides a higher resolution compared to aggregated island-wide yields. Such detailed spatial information allows for a more precise assessment of climatic variations and soil properties across different areas over time (Fowler et al., 2024). Similarly, spatially mapping the potential of energy resources is essential for effective energy planning (Ramachandra and Shruthi, 2007). Regarding the temporal resolution of geographical data, crop water requirements vary according to growth stages, and monthly trends in water demand have been extensively studied to account for different growth periods of crops (Parmar et al., 2023) (Chiarelli et al., 2020). Therefore, monthly rainfall data must be collected. For crop yields, annual data are sufficient, as we aim to maximize the food SSR for each annual time step. The same applies to energy resources, where annual data are adequate since electricity production is calculated annually. Details of the data acquisition process are provided in Chapter 4.

3.5.2 Implementing comprehensive scenarios within the allocation process

Comprehensive scenarios are implemented at the allocation step through the application of geographical constraints, which specifically influence the permitted land uses for potential allocation. For instance, permitted land use for crop production might include agricultural wastelands or existing cultivated areas, enabling crop diversification. Alternatively, it could involve converting areas currently dedicated to export crops into subsistence farming. Similarly, permitted land use for electricity production may include agricultural wastelands or areas currently dedicated to export crops, which could be repurposed for electricity production projects. Conversely, the allocation of **potential areas** for urban development is not scenario-dependent.

Definition 33 ***Potential areas*** *refer to parcels that have been assigned a potential land use resulting from the allocation model (see the following subsection).*

With the methodology for allocating potential land uses now outlined, the next step involves proceeding to the modeling phase, where potential land uses are allocated to each parcel.

3.5.3 Allocation model

The main challenge in this allocation process lies in assigning a potential for urban development to characterize urban sprawl, and it is therefore necessary to define neighborhood relationships between parcels (refer to subsection 3.5.1). These relationships can be modeled through an interaction graph that links neighboring parcels. A powerful language for processing the dynamics of land use change using interaction graphs is *Ocelet*, a domain-specific language (refer to subsection 2.3.2). Designed to simulate spatial dynamics based on

relationships among spatial entities interconnected by an interaction graph (Degenne and Lo Seen, 2016), *Ocelet* plays a crucial role in our modeling approach by assisting in the identification of potential areas for urban development. As a result, the allocation of potential land uses is performed using *Ocelet*. The specifications of the allocation process are outlined in Table 3.2, and the *Ocelet* model is provided in Algorithm 1, using the structures defined within the language for the specific needs of modeling spatial dynamics.

Table 3.2: Specifications of the allocation process.

Given:	
Layers:	
CLU_{layer}	Land use layer delineated by cadastral parcels
Alt_{layer}	Altitude layer
$Slope_{layer}$	Slope layer
$Rain_{layer}$	Rainfall layer
$Irrig_{layer}$	Irrigated perimeters layer
Pot_ener_{layer}	Layer of energy resource potential
$Yields_{layer}$	Crop yield layer
Constraint values:	
$lct_{permitted}$	Permitted land use type(s)
alt_{max}	Maximum altitude (in m)
$slope_{max}$	Maximum slope (in %)
d_{max}	Maximum distance between urbanizable and urban parcels (in m)
w_{min}	Minimum crop water requirements (in mm)
S_{min}	Minimum surface area (in ha)
Find:	
The potential land uses for each parcel	
Subject to the following constraints:	
Parcels designated as natural protected area have no potential land use	
Upper and lower bound constraints set the requirements for potential land use	

First and foremost, average values of slope (in %), altitude (in m), monthly rainfall (in mm), energy resource potential (in GWh/ha), and crop yields (in ton/ha) are assigned to each parcel. Given the sufficiently small size of cadastral parcels, this method is deemed realistic for our purposes. This is achieved by linking each layer (Alt_{layer}, $Slope_{layer}$, $Rain_{layer}$, Pot_ener_{layer}, and $Yields_{layer}$) with the land use layer delineated by cadastral parcels (CLU_{layer}) using the *Mean* aggregation function **(lines 1-3, 17-20)**. Through the connection of a parcel list to a cell list, *Ocelet* automatically connects entities through spatial overlap. The process of allocating potential for urban development begins by filtering parcels. Initially, urban parcels (lct = $'urban'$) and those with land use types permitted for urban development (lct = $lct^{urb}_{permitted}$) are selected via the *parcel_type*() filter. These parcels must also adhere to a maximum distance limit (d_{max}) via the *neighbor*() filter and a maximum slope limit ($slope^{urb}_{max}$) via the *slope*() filter. A graph is then generated between these parcels **(lines 4-5, 21-30)**. Thereafter, we apply an interaction function *applyStrategy()* to the graph to assign potential for urban development to each parcel on the graph **(line 6, 31-35)**. The assignment of other potential land uses is then governed by geographical constraints such as minimum surface area S_{min}, maximum altitude alt_{max}, maximum slope $slope_{max}$, and permitted land use $lct_{permitted}$ for allocating potential for electricity produc-

tion **(lines 7-10)**. Additionally, further constraints, such as minimum water requirements w_{min}, are applied when allocating potential for crop production **(lines 11-16)**.

Algorithm 1 Allocation model

Require: $slope_{max}$, alt_{max}, d_{max}, S_{min}, $lct_{permitted}$, w_{min}, CLU_{layer}, Alt_{layer}, $Slope_{layer}$, $Rain_{layer}, Pot_ener_{layer}, Yields_{layer}$

1: fix r_cell_parc = new $Parc_Cell$
2: $r_cell_parc.connect(list_cells, list_parcels)$
3: $r_cell_parc.parcel_cell()$
4: fix r_{pp} = new $relParcels$
5: $r_{pp}.complete.parcel_type.neighbor(d_{max}).slope(slope^{urb}_{max}).connect$
6: $r_{pp}.applyStrategy()$

Allocation of potentials for electricity and crop production

7: **for** $p \in P$ **do**
8: **if** (p.lct == $lct^{electricity}_{permitted}$, p.slope < $slope^{electricity}_{max}$, p.alt < $alt^{electricity}_{max}$, p.area > $S^{electricity}_{min}$) **then**
9: $p.potential_electricity \leftarrow 1$
10: **end if**
11: **if** (p.lct == $lct^{crop}_{permitted}$, p.slope < $slope^{crop}_{max}$, p.alt < alt^{crop}_{max}, p.area > S^{crop}_{min}) **then**
12: **if** (p.rainfall > w^{crop}_{min}) || (p.irrigation == 'within') **then**
13: $p.potential_crop \leftarrow 1$
14: **end if**
15: **end if**
16: **end for**

17: **relation** $Parc_Cell < Cell\ c, Parcel\ p >$
18: **interaction** parcel_cell()
19: $p.value = c.value$
20: **agg** $\{p.value << Mean\ \}$

Allocation of potential for urban development

21: **relation** $relParcels < Parcel\ p1, Parcel\ p2 >$
22: **filter** parcel_type()
23: **return** (((p1.lct == $lct^{urb}_{permitted}$) && (p2.lct == $'urban'$)) || ((p1.lct == $'urban'$) && (p2.lct == $lct^{urb}_{permitted}$)))
24: **filter** neighbor(Double d_{max})
25: **return**(p1.geom.distance(p2.geom) $\leq d_{max}$) && (p1.geom.distance(p2.geom) $\leq d_{max}$)
26: **filter** slope(Double $slope^{urb}_{max}$)
27: **if**(p1.lct == $lct^{urb}_{permitted}$) **then**
28: **return** (p1.slope < $slope^{urb}_{max}$)
29: **else**:
30: **return** (p2.slope < $slope^{urb}_{max}$)
31: **interaction** applyStrategy():
32: **if**(p1.lct == $lct^{urb}_{permitted}$):
33: $p1.potential_urban \leftarrow 1$
34: **else**:
35: $p2.potential_urban \leftarrow 1$

Upon completion, a map of potential land uses for each parcel is generated. Based on the analysis conducted around the allocation process, we derive a flow chart that presents an overview of this initial modeling step, as shown in Figure 3.6.

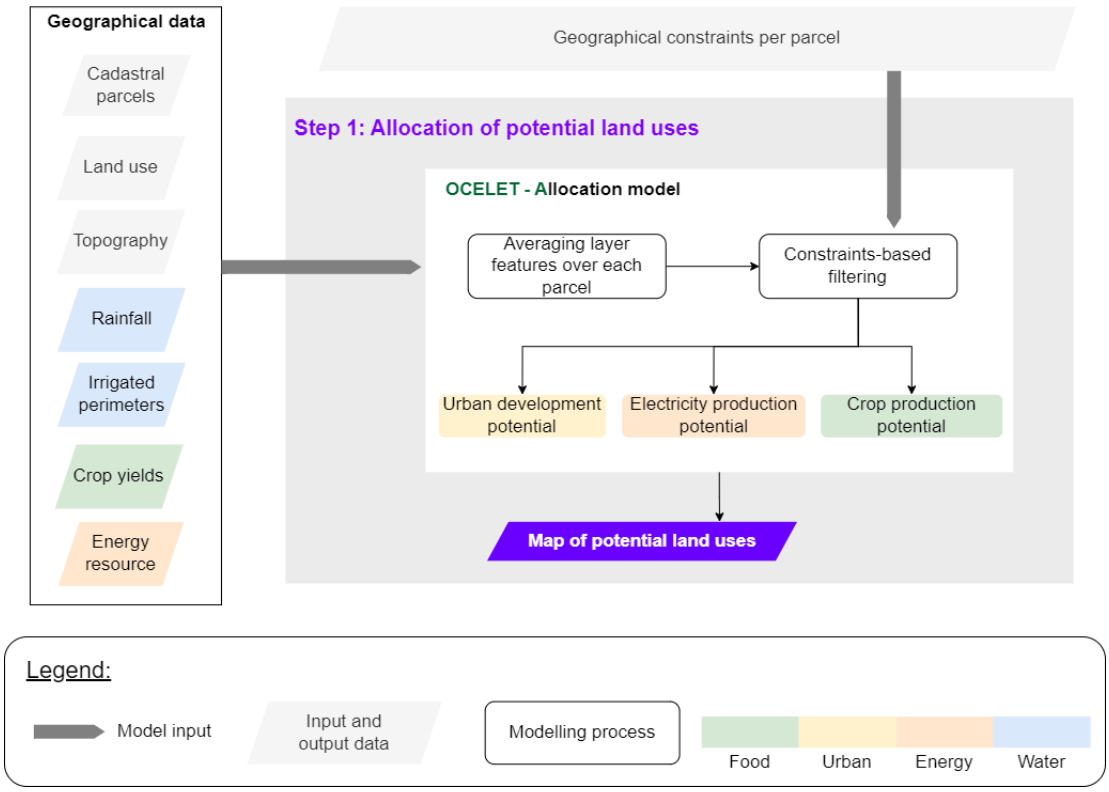


Figure 3.6: Flow chart of the allocation process.

This map of potential land uses is then transformed into a set of parcel attributes through a pre-processing step, which subsequently serves as input for the optimization model.

3.6 Pre-processing step

In computational optimization models, spatial data presents unique challenges due to its inherently complex and multidimensional nature (Cao et al., 2024). This is particularly true when working with vector data containing cadastral parcel information, which encompasses several attributes. Directly integrating raw spatial data, such as vector data, into optimization models is not feasible. To address this issue, a pre-processing step is necessary to extract and convert relevant parcel attributes from the vector data into a numerical format compatible with the optimization model. During this pre-processing phase, the following attributes are extracted for each cadastral parcel:

- Energy resource potential (in GWh/ha)
- Surface area (in ha)
- Crop yields (in ton/ha)

Once the data have been pre-processed, it can be effectively incorporated into the optimization model, enabling the integration of spatial information while conforming to the model's required data structure.

3.7 Land use optimization

The optimization model takes as input a set of parcel attributes and projections data, including projected demographic growth and resource demand data. Specifically, our ap-

proach focuses on electricity and food demand by 2035, with annual projections derived from estimates provided by relevant institutes and companies, as detailed in Chapter 4. At each annual time step, the model selects the optimal land use(s) for each parcel from its potential land uses, taking into account constraints and an objective function for the time horizon 2035. The goal of the optimization is to maximize the food SSR. The optimization model is custom-developed in Python using the Python Optimization Modeling Objects (Pyomo) software package, which supports the formulation and analysis of mathematical models for optimization applications. To solve the optimization problem, we use the linear optimization solver CPLEX that derives solution values for the variables such that the constraints hold and the cost function takes the maximum possible value (Bynum et al., 2021).

3.7.1 Validation and reliability of the results

Projected values can be statistical or deterministic by means of intervals that encompass potential values. Such intervals are determined by domain knowledge and ensure a robust approximation of the projected value (e.g., $Value = [\underline{Value}, \overline{Value}]$) as described in (Chinneck and Ramadan, 2000) and (Ben-Tal and Nemirovski, 1999). These robust boundaries allow us to specify **best and worst case scenarios** as detailed below.

Definition 34 *In our approach, the* ***best case scenario*** *is characterized by the lowest food and electricity demands, based on low population projections, while the* ***worst case scenario*** *is characterized by the highest food and electricity demands, based on high population projections.*

By employing both scenarios, we can systematically explore the boundaries of the solution space, establishing a robust range that encompasses all other possible solutions. This approach ensures the robustness of the model and the reliability of the solutions.

3.7.2 Specifications of the optimization problem

The optimization problem is specified in Table 3.3. We outline hereafter: (i) the decision variables, (ii) the optimization constraints and (iii) the objective function.

Decision variables. The decision variables are designed to highlight land use competition among all the potential land uses that have been defined. Hence, these variables depict the surface area allocated to (1) *urban development*, (2) *crop production* and (3) *electricity production from a specific energy source* within each parcel at each time step. These variables range across a real interval and are increasing over time, reflecting the evolving nature of land use throughout the modeling period.

(1) $\forall t \in T,\ \forall p \in P_u,\ \boldsymbol{s_{t,p,u}} \in [0,\ S_p]$
(2) $\forall t \in T,\ \forall p \in P_c,\ \boldsymbol{s_{t,p,c}} \in [0,\ S_p]$
(3) $\forall t \in T,\ \forall p \in P_e,\ \boldsymbol{s_{t,p,e}} \in [0,\ S_p]$

Table 3.3: Specifications of the optimization problem.

Given:	
Unit: Year $t \in T = \{2023...2035\}$	
Unit: Parcel $p \in P = \{set\ of\ parcels\}$	
Unit: Crop $c \in C = \{set\ of\ crops\}$	
Unit: Energy source $e \in E = \{set\ of\ primary\ energy\ sources\}$	
Unit: Energy source $e_1 \in E_1 = \{set\ of\ intermittent\ RES\}$	
Set of parcels with potential of production of crop c	P_c
Set of parcels with potential of electricity production from source e	P_e
Set of parcels with potential for urban development	P_u
Projected electricity demand for a year t (GWh)	$d_t^{elec} = [\underline{d_t^{elec}}, \overline{d_t^{elec}}]$
Surface energy density from a primary source e for a parcel p (GWh/ha)	$\sigma_{p,e}$
Electricity production from a primary source e for a year t (GWh)	$P_{t,e}^{elec} = [\underline{P_{t,e}^{elec}}, \overline{P_{t,e}^{elec}}]$
Maximum penetration threshold of intermittent RE in the grid for a year t	τ_t
Surface of parcel p (ha)	S_p
Projected number of households for a year t	$h_t = [\underline{h_t}, \overline{h_t}]$
Urban development surface per new household for a year t $(ha/household)$	δ_t
Urban development surface for non residential areas for a year t (ha)	α_t
Projected demand for crop c for a year t (ton)	$d_{t,c} = [\underline{d_{t,c}}, \overline{d_{t,c}}]$
Yield of crop c for a parcel p (ton/ha)	$Yield_{p,c}$
Calories per ton of crop c $(kcal/ton)$	$kcal_c^{ton}$
Maximum surface area for converting potential areas of crop c for a year t	$S_{t,c}^{lim}$
Production of crop c for a year t (ton)	$P_{t,c}^{crop} = [\underline{P_{t,c}^{crop}}, \overline{P_{t,c}^{crop}}]$
Find:	
The optimal land use(s) for a parcel among all its potential land uses	
The surface area allocated to urban development, crop and electricity production	
Objective function:	
Maximize food SSR	
Such that the following constraints hold for each year t at the island scale:	
Local crop production must not exceed demand	
Total electricity production must meet demand	
Fossil fuels imports are decreasing	
Limitations on intermittent RE existing and new production	
Restrictions on urban development	

Constraint on crop production. The initial set of constraints pertains to annual crop production, ensuring that it does not exceed the projected annual demand in both the best case scenario and worst case scenario at each time step, in order to delineate multidimensional thresholds. Note that exceeding these thresholds while satisfying electricity and housing demands would entail producing in protected natural areas and urban areas.

Best case scenario: $\forall t \in T, \forall c \in C$,

$$\underbrace{\sum_{p \in P_c} \boldsymbol{s_{t,p,c}} * Yield_{p,c} + P^{crop}_{t_0,c}}_{\underline{P^{crop}_{t,c}}} \leq \underline{d_{t,c}} \tag{3.1}$$

Worst case scenario: $\forall t \in T, \forall c \in C$,

$$\underbrace{\sum_{p \in P_c} \boldsymbol{s_{t,p,c}} * Yield_{p,c} + P^{crop}_{t_0,c}}_{\overline{P^{crop}_{t,c}}} \leq \overline{d_{t,c}} \tag{3.2}$$

Constraint on electricity production. The second set of constraints ensures that total electricity production, from both new and existing facilities, meets the projected electricity demand for each time step. This alignment is necessary for both the best case scenario and worst case scenario. These constraints illustrate the impact of electricity generation on land use, emphasizing the primary energy source used. The goal is to balance electricity supply with demand while accounting for the land requirements of different electricity production systems.

Best case scenario: $\forall t \in T$,

$$\sum_{e \in E} \underbrace{\sum_{p \in P_e} \boldsymbol{s_{t,p,e}} * \sigma_{p,e} + P^{elec}_{t_0,e}}_{\underline{P^{elec}_{t,e}}} = \underline{d^{elec}_t} \tag{3.3}$$

Worst case scenario: $\forall t \in T$,

$$\sum_{e \in E} \underbrace{\sum_{p \in P_e} \boldsymbol{s_{t,p,e}} * \sigma_{p,e} + P^{elec}_{t_0,e}}_{\overline{P^{elec}_{t,e}}} = \overline{d^{elec}_t} \tag{3.4}$$

Constraint on fossil fuels imports. The third set of constraints focuses on fossil fuels imports. This constraint is designed to ensure that electricity generation from imported fossil fuels gradually declines to zero throughout the planning horizon. This transition supports energy independence and aligns with the SDGs by prioritizing local RES (UN, 2015).

Constraint on intermittent RE production. The proportion of intermittent RE in the electricity mix can be adjusted over time, allowing for an adaptive strategy for electricity production that can respond to evolving conditions and technological advancements. Therefore, a time-dependent maximum threshold is set for ground-mounted PV and wind power production to manage the variability of intermittent RES and maintain grid reliability in island systems (Alves et al., 2020).

Best case scenario: $\forall t \in T$,

$$\sum_{e_1 \in E_1} \sum_{p \in P_{e_1}} \boldsymbol{s_{t,p,e_1}} * \sigma_{p,e_1} + P^{elec}_{t_0,e_1} \leq \tau_t * \left(\sum_{e \in E} \underline{P^{elec}_{t,e}} \right) \tag{3.5}$$

Worst case scenario: $\forall t \in T$,

$$\sum_{e_1 \in E_1} \sum_{p \in P_{e_1}} \boldsymbol{s_{t,p,e_1}} * \sigma_{p,e_1} + P^{elec}_{t_0,e_1} \leq \tau_t * \left(\sum_{e \in E} \overline{P^{elec}_{t,e}} \right) \tag{3.6}$$

Constraint on solar self-consumption. This set of constraints reflects the intention to preserve land and limit the development of ground-mounted PV systems due to the low power density of solar energy (Trainor et al., 2016). We assume that some urban parcels will be equipped with rooftop photovoltaic panels for solar self-consumption. This setup allows industrial or domestic consumers to directly use their own generated electricity, thereby reducing dependency on the power grid and fostering a decentralized energy system. By promoting the installation of rooftop PV systems in urban areas, the need for extensive ground-mounted PV installations -which consume valuable land that could be used for other purposes- is reduced. This approach not only supports land optimization but also enhances energy self-sufficiency within urban environment (Lis et al., 2024).

Constraint on urban development. This set of constraints regulates urban sprawl driven by urban growth, taking into account economic development and projected demographic growth under both the best case and worst case scenarios. It aims to concentrate urban development within predefined zones.

Best case scenario: $\forall t \in T$,

$$\sum_{p \in P_u} \boldsymbol{s_{t,p,u}} = \delta_t * (\underline{h_t} - h_0) + \alpha_t \tag{3.7}$$

Worst case scenario: $\forall t \in T$,

$$\sum_{p \in P_u} \boldsymbol{s_{t,p,u}} = \delta_t * (\overline{h_t} - h_0) + \alpha_t \tag{3.8}$$

Constraint on land use conversion of potential areas. At each time step, a maximum surface area is set for converting potential areas designated for crop production into active production areas. This constraint prevents the full conversion of all available potential areas in the initial phases, thereby managing land use over time. The surface area limit varies based on the type of food crop, enabling tailored land use planning that aligns with the specific needs of each crop.

$\forall t \in T, \forall c \in C$,

$$\sum_{p \in P_c} \boldsymbol{s_{t,p,c}} \leq S^{lim}_{t,c} \tag{3.9}$$

Maximize food SSR. The objective function is the food SSR, which considers the best or worst case value of $d_{t,c}$ (projected demand for crop c). This ratio is calculated specifically for the crops included in the model. Then, the function to maximize is:

$\forall t \in T$,

$$\sum_{c \in C} \sum_{p \in P_c} \frac{\boldsymbol{s_{t,p,c}} * Yield_{p,c} * kcal_c^{ton}}{\sum\limits_{c \in C} d_{t,c} * kcal_c^{ton}} \tag{3.10}$$

Ultimately, a map of optimal land uses is generated for each time step, incorporating various comprehensive scenarios.

3.7.3 Implementing comprehensive scenarios within the optimization model

Comprehensive scenarios are integrated into the optimization model through the following constraints: (1) the *constraint on crop production*, which incorporates the dietary behaviors of the population, (2) the *energy-related constraints*, which account for the contributions of diverse energy sources to electricity production, and (3) the *constraint on urban development*, which specifies different urban densification rates. We now outline each constraint designed to incorporate the comprehensive scenarios. The other constraints defined in the optimization model are not scenario-dependent. Let Ω represent the set of comprehensive scenarios.

Constraint on crop production. We account for variations in food crop demand based on the dietary behaviors of the population.

Best case scenario: $\forall t \in T, \forall c \in C, \forall \omega \in \Omega$,

$$\sum_{p \in P_c} \boldsymbol{s_{t,p,c,\omega}} * Yield_{p,c} + P_{t_0,c}^{crop} \leq \underline{d_{t,c,\omega}} \tag{3.11}$$

Worst case scenario: $\forall t \in T, \forall c \in C, \forall \omega \in \Omega$,

$$\sum_{p \in P_c} \boldsymbol{s_{t,p,c,\omega}} * Yield_{p,c} + P_{t_0,c}^{crop} \leq \overline{d_{t,c,\omega}} \tag{3.12}$$

Constraint on electricity production. We consider the amount of imported biomass variable. In particular, biomass imports are considered across different time horizons in the model, where it can be classified as either a supplementary or primary energy source. This approach enables to reflect diverse strategies for electricity production and possible shifts in reliance on imported biomass over time.

Constraint on intermittent RE production. Due to technological advancements, the share of intermittent RE in the electricity mix is expected to increase in the future (Alves et al., 2020). We account for this flexibility, with specific targets set for the 2035 horizon.

Best case scenario: $\forall t \in T, \forall \omega \in \Omega$,

$$\sum_{e_1 \in E_1} \sum_{p \in P_{e_1}} \boldsymbol{s_{t,p,e_1,\omega}} * \sigma_{p,e_1} + P_{t_0,e_1}^{elec} \leq \tau_{t,\omega} * \left(\sum_{e \in E} \underline{P_{t,e}^{elec}} \right) \tag{3.13}$$

Worst case scenario: $\forall t \in T, \forall \omega \in \Omega$,

$$\sum_{e_1 \in E_1} \sum_{p \in P_{e_1}} \boldsymbol{s_{t,p,e_1,\omega}} * \sigma_{p,e_1} + P_{t_0,e_1}^{elec} \leq \tau_{t,\omega} * \left(\sum_{e \in E} \overline{P_{t,e}^{elec}} \right) \tag{3.14}$$

Constraint on solar self-consumption. We consider a varying share of solar self-consumption within the electricity mix. Specifically, different size limits are specified for urban parcels eligible for solar installations intended for industrial or domestic self-consumption. This variation significantly impacts electricity production from solar self-consumption, thereby influencing the broader dynamics of electricity generation and consumption.

Constraint on urban development. We specify different values for predefined parameters, such as the urban development surface per new household and the urban development surface for non-residential areas. These variations reflect multiple levels of urban densification, capturing various dynamics of urban development.

Best case scenario: $\forall t \in T, \forall \omega \in \Omega$,

$$\sum_{p \in P_u} \boldsymbol{s_{t,p,u,\omega}} = \delta_{t,\omega} * (\underline{h_t} - h_0) + \alpha_{t,\omega} \tag{3.15}$$

Worst case scenario: $\forall t \in T, \forall \omega \in \Omega$,

$$\sum_{p \in P_u} \boldsymbol{s_{t,p,u,\omega}} = \delta_{t,\omega} * (\overline{h_t} - h_0) + \alpha_{t,\omega} \tag{3.16}$$

Based on the analysis conducted around the optimization process, we present an overview of this final modeling step in the flow chart shown in Figure 3.7.

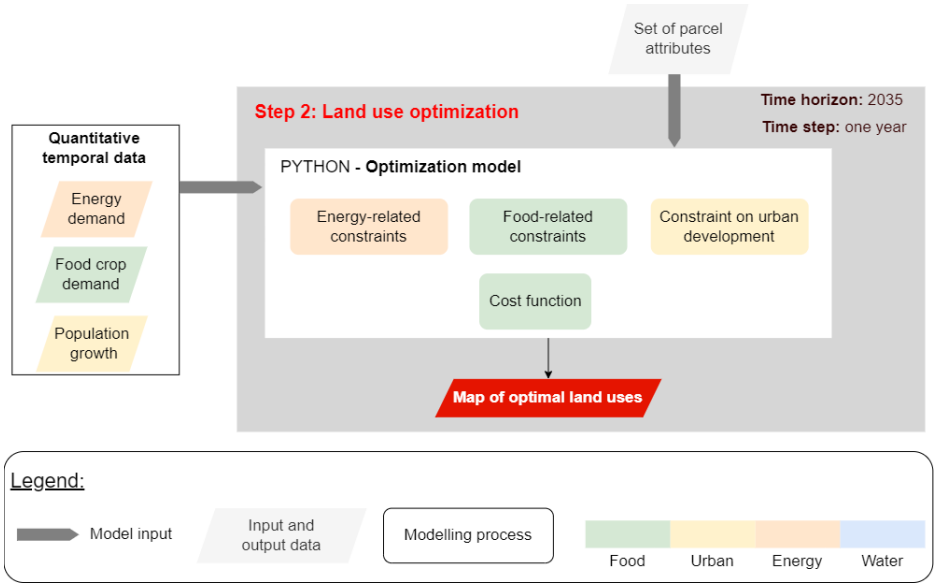


Figure 3.7: Flow chart of the optimization process.

Finally, the integrated methodological framework is depicted in Figure 3.8.

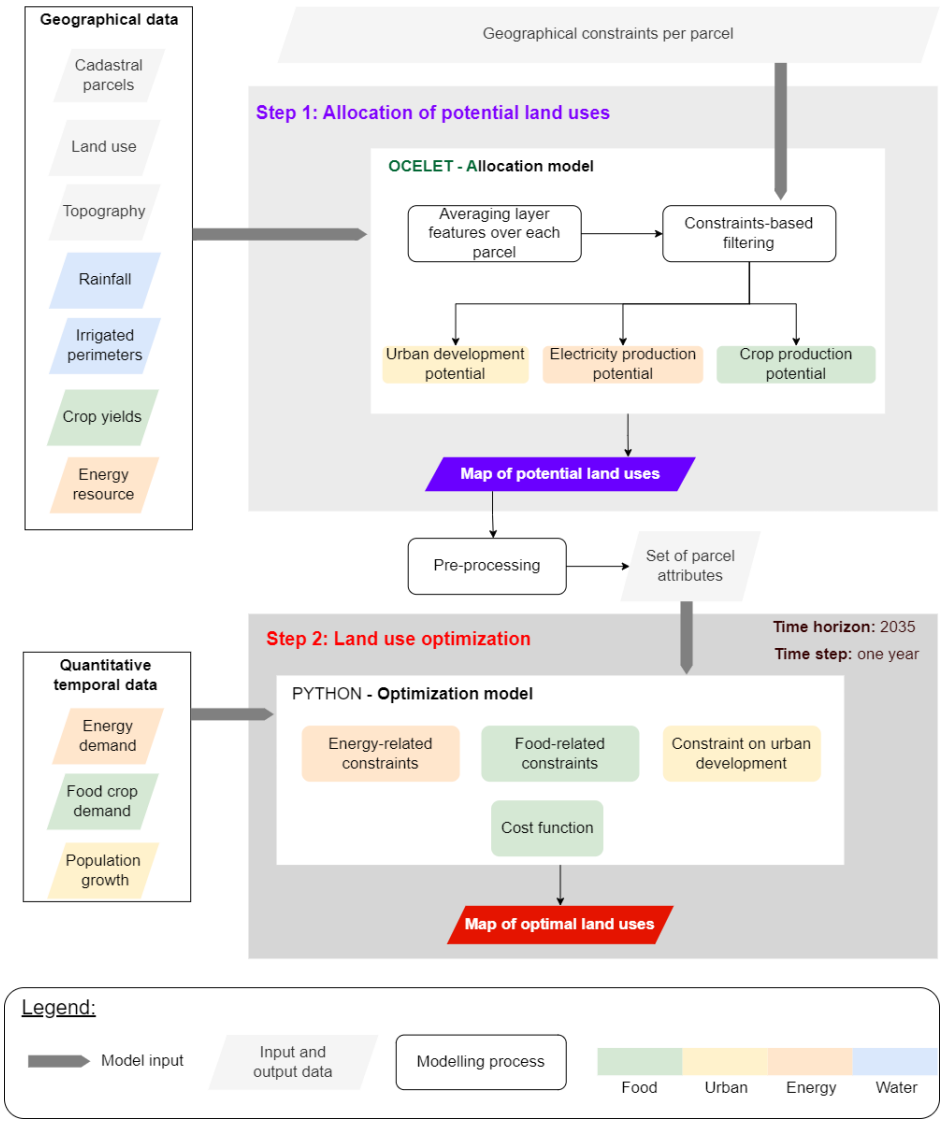


Figure 3.8: Integrated methodological framework.

3.8 Summary

We presented our integrated modeling framework that highlights land use competition between the uses of local resources and urban development. This framework integrates two models, enabling the consideration of territorial specificities, spatio-temporal and geographical constraints, and an objective function -the food SSR- to be maximized. The model's generic design ensures replicability across other small islands with similar characteristics. Its flexibility allows stakeholders to explore multiple scenarios. Additionally, it provides tools for assessing the combined impacts of resource uses and urban development, enabling optimized land management. This approach has been evaluated on a case study with extensive field data, a small island characterized by multi-sectoral vulnerabilities: Reunion island. We present this in Chapter 4.

CHAPTER 4

Case study and evaluation: Reunion island

Reunion island is an overseas French department located in the Indian Ocean, approximately 200 km southwest of Mauritius and 900 km east of Madagascar. The island is highly reliant on imported food and energy sources, making it vulnerable to any disruptions in supply chains (CIRAD, 2021). Its population, which stood at 871,157 in 2021 (INSEE, 2024), is expected to exceed one million by 2050 under a reference scenario (INSEE, 2022). This population growth, combined with decreasing household sizes, is expected to drive increased demand for housing by 2035 (INSEE, 2018), contributing to further urban sprawl (SAR, 2011). This urban sprawl has a profound impact on land due to these severe territorial constraints. Notably, it leads to the conversion of agricultural land (DEAL, 2017). Therefore, land use planning on Reunion is a critical challenge, given the island's limited space (with a surface area of 2,512 km^2) and the need to preserve natural areas.

A land use map of Reunion island, delineated by cadastral parcels, is illustrated in Figure 4.1. The map is derived from various geographical data sources, including an original land use map (Le Mézo et al., 2022) and a cadastral parcel layer (Etalab, 2023). Three main areas are highlighted: agricultural areas, artificial areas, and natural areas including forest plantations. White spaces represent areas between parcels, such as roads, waterways, as well as the volcano. Notably, most natural areas and forest plantations are located within the national park, which covers 42 % of the island's territory. Meanwhile, agricultural and artificial areas are concentrated mainly along the coast. In 2018, the island's **Utilized Agricultural Area** (UAA), labeled as 'Agricultural area' on the map, spanned 42,000 hectares. This land was primarily used for sugarcane cultivation (54.4 %), livestock breeding (29 %), and other crops, including fruits and vegetables (16.6 %) (CIRAD, 2021).

Definition 35 *The **Utilized Agricultural Area** (UAA) refers to the total area used for agricultural purposes, including arable land (such as temporary pastures, fallow land, greenhouse crops, family gardens, etc.), areas permanently under grass cover, and permanent crops (vines, orchards, etc.) (INSEE, 2020).*

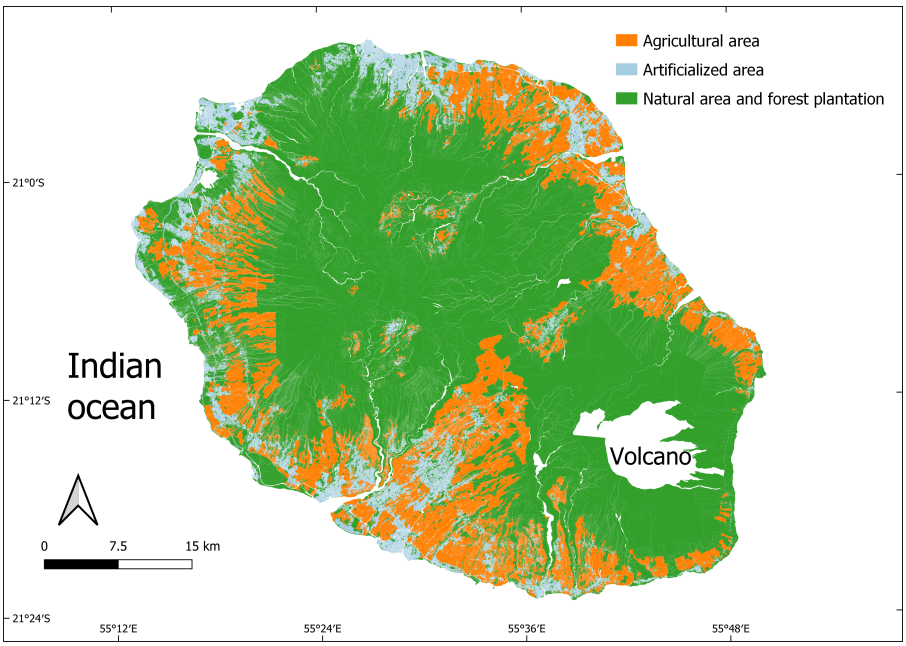


Figure 4.1: Land use map delineated by cadastral parcels.

4.1 Evolution of dietary behaviors and agricultural practices since the 18th century

Insights into the challenges of food system resilience are closely tied to the island's agricultural practices and dietary behaviors throughout its history (Guell et al., 2022). Over the centuries, the Reunionese food system has undergone significant transformations (CIRAD, 2021) (Méjean et al., 2020). Examining these changes, from past practices to current trends, provides knowledge for strengthening the resilience of the food system.

4.1.1 Evolution of agricultural practices (18th century - 1940)

Cereal growing on Reunion Island began in the 18th century, with rice and wheat production becoming substantial by 1783, reaching up to 4 tons for wheat. However, rice cultivation was later abandoned due to climatic conditions, such as droughts, and a lack of labor. In the early 19th century, sugarcane cultivation began to expand, growing from 21 tons in 1815 to 73,000 tons in 1860. This increase was driven by waves of immigration that intensified after the abolition of slavery in 1848. Consequently, by 1860, 62 % of agricultural land was dedicated to sugarcane. This shift led to a reliance on food imports due to the decline of subsistence farming around 1850 and the need to meet the population's demands. After a decline in sugarcane production at the end of the 19th century due to health issues, production rebounded between 1920 and 1940, rising from 40,346 tons in 1922 to 110,702 tons by 1940. By the mid-20th century, Reunion Island's agricultural lands were divided into three zones: the *"sugarcane domain"* on the coastal plains, the *"tobacco and geranium domain"* in the Highlands and the Plains under the Wind, and at higher altitudes, the cirques formed the *"domain of vegetable and shrub cultivation"* (CIRAD, 2021). However, the events of World War II in 1940 drastically altered this agricultural landscape.

4.1.2 Forced dietary and agricultural transition (1940-1942)

In 1940, World War II led to a blockade of Reunion Island for nearly two years, resulting in significant consequences for food, energy, and health through:

- The near-complete substitution of petroleum with a biofuel derived from sugarcane alcohol.
- The introduction of subsistence crops on two-thirds of the agricultural land, including cassava, soybeans, and red beans intercropped with maize. This transition presented a major challenge for an island heavily reliant on monoculture, as it needed to develop subsistence farming to meet local needs and reduce sugarcane production.
- The cultivation of medicinal plants to address shortages in pharmaceutical supplies.
- The development of alternative construction materials in the building sector, such as replacing cement with "sugar mortar".

This forced transition, coupled with disruptions of the island's logistics chain, led to widespread nutritional deficiencies, marked by socio-economic disparities. Between 1940 and 1948, fat consumption was notably low, and there were significant shortages of meat, fish, and dairy products. Access to animal proteins was largely restricted to wealthier populations. From a health perspective, high mortality rates were due to the proliferation of mosquitoes, which transmitted diseases such as malaria, yellow fever, and dengue.

In summary, this forced transition triggered agricultural, energy, and ecological difficulties, as well as economic challenges, including the loss of income from sugar exports, logistical disruptions, health crises, and socio-cultural impacts such as poverty and class inequalities (Corral-Broto, 2021). This multi-sectoral crisis underscored the island's dependence on external resources and its vulnerability to such shocks. However, despite the lessons learned during this period, Reunion Island did not move towards long-term subsistence farming...

4.1.3 Current agricultural production

Currently, over 50 % (54 %) of the UAA is devoted to sugarcane cultivation, while forage crops account for 28 % of the UAA. The remaining 18 % is allocated to fruits and vegetables, along with traditional sectors such as aromatic plants, coffee, vine, and lentils. In total, agricultural land accounts for nearly 17 % of the island's territory. At the same time, there is a noticeable trend towards farm diversification and the development of subsistence farming for self-consumption across the island, with distinct regional characteristics. In the east, agroforestry is particularly prominent; livestock farming is mainly concentrated in the south; while the west faces issues of land abandonment and encroachment (CIRAD, 2021). While significant changes in agricultural practices have occurred over time, dietary behaviors have also evolved notably, especially by the end of the 20th century.

4.1.4 Evolution of dietary behaviors

Since the 1980s, the diet in Reunion Island has undergone significant changes. Before this time, meals were largely based on rice and grains, with limited inclusion of animal proteins and fats. However, starting in the 1980s, traditional Creole meals began to include appetizers and desserts, while bread and pasta started to replace rice as staples. In the 1990s and 2000s, new eating trends have emerged, characterized by the consumption of simplified meals like pizza, sandwiches, and hamburgers (Méjean et al., 2020). Although

the diet remains predominantly Creole, with rice as a staple, distinct dietary behaviors have emerged, influenced by social and economic factors such as age and household income. These variations are illustrated in Figure 4.2:

- On one hand, there is a *Traditional* diet associated with the Creole model, which focuses on rice and poultry, involves an under-consumption of fruits and vegetables, and a high consumption of oils. These dietary characteristics are particularly prevalent among lower-income households.
- On the other hand, there is a *Mediterranean* diet characterized by lower consumption of rice and poultry, and higher consumption of fruits, vegetables, and olive oil, alongside a high intake of sugary drinks. These characteristics are more common among wealthier households.

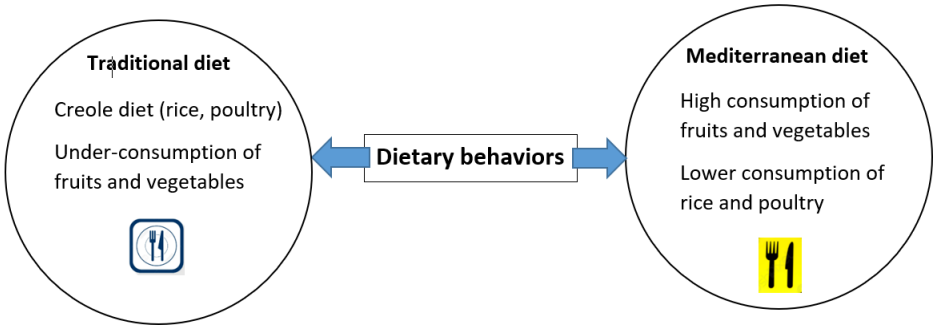


Figure 4.2: Dietary behaviors in Reunion. Adapted from (INSEE, 2021), (Méjean et al., 2020), and (INSEE, 2015).

Understanding the historical context of dietary behaviors and agricultural practices is essential for embedding our approach within the framework of food system resilience in island environments. This perspective informs the selection of appropriate crops, as well as the relevant dietary behaviors and agricultural practices for scenario development. For instance, incorporating local rice production into our scenarios makes sense given its historical presence, despite its current near-zero production. The scenario-building process has also been significantly influenced by insights gathered from field interviews.

4.1.5 Field interviews: understanding today's context

Over a four-month period in Reunion, we conducted numerous interviews with a diverse range of local stakeholders. These interviews enabled the collection of non-public data from the department and *Météo France*, and were primarily aimed at contributing to the development of comprehensive scenarios by incorporating both qualitative and quantitative information. Through this process, it became evident that the population is increasingly aware of the island's vulnerabilities, particularly its dependence on food imports. This awareness has given rise to associations such as *Association Riz Réunion* and *Riziculteurs Péi 974*, which are focused on reintroducing rice cultivation. Additionally, citizen groups such as *Oasis Réunion* are actively proposing solutions to public authorities to achieve food self-sufficiency. Despite the growing number of stakeholders, communication remains challenging due to differing future visions and approaches. The interviews also highlighted ongoing debates about sugarcane, which is mainly intended for export. Some stakeholders see sugarcane, as a hindrance to support the food self-sufficiency process, while others advocate for its preservation due to economic reasons. Notably, we were unable to contact *Tereos*,

an agro-industrial actor in the cane-sugar-rum-energy value chain, to discuss matters related to food self-sufficiency and the possible diversification of sugarcane. Therefore, sugarcane remains a major pillar of the food system, and its production levels are assessed through comprehensive scenarios. The comprehensive scenarios we developed capture the diverse perspectives of local stakeholders we encountered and propose compromises to facilitate decision-making.

An overview of the key actors involved, the questions asked, the type of data collected, and the specific objectives of these interviews is provided in Figure 4.3.

Regional planning	agorah	Urban planning agency structured to study and anticipate the impact of demographic growth on the island	1) How much land will be taken up by urban sprawl in 2035 ? 2) How much land will be lost to urban development ? 3) How much land will energy projects take up ?	GIS / quantitative / qualitative data	Assessing the impact of urban sprawl on land as well as on the uses of resources
Energy	SPL Enérgie Réunion (Horizon Reunion)	Public company supporting local authorities in the development of energy projects	1) What are the scenarios for energy demand and production by activity sector and by energy source in 2035 ? 2) What is the outlook for the penetration threshold of intermittent RES in the grid ? 3) What strategies are put in place to achieve energy self-sufficiency ?	Quantitative / qualitative data	Study of the influence of electricity production sources on land use
Water	Office de l'eau	Implements water management policy	1) GIS data for irrigated areas for agriculture ? 2) What will be the water requirements for food crops in 2035 ?	GIS / quantitative data	Determining water requirements for food crops
Agriculture / Dietary behaviors	CEMOI	Indian Ocean Centre for Economics and Management	1) What are the current studies on dietary behaviors ? 2) Which consumption trends have been observed ?	Qualitative data	Determine diverse dietary behaviors and their evolution in relation to socio-cultural practices
	Association Riz Reunion Riziculteurs PEI 974	Associations of agricultural stakeholders that aim of reintroducing rainfed rice cultivation in Reunion	1) What is the theoretical yield per hectare for rice ? 2) What type of farming practices are recommended for rice cultivation ? 3) What are the land use requirements for consdering a rice parcel ?	Quantitative / qualitative data	Evaluation of theoretical rice production up to 2035
	CIRAD La Réunion	Research organisation	1) What is the vision regarding the objective of full food self-sufficiency (impact on land, social acceptance, etc.) ? 2) What are the specific characteristics of Reunion's agriculture (inputs, labour) ? 3) GIS data on agricultural yields ?	GIS / qualitative data	Understand how the issue of food self-sufficiency is addressed on the island and what are the associated challenges
	Oasis Réunion	Group of citizens aiming to transform Reunion's agriculture	1) What is the potential of conversion of agricultural wastelands ? 2) How feasible is organic farming at the island scale ?	Quantitative / qualitative data	Understand the strategies that can enhance the food self-sufficiency process

Figure 4.3: Overview of field interviews.

Overall, this analysis of the historical context and insights from field interviews reveals the island's dependence on food products not produced on the territory (data.gouv,

2020). Currently, the state of the food self-sufficiency process on the island is concerning, primarily due to high rice consumption and virtually no local production (Billen et al., 2024). Therefore, it is essential to enhance the food self-sufficiency process to mitigate external disruptions, as underscored by historical events like the blockade during World War II (Corral-Broto, 2021), which illustrates the vulnerability of the island's food system.

4.2 Defining and locating potential areas in Reunion

As depicted in Figure 4.1, the coexistence of agricultural and urban areas in Reunion is largely driven by the significant expanse of the national park. This sets the stage for land use competition.

4.2.1 Food and energy resources in Reunion Island

Emphasizing land use competition in our approach begins with the selection of specific food and energy resources according to the territory's characteristics.

Energy. Various energy sources are taken into account, encompassing all those involved in electricity production. Imported energy sources include imported biomass, oil, and coal, while local sources consist of wind, solar, hydro, and locally sourced biomass. Hereafter, local biomass is considered to come exclusively from a fibrous residue of sugarcane, known as bagasse (DEAL, 2020). Imported biomass, in this context, refers to wood pellets imported from North America. In 2022, the electricity mix was distributed as follows: oil (43 %), hydroelectric power (21 %), coal (19 %), sugarcane bagasse (6 %), imported biomass (2 %), and other renewables (9 %) (OER, 2023a).

Food. We focus on the following food products: **fruits, vegetables, and rice**. These food products are representative of the Creole diet and exhibit the most uneven consumption patterns across the territory, largely influenced by household incomes (INSEE, 2015). By selecting these specific food products, we capture the diverse dietary behaviors that exist, as reflected in their varying consumption levels.

4.2.2 Specifications of potential land uses

Given the careful selection of food and energy sources, it is crucial to assess the future land footprint associated with their uses, along with the impacts of urban development, to accurately model land use competition on Reunion Island.

Energy. Regarding electricity production systems, ground-mounted solar PV systems contribute to land use competition, aligning with the objectives related to electricity project development (DEAL, 2020). The objectives for onshore wind turbines will primarily focus on renewing existing wind farms in the coming years (DEAL, 2020), which means that future production is not expected to contribute to land use competition. We do not consider future projects of electricity production involving coal, and oil, as these are excluded from the modeling (refer to the *optimization constraints* in subsection 3.7.2). Prospects for hydroelectricity will concentrate on optimizing existing power plants (DEAL, 2020), making the land footprint of future hydroelectric projects negligible. Similarly, the future land footprint of biomass power plants is considered negligible.

Food. The future land footprint associated with the cultivation of rice, fruits, and vegetables are taken into account, and we consider that fruit and vegetables can be cultivated in the same areas.

Therefore, we limit the set of potential land uses to the four most relevant: (1) potential for electricity production from ground-mounted PV systems, (2) potential for rice production, (3) potential for fruit and vegetable production, and (4) potential for urban development.

With these potential land uses identified, it is essential to determine their exact locations and assess whether these areas might compete with one another. However, the spatial distribution of these potential areas is highly dependent on the agricultural practices employed, particularly regarding the conversion of some agricultural parcels for alternative purposes. In that sense, what impact do different agricultural practices have on the quantity and spatial distribution of these potential areas ? How can our findings offer stakeholders actionable insights for effective land management ?

To answer these questions, we first need to develop a set of agricultural practices that are informed by both historical practices and insights from field interviews (refer to subsection 4.1). Given that 54 % of the UAA is currently devoted to sugarcane cultivation, sugarcane serves as a key leverage point for the emergence of alternative agricultural practices. Accordingly, we propose to incorporate the following two agricultural practices into our comprehensive scenarios:

- *Sugarcane conservation:* The current surface area dedicated to sugarcane cultivation is maintained, constraining future crop production (rice, fruits, vegetables), ground-mounted PV systems and urban development in agricultural wastelands or in rotation with vegetable crops in the case of rice cultivation (information provided by *Association Riz Réunion*).

- *Subsistence farming:* Crops intended for local consumption are prioritized over sugarcane. It illustrates the commitment to support the food self-sufficiency process.

Then, as outlined in subsection 3.5, we proceed with the allocation of potential land uses for each parcel under for both **scenario A (sugarcane conservation)** and **scenario B (subsistence farming)**. The allocation model requires multiple geographical data from various sources and takes into account various geographical constraints previously identified.

4.2.3 Data acquisition

These geographical data and constraints are specified in Table 4.1 and Table 4.2 for both scenarios A and B. It is important to note that we consider only one production cycle per year for rice, spanning four months between November and February.

Table 4.1: Specifications of geographical data.

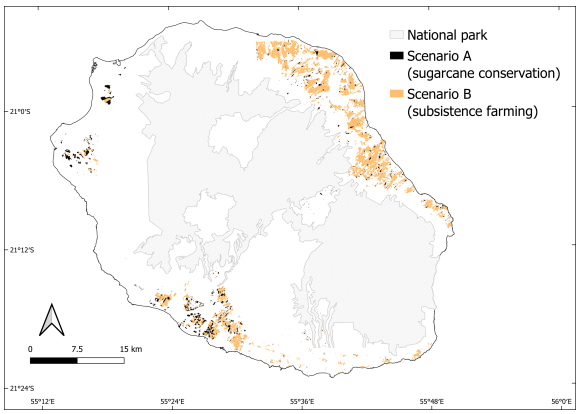
Geographical data	Specifications
Land use	The land use map for 2021 is obtained from CIRAD in vector format. The detailed methodology of land use classification is documented in (Le Mézo et al., 2022).
Irrigated perimeters	The irrigated perimeters layer is confidential data collected from the Reunion department in vector format.
Topography	The topography layer is extracted from (CGIAR-CSI, 2008) in raster format.
Cadastral parcels	The cadastral parcel layer is sourced from (Etalab, 2023) in vector format.
Rainfall	Monthly rainfall data, provided by *Météo France*, are confidential and have been converted into raster format.
Energy resource	Yearly data on the potential for practical photovoltaic power are extracted from (World Bank Group, 2020) in raster format.
Crop yields	The crop yields layer, in vector format, is confidential data derived from the work of (Russeil, 2023).

Table 4.2: Constraint specifications for the allocation of potential land uses per parcel in the Ocelet model.

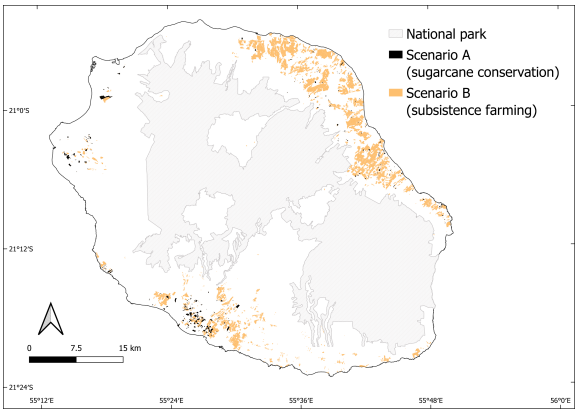
Constraints	**Rice**	**Urban**	**PV**	**Vegetables and fruits**
Permitted land use for **Scenario A**	Agricultural wastelands, vegetable crops	Agricultural wastelands	Agricultural wastelands	Agricultural wastelands
Permitted land use for **Scenario B**	Agricultural wastelands, vegetable crops, **sugarcane**	Agricultural wastelands	Agricultural wastelands, **sugarcane**	Agricultural wastelands, **sugarcane**
Minimal surface area	240 m^2 *(Association Riz Réunion)*	/	3000 m^2 *(author)*	/
Maximal altitude	1200 m *(Association Riz Réunion)*	/	/	1800 m (Le Mézo et al., 2022)
Maximal slope	10 % (Makungwe et al., 2021)	30 % (Lajoie and Hagen-Zanker, 2007)	10 % (Nebey et al., 2020)	30 % (DAAF, 2017)
Minimum water requirements	300 *mm/cycle (Association Riz Réunion)*	/	/	300 *mm/year* (DAAF, 2017)
Maximal neighborhood distance with urban parcels	/	20 m *(author)*	/	/

4.2.4 Location of potential areas

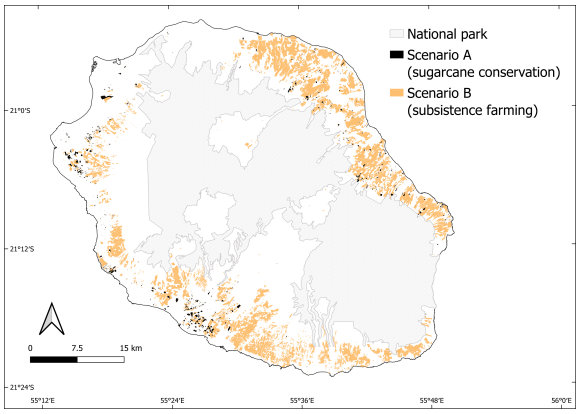
Maps of potential land uses are presented for potential areas for rice production (Figure 4.4a), ground-mounted PV systems (Figure 4.4b), fruit and vegetable production (Figure 4.4c), and urban development (Figure 4.4d) under both scenario A (sugarcane conservation) and scenario B (subsistence farming).



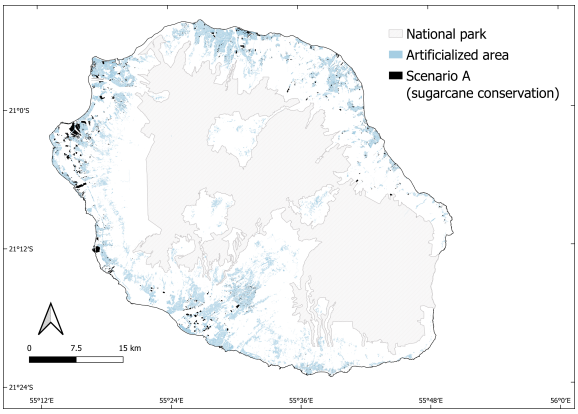
(a) Potential areas for rice production.



(b) Potential areas for ground-mounted PV systems.



(c) Potential areas for fruit and vegetable production.



(d) Artificial and potential areas for urban development.

Figure 4.4: Maps of potential land uses.

Firstly, a comparison of these figures reveals that the potential areas in Figures 4.4a, 4.4b, and 4.4c are significantly greater for scenario B compared to scenario A. This increase is due to the conversion of some sugarcane areas for alternative purposes, such as electricity production and diversified crop production. Secondly, we observe that the potential areas for rice production and ground-mounted PV systems (Figure 4.4a and Figure 4.4b) are concentrated in the same sites: mainly in the northeast of the island, with a smaller portion in the southwest for scenario B, and mainly in the southwest for scenario A. This illustrates the possible future land use competition between agriculture and energy. It is important to note that in scenario B (subsistence farming), the absence of potential areas for rice production and ground-mounted PV systems in the west is due to the excessively steep slopes (> 10 %) of many sugarcane parcels. Conversely, as depicted in Figure 4.4c, potential areas for fruit and vegetable production are more scattered along the coast in scenario B. In the eastern region, we identify areas that directly compete with rice and ground-mounted PV systems, unlike those in the western region. The presence of potential areas for fruit

and vegetable production in the west can be attributed to the inclusion of parcels with steep slopes (< 30 %) within these areas. In scenario A (sugarcane conservation), the same locations are identified for potential areas for fruit and vegetable production, rice production, and ground-mounted PV systems, mainly in the southwest. Finally, Figure 4.4d illustrates both existing artificial areas and potential areas for urban development for scenario A. The same map applies to scenario B (refer to Table 4.2). Here, we observe that potential areas for urban development are concentrated in the northwest, very close to the coast, where agricultural wastelands adjacent to urban parcels are located. Therefore, we can assume that the locations of these potential areas do not directly compete with the other defined potential areas.

These maps offer valuable insights into the location of potential areas and the strategies required for their conversion. Priority should be given to converting parcels with unique potential land use over those with multiple potential land uses to minimize conflicts between urban, energy, and agricultural uses. This approach helps answer the question: Among these parcels, which are the most easily convertible to a particular use ? Accordingly, these maps are essential tools for spatial analysis, enabling informed decision-making for land use management on Reunion Island. They also provide a foundation for policies that favor the conversion of agricultural land for subsistence crops. Furthermore, these maps underscore the perspective of land use competition, highlighting the need to consider compromises when conflicts arise. To address this, it is important to examine how land use competition affects the food SSR. In this context, we study the impact of various sources of electricity production on the food SSR through our optimization model (see specifications in section 3.7.2). The previously mentioned scenarios of agricultural practices (*subsistence farming* and *sugarcane conservation*) are enhanced by incorporating different sources of electricity production by 2035. This additional layer of analysis will provide deeper insights for effective decision-making.

4.3 Data acquisition and additional constraints for optimization

The methodology for acquiring and generating projections data related to demographic growth, electricity demand, and food demand is outlined in Table 4.3. Additionally, Table 1 in the Appendix summarizes the static parameters used in the optimization model. Additional constraints, beyond those defined in section 3.7.2, need to be specified and incorporated into the optimization model:

Wind power. Electricity production from wind power is set to increase due to the renovation of the Sainte Suzanne wind farm, with an expected production of 50 GWh/year from 2023 onwards. Additionally, the Sainte Rose wind farm contributes approximately 2.3 GWh annually (data from 2021). Therefore, we assume a maximum annual electricity production of 53 GWh for the time horizon 2035 (OER, 2023c).

Hydropower. We treat hydroelectric output as a stochastic variable, following a uniform distribution within a specified range derived from hydropower data collected between 2000 and 2022 (OER, 2023c).

Local biomass. Electricity production from local biomass relies on the variable quantity of sugarcane bagasse collected over time (OER, 2023c). To simplify, we assume that the amount of bagasse harvested is directly related to the area of sugarcane cultivation and its yield.

Fossil fuels imports. Targets for reducing electricity generation from fossil fuels have been outlined by (DEAL, 2020). Based on these targets, we anticipate a significant decline in fossil fuel imports, specifically oil and coal. We assume that coal-based electricity production is reduced to zero after the first iteration, and oil-based production is phased out by the end of 2030. Consequently, electricity production will increasingly rely on local resources (solar, wind, hydro, and local biomass) and imported biomass to offset the reduction in fossil fuel supply.

Land use conversion of potential areas. For each time step, we establish the maximum surface area for converting potential areas for crop production into active production areas, given the lack of existing data.

Table 4.3: Methodology of collection and production of projections data.

Data	Description
Population	Population projection data are provided by (INSEE, 2022) for each annual time step up to 2035 using the *Omphale* simulation model, which projects population changes based on parameters such as fertility, mortality, and migration.
Electricity demand	Existing consumption data from 2022 serve as the baseline for projecting electricity demand for the horizon 2035 (OER, 2023b). Electricity demand depends on various factors, including economic development, household growth, and evolving lifestyles (DEAL, 2020). However, annual fluctuations in electricity consumption are largely driven by demographic growth (OER, 2023b). For simplicity, we assume a uniform standard of living across all inhabitants and stable electricity consumption from large consumers, local authorities and business customers. Consequently, future increases in electricity demand will only depend on the growth in the number of households on the island and the expansion of the electric vehicle fleet (DEAL, 2020).
Food demand	Similarly, existing consumption data from 2022 have been used as the baseline to project food demand for the horizon 2035 (Chambre d'agriculture, 2023) (AGRESTE, 2023). The projected increase in food demand is assumed to depend solely on the growth in the number of households on the island.

4.4 Integration of various sources of electricity production

As discussed in the previous chapter, electricity production systems utilizing intermittent RES have a significant land footprint (Trainor et al., 2016). In this context, we investigate how different sources of electricity production influence the food SSR.

4.4.1 Influence of electricity production sources on the food SSR

To represent a broad spectrum of possible electricity mixes in the future, we consider the following mixes outlined in Table 4.4:

Table 4.4: Characteristics of potential electricity mixes in the future.

Electricity mix	Specifications
Mix 1	Intermittent RE threshold is set to 32 % (EDF-SEI, 2023). Substantial biomass imports limit the deployment of ground-mounted PV systems, with biomass contributing up to 77 % of future electricity production during the planning horizon.
Mix 2a	Intermittent RE threshold is set to 50 %. Imported biomass serves as a backup energy source, contributing up to 30 % of total electricity production. Electricity generation from ground-mounted PV is on the rise during the planning horizon, with solar self-consumption considered for urban parcels smaller than 100 m^2 (from 11.1 % to 12.3 % of total electricity production).
Mix 2b	Similar to mix 2a, but solar self-consumption is considered for urban parcels smaller than 70 m^2 (from 5.9 % to 6.6 % of total electricity production).
Mix 3	Similar to mix 2a, but without considering solar self-consumption.

For scenario B (subsistence farming), none of the proposed mixes impact the food SSR. Although potential areas for rice production and ground-mounted PV systems overlap in some locations (refer to Figure 4.4a and Figure 4.4b), there are areas designated solely for ground-mounted PV, and these are sufficient to host ground-mounted PV systems regardless of the mix. As a result, areas with dual potential will not need to be converted. In the absence of land use trade-offs, policymakers can direct policies towards what they identify as an optimal electricity mix. If the criteria for selecting the optimal mix prioritize minimizing the land footprint and reducing energy imports, an electricity mix with a high share of solar self-consumption, such as mix 2a, appears to be the most preferable.

The sources of electricity production significantly influence the food SSR for scenario A (sugarcane conservation), as illustrated in Figure 4.5, showing projections up to 2035 for mixes 1, 2a, 2b and 3 for the worst case. The evolution of the food SSR can be segmented into four distinct phases. The initial phase, characterized by a sharp increase, is attributed to the attainment of 100 % SSR for fruits and vegetables. This is largely because few additional surfaces need to be converted, given the high yields per hectare and the already substantial production. After reaching this 100 %, the SSR continues to rise slightly due to the gradual conversion of potential areas for rice production into active rice-producing parcels (refer to the constraint on *Land use conversion of potential areas* in subsection 3.7.2). The increase is modest at first because the conversion rate of potential areas for rice production is low early in the simulation. For mix 3, which includes a high share of ground-mounted PV, the SSR curve remains flat during this phase due to the conversion of areas with dual potential (rice and ground-mounted PV) into ground-mounted PV systems. The third phase is marked by a significant rise in the SSR, corresponding to the accelerated conversion of parcels into rice-producing areas. A peak in the SSR is then reached at different time steps, depending on the mix. Note that the more ground-mounted PV is developed, the faster this peak is reached. After reaching this peak, a declining phase is observed. This is attributed to the impact of demographic growth on food demand. This decline follows a linear trend, as dictated by the linear population projections provided by (INSEE, 2018).

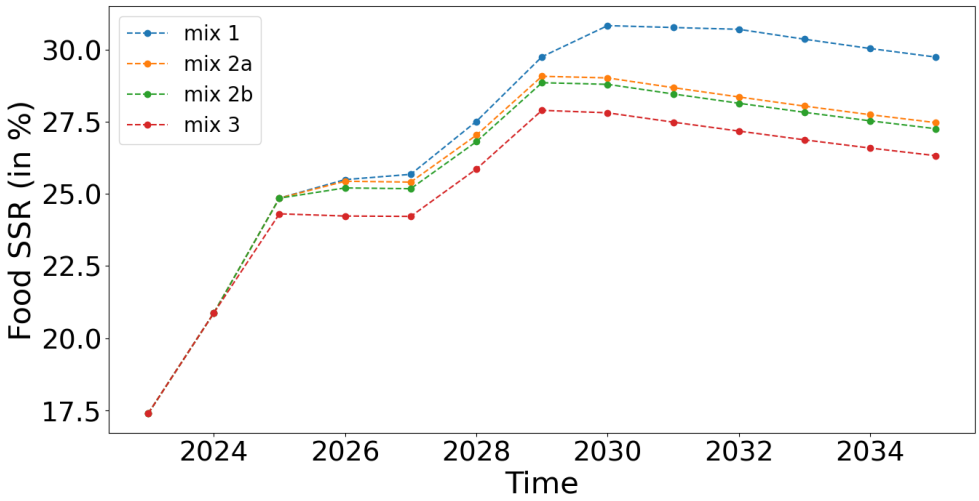


Figure 4.5: Influence of the electricity mix on the food SSR for scenario A for the worst case.

It is notable that mix 1 (refer to the specifications in Table 4.4) has a more favorable impact on the food SSR due to the limited expansion of ground-mounted PV (with penetration threshold set at 32 %) and the extensive use of imported biomass. This combination prevents land use competition between agricultural and electricity production. Conversely, mix 3 has the most detrimental impact on the food SSR, primarily due to the large surfaces required by ground-mounted PV systems, which directly compete with agricultural lands. Moreover, increasing solar self-consumption, as seen in mixes 2a and 2b, positively influences the food SSR by saving space. These differences demonstrate the model's ability to depict conflicts between agricultural and energy uses effectively.

4.4.2 Delineation of multidimensional thresholds related to food self-sufficiency

Given that the differences between the food SSR curves for mixes 1 and 2a are relatively small (with a maximum loss of 2.38 % SSR at each time step), it is meaningful to identify multidimensional thresholds related to food self-sufficiency for scenarios A and B with mix 2a, which appears more preferable than mix 1 due to lower biomass imports (refer to the specifications in Table 4.4). Multidimensional thresholds related to food self-sufficiency are then depicted for each scenario under mix 2a in Figure 4.6, using the food SSR indicator. By 2035, the food SSR is projected to range from 72 % to 90 % for scenario B (subsistence farming) and from 27 % to 32 % for scenario A (sugarcane conservation).

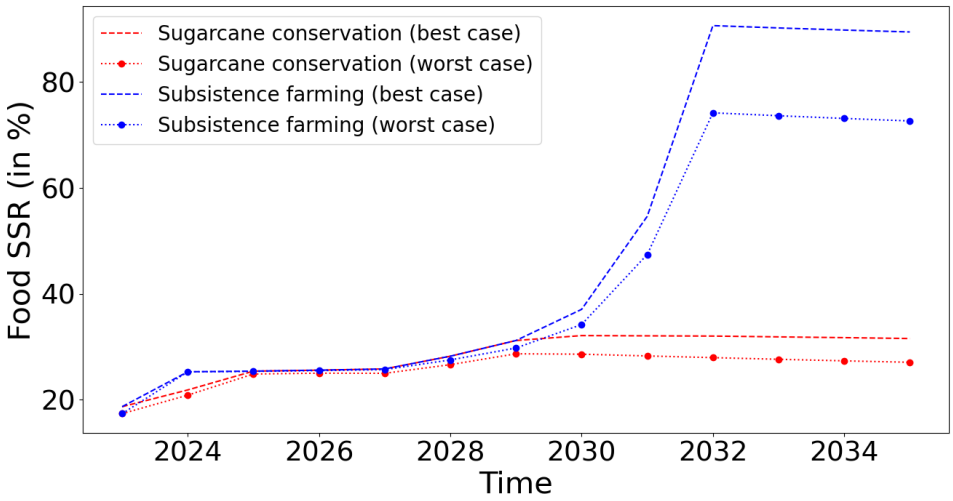
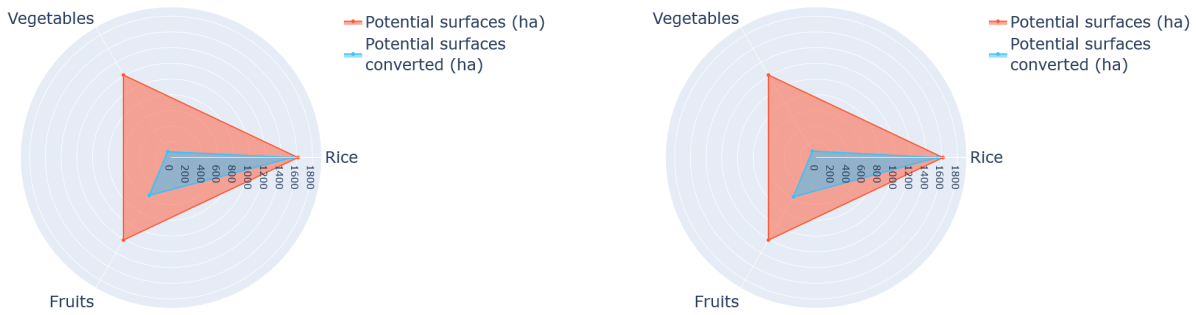


Figure 4.6: Evolution of the food SSR for scenarios A and B with mix 2a.

Finally, to understand how the food SSR reaches a peak, we plot the surfaces occupied by the three considered crops in 2030, as shown in Figure 4.7a for scenario A (sugarcane conservation) under the best case. The peak reached by 2030 is due to the conversion of all potential areas for rice production into active rice-producing areas. Then, rice becomes the limiting crop due to its low yield per hectare (2.8 to 3.3 tons/hectare) and the lack of current production. Conversely, local fruit and vegetable production can satisfy the demand until 2030. The differences between Figures 4.7a and 4.7b are minimal, as rice production occurs on multiple potential areas, reducing available land for fruit and vegetable cultivation. However, the SSR for fruits and vegetables declines by only 1 % between 2030 and 2035, decreasing from 100 % to 99 %. For scenario B (subsistence farming), the analysis reveals that all potential areas for rice production are converted by 2032 due to a larger number of surfaces.



(a) t = 2030.

(b) t = 2035.

Figure 4.7: Potential surfaces converted and potential surfaces for scenario A for the best case.

Since potential areas for fruit and vegetable production can nearly fully meet the demand by 2035 (99 %) in scenario A (sugarcane conservation), sugarcane areas with only a potential for fruit and vegetable production are largely preserved in scenario B (subsistence farming).

4.4.3 Decision support elements

Through the integration of different sources of electricity production, we demonstrated the importance of integrating land use management for both electricity and agricultural planning to effectively address challenges related to the uses of local resources. In that regard, key decision support elements include (1) minimizing land conversion by promoting solar self-consumption, (2) developing ground-mounted PV systems while limiting biomass imports, and (3) shifting agricultural practices towards subsistence farming to significantly increase the food SSR by converting suitable sugarcane parcels.

We have identified subsistence farming as a major lever for enhancing the food self-sufficiency process. Now, we can explore how specific dietary behaviors might further influence the food SSR. This raises important questions: Can changing dietary behaviors become a significant lever in increasing the food SSR while still preserving all current sugarcane production ? What would be the implications for the allocation of agricultural land ? Evaluating these aspects is crucial for crafting comprehensive roadmaps aimed at strengthening food system resilience.

4.5 Integration of dietary behaviors

As outlined in subsection 4.1.4, two dietary behaviors have been identified based on current trends on the island (INSEE, 2015). We remind the selected dietary behaviors:

- *Traditional diet:* Characterized by high consumption of rice and poultry, along with a low intake of fruits and vegetables.
- *Mediterranean diet:* Characterized by lower consumption of rice and poultry, with a higher intake of fruits and vegetables compared to the *Traditional* diet.

Details of food consumption for both diets are provided in Table 2 in the Appendix.

New scenarios are designed by combining different dietary behaviors (demand-side) with agricultural practices (supply-side) to assess their combined influence on the food SSR. The resulting four scenarios are detailed in Table 4.5.

Table 4.5: Scenarios on agricultural practices and dietary behaviors.

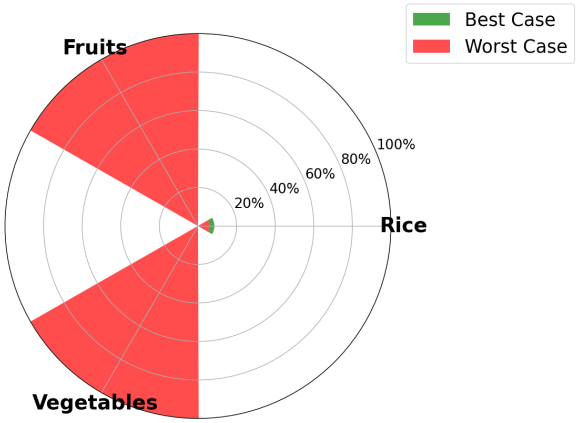
Specifications	**S1 (Business As Usual)**	**S2 (Agri shift permitted)**	**S3 (Dietary shift)**	**S4 (Dietary + agri shift permitted)**
Demand	Traditional	Traditional	Mediterranean	Mediterranean
Production	Sugarcane conservation	Subsistence farming	Sugarcane conservation	Subsistence farming

4.5.1 Influence of dietary behaviors on the food SSR

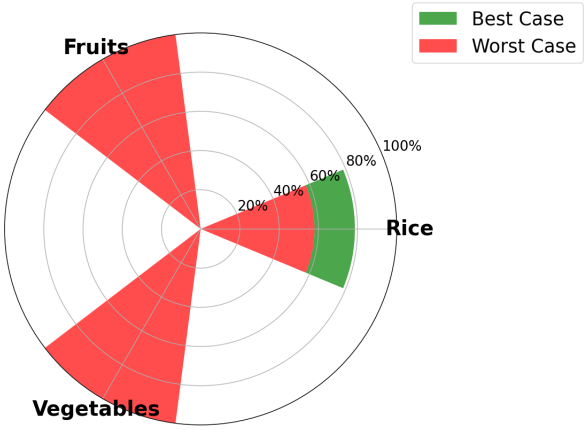
As outlined in the previous section, electricity production can impact the food SSR. In this section, we focus on electricity production that relies heavily on ground-mounted PV and includes limited biomass imports through 2035. While this choice intensifies land

use competition, which negatively impacts the food SSR, it also mitigates dependence on imported energy sources.

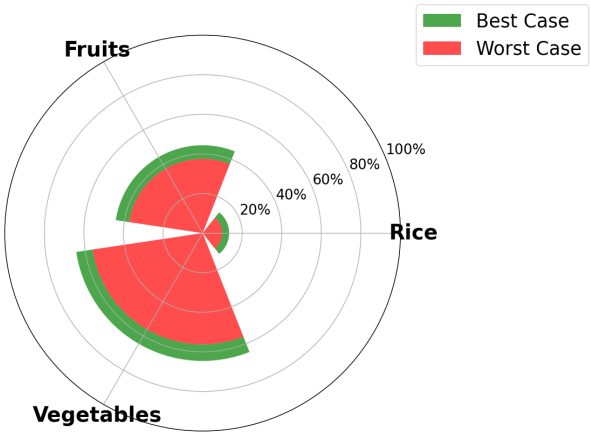
The crop-specific SSR for 2035 are illustrated in Figure 4.8a for scenario S1, Figure 4.8b for scenario S2, Figure 4.8c for scenario S3, and Figure 4.8d for scenario S4 (refer to Table 4.5 for scenario specifications). These results are visually represented using donut charts, which include gauges to indicate the levels of crop-specific SSR, effectively capturing the graphical results while highlighting both the best case and worst case within their circular design.



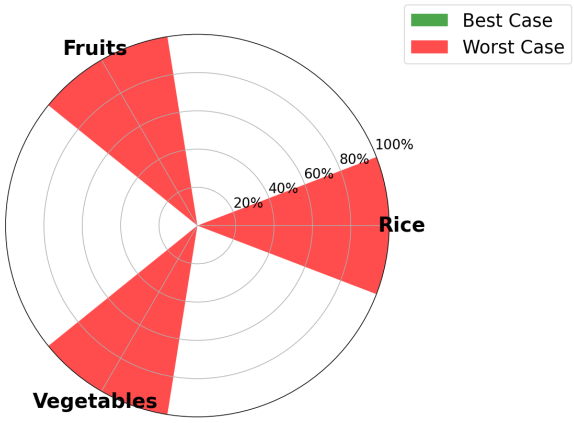
(a) Crop-specific SSR for scenario S1.



(b) Crop-specific SSR for scenario S2.



(c) Crop-specific SSR for scenario S3.



(d) Crop-specific SSR for scenario S4.

Figure 4.8: Crop-specific SSR according to scenarios for 2035.

Multidimensional thresholds related to food self-sufficiency are observed in Figures 4.8a, 4.8b, and 4.8c where land use competition leads to the conversion of potential areas into crop production until no potential areas remain. The SSR for fruits and vegetables reaches 100 % in scenarios S1, S2, and S4 (see Figures 4.8a, 4.8b, and 4.8d). However, in scenario S3 (Figure 4.8c), local production falls short of meeting the demand for fruits and vegetables if all sugarcane parcels are preserved until 2035. A closer look at Figures 4.8a, 4.8b, and 4.8c reveals that rice is the limiting crop, mainly due to the limited land available for rice production, particularly when sugarcane is preserved (refer to Figures 4.8a and 4.8c). The combination of low yields, high demand, and the lack of existing production on the island exacerbates this limitation. Conversely, Figures 4.8b and 4.8d show a significant increase in the SSR for rice when suitable sugarcane parcels are converted for rice production. Scenario

S4 (Figure 4.8d) even achieves 100 % SSR, thanks to lower per-household rice consumption under the *Mediterranean* profile. However, in scenario S2 (*Traditional* profile), food self-sufficiency remains unattainable, even after converting suitable sugarcane parcels (refer to Figure 4.8b). According to these observations, scenario S4 is optimal with respect to the SSR. Furthermore, the prospects for transitioning towards this scenario seems promising, as the *Mediterranean* diet, currently adopted by only 20 % of households, has room to expand, compared to the 80 % adherence to the *Traditional* profile (INSEE, 2015) (refer to Figure 4.9).

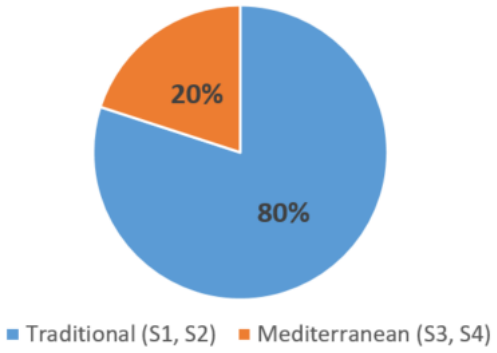


Figure 4.9: Distribution of the current dietary behaviors in Reunion island.

4.5.2 Influence of dietary behaviors on agricultural land distribution

The distribution of agricultural land under these scenarios, in comparison to the current distribution of agricultural land, is illustrated in Figure 4.10 for the best case in 2035.

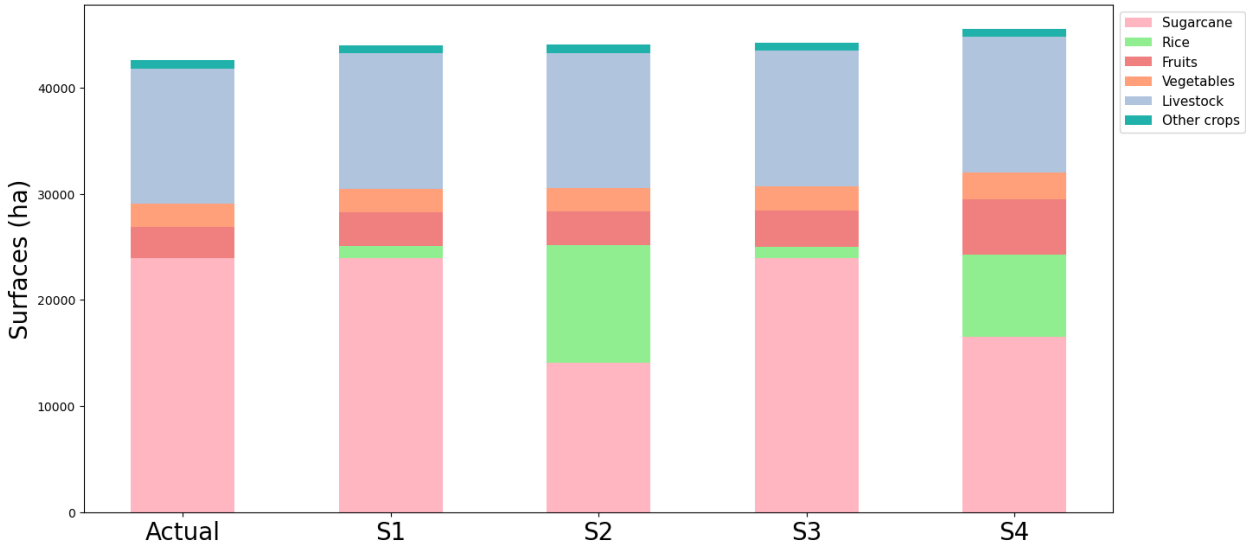


Figure 4.10: UAA specified by crops for the best case in 2035 compared to the current distribution of agricultural land.

First and foremost, we assume that the areas dedicated to livestock and other crops are preserved across all scenarios. In scenarios S1 and S3, all the sugarcane is preserved throughout the simulation process, limiting the expansion of rice, vegetable, and fruit production to

agricultural wastelands. As a result, the histograms for scenarios S1 and S3 show the same distribution, as space constraints inhibit the development of crop production. In contrast, scenarios S2 and S4 exhibit a notable reduction in sugarcane areas due to the conversion of some parcels for rice production, and to a lesser extent, vegetable and fruit production. We see that, despite the conversion of some sugarcane areas, we have at least 14,000 hectares still under cultivation (scenario S2). Finally, the UAA increases for all scenarios compared to the current UAA, driven by the conversion of agricultural wastelands into crop production areas.

4.5.3 Decision support elements

By integrating both supply-side measures, such as expanding agricultural areas for subsistence farming, and demand-side shifts towards high-value crops like fruits and vegetables, these scenarios demonstrate that modifying dietary behaviors, alongside effective policies on land use, can significantly increase the food SSR. Regarding sugarcane production, the issue is not about whether to completely abandon the sector, but rather about preserving current production levels while balancing crop selection to shift towards subsistence farming, given the island's physical constraints and with the aim of supporting the food self-sufficiency process. In summary, effective land use management must also consider individual dietary behaviors. However, to undergo transition from the predominantly *Traditional* profile (covering 80 % of the population) to the *Mediterranean* profile (covering 20 %), requires more than just raising awareness about emerging trends like "deconsumerism". It also necessitates addressing the affordability challenges that consumers face when adopting these practices (Pothin, 2017). Notably, these dietary shifts are more prevalent among wealthier households (INSEE, 2015), underscoring the socioeconomic dimensions that must be taken into account when designing policies aimed at promoting more resilient food systems.

It is noteworthy that these findings are based on the assumption that future urban developments will come with a high density, as advocated by the *Regional Planning Scheme* (AGORAH, 2016). In this context, it raises important questions: What impact would less stringent urban planning policies have on agricultural and electricity production ? How would this increase land use competition ? And finally, to facilitate decision-making, where should priority be given to future areas for urban development ?

4.6 Integration of urban development dynamics

Urban planning scenarios are formulated to comprehensively depict the range of impacts of urban development on land use. The delineation of potential areas for urban development must consider territorial specificities. These areas are designated to accommodate urban development, regardless of the land use policy at hand, ranging from highly planned to unplanned scenarios (refer to subsection 3.2.4). Previously, potential areas for urban development were located on agricultural wastelands. Now, restrictions on urban development areas include natural and protected areas, as well as all agricultural lands, except sugarcane fields and agricultural wastelands. Indeed, in scenarios where urban densification rates are low, agricultural wastelands surfaces located near urban areas are insufficient to accommodate urban development. Therefore, the conversion of suitable sugarcane areas is considered to preserve subsistence farming and protected areas from urban development. The future of the sugarcane industry thus becomes a major subject for discussion when considering urban development dynamics. The scenarios are based on household projections provided by (INSEE, 2018). Three distinct scenarios are defined, with the values associated with

δ (urban development surface per new household) and α (urban development surface for non-residential areas) specified for each scenario in Table 3 in the Appendix.

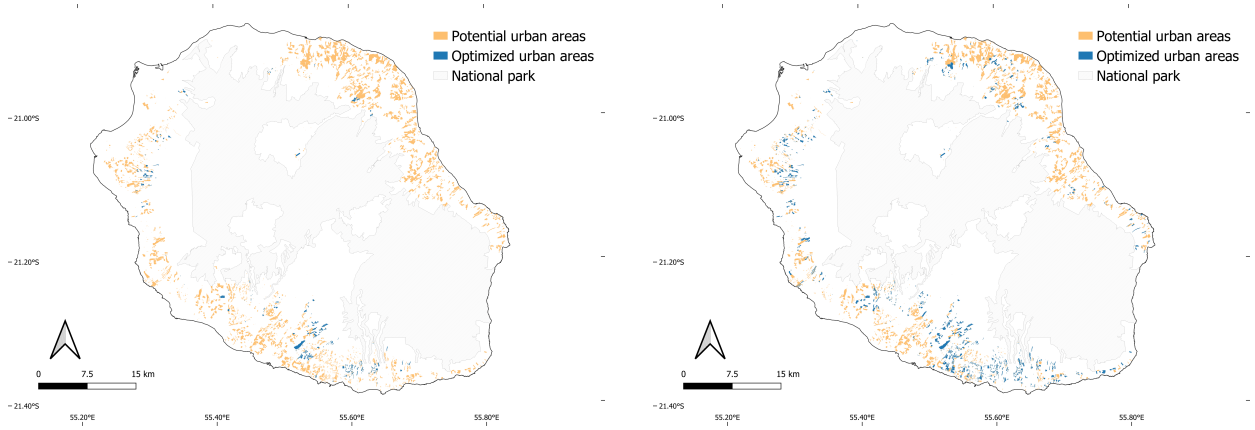
The results presented in the following subsections offer key insights through (1) maps delineating future urban areas and (2) an analysis of how urban planning scenarios impact the food SSR and electricity production. This holistic approach highlights the broader impacts of urban planning scenarios, particularly how they influence the uses of local resources. These findings will provide policymakers with the knowledge needed to identify and manage key variables for balancing the interconnected uses of resources and controlling urban sprawl.

4.6.1 Finding the location of future urban areas

As in the previous section, we focus on electricity production that relies heavily on ground-mounted PV and includes limited biomass imports through 2035. We assume an average per capita food consumption, without accounting for variations in dietary behaviors. We present maps delineating both potential areas for urban development and **optimized urban areas** for 2035, under the best case, for scenario S1 (highly planned), scenario S2 (continuity planning), and scenario S3 (unplanned).

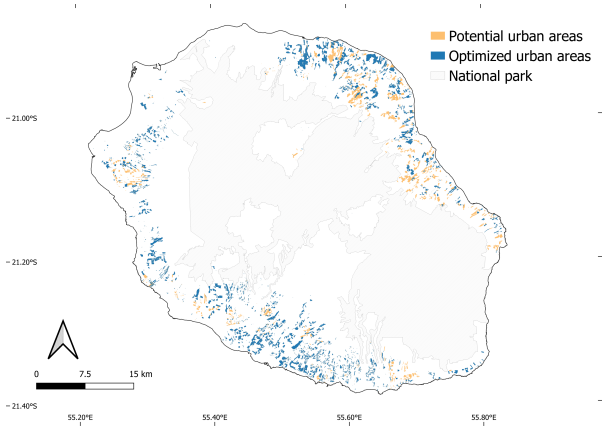
Definition 36 *We define **optimized urban areas** as parcels with potential for urban development, where the urban surface area determined by the optimization process exceeds zero.*

These maps are depicted in Figures 4.11a, 4.11b, and 4.11c. The impact of decreasing densification rates on the conversion of these potential areas for urban development into urban areas (referred to as optimized urban areas here) is clear. Notably, we observe that urban sprawl is primarily concentrated in the southwest of the island across all scenarios. Scenario S3, which features low densification rates, exhibits further development of the urban spot in the northeast (refer to Figure 4.11c). The allocation of future urban areas (optimized urban areas) is guided by the optimization process, favoring sugarcane parcels with the highest yields to be retained rather than converted into urban areas. This strategy aims to preserve the highest share of local biomass, consequently minimizing the development of ground-mounted PV systems. Indeed, by restricting ground-mounted PV development, there is greater flexibility to repurpose parcels with potential for crop and electricity production into areas dedicated to crop production, thus supporting the objective of maximizing the food SSR. Moreover, sugarcane parcels located outside irrigated perimeters and featuring steep slopes, particularly those in the southwest, are unsuitable for cultivation. Consequently, these parcels are favored for urban development due to the lack of land use competition with crop production. This preference explains the consistent pattern of urban sprawl in the southwest, and subsequent development in the northeast across all scenarios.



(a) S1 (highly planned).

(b) S2 (continuity planning).



(c) S3 (unplanned).

Figure 4.11: Potential and optimized urban areas for the best case for 2035.

In summary, these maps provide valuable insights into how constraints on electricity production sources and the objective function shape the allocation of future urban areas (optimized urban areas). It is important to note that converting potential areas for urban development into urban areas reduces the available space for crop production and electricity production projects. This underscores the profound impact of urban sprawl on crop and electricity production, as further examined in the following subsection.

4.6.2 Influence of urban planning scenarios on crop and electricity production

For policymakers, the challenge lies in restricting urban sprawl to areas not dedicated to future agricultural and electricity production, all the while conserving natural and protected areas. In this regard, the impact of urban planning scenarios on electricity and crop production is examined for the best case. The food SSR is illustrated in Figure 4.12 across all scenarios up to 2035. While scenarios S1 and S2 show similar trends, disparities arise with scenario S3. These differences can be attributed to the following factors:

- As illustrated in Figure 4.13, the electricity production from ground-mounted PV systems follows a similar trajectory across all scenarios by the end of the simulation. This indicates that a comparable amount of potential areas for ground-mounted PV systems have been converted in each scenario.

- As shown in Figure 4.14, the plateau reached for electricity production from local

biomass towards the end of the simulation for scenario S3 suggests no further possibilities for converting sugarcane parcels for food, urban or energy purposes.

- Finally, scenario S3 reveals larger optimized urban areas compared to scenario S1 and S2, as shown in Figures 4.11a, 4.11b, and 4.11c.

Consequently, these combined effects shed light on the observed differences in the food SSR curves across the scenarios. Specifically, the conversion of potential areas in urban areas, rather than allocating them for crop production as in scenarios S1 (highly planned) and S2 (continuity planning), alongside the shortage of available sugarcane parcels for crop production, significantly contributes to the variation in the food SSR levels (up to 20 % variation). Moreover, to achieve the same level of food SSR for each time step in scenario S2 (continuity planning) as in scenario S1 (highly planned), a greater number of sugarcane parcels must be converted to accommodate the same housing needs (refer to Figure 4.15). As a result, this conversion leads to a reduction in electricity production from local biomass compared to scenario S1 (highly planned), as indicated in Figure 4.14. Note that in scenario S2 (continuity planning), achieving the same level of food SSR while minimizing the reduction in electricity production from local biomass is attributed to the dominance of sugarcane in Reunion island's agricultural landscape. Consequently, by 2035, these sugarcane areas can support urban development, even under minimal urban planning, while still allowing for conversion into subsistence farming crops. Nonetheless, beyond 2035, once the minimum of electricity production from local biomass is reached (refer to Figure 4.14), a decline in food SSR is expected for scenario S2 (continuity planning).

In Figure 4.13, we observe slight variations in electricity production from ground-mounted PV systems throughout the time horizon across different scenarios, driven by two primary factors: (1) variability in hydroelectric production, which ranges from 357.9 GWh to 658.1 GWh at each time step, and (2) fluctuations in local biomass production across scenarios, resulting from the conversion of varying numbers of sugarcane parcels into urban areas to meet the population's housing needs.

Figure 4.14 illustrates the rapid conversion of sugarcane parcels in scenario S3 (unplanned) to accommodate both extensive urban development, driven by low densification rates, and maximize crop production according to the objective function. By the end of the simulation, a loss of 10 GWh is observed in scenario S3 compared to the scenario S1 (highly planned). We do not observe identical patterns between production and surface curves in Figure 4.14 and Figure 4.15 because we consider variations in sugarcane yields between parcels (Russeil, 2023).

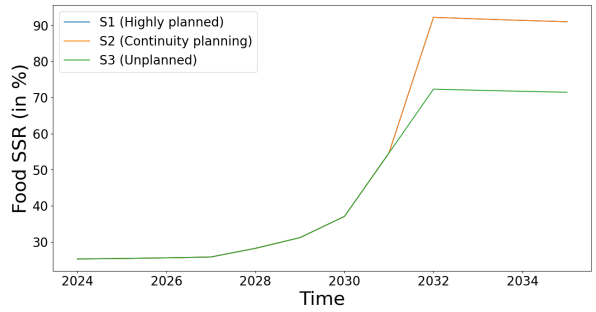


Figure 4.12: Evolution of the food SSR for the best case.

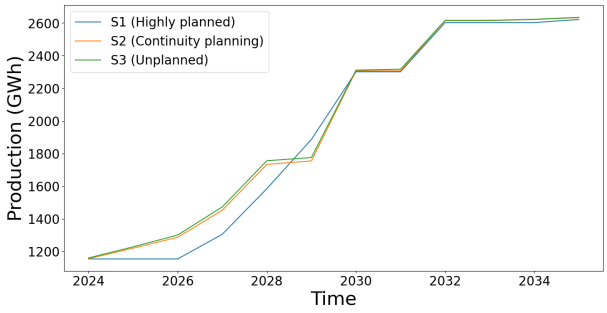


Figure 4.13: Electricity production from ground-mounted PV systems for the best case.

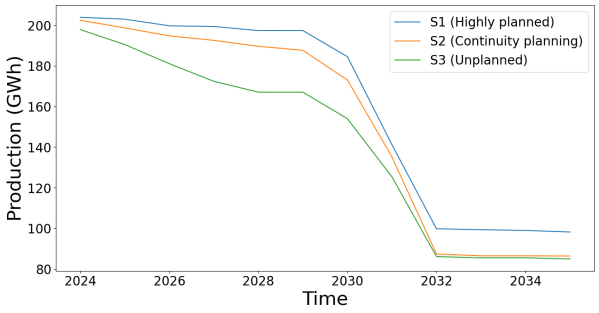


Figure 4.14: Electricity production from local biomass for the best case.

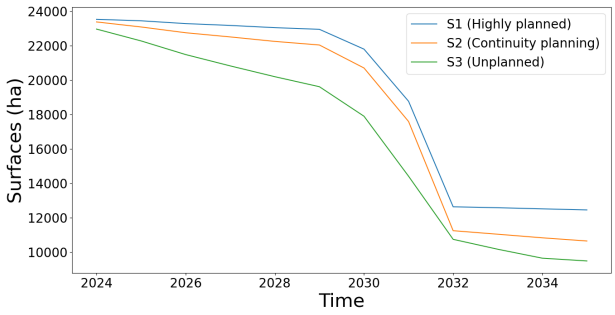


Figure 4.15: Amount of sugarcane land for the best case.

We consider that urban sprawl results in downgrading agricultural wastelands and suitable sugarcane parcels, undermining their capacity for conversion into subsistence crops. However, given the limited surfaces of agricultural wastelands with a potential for urban development (652 hectares) compared to sugarcane surfaces with similar potential (9,935 hectares), a portion of sugarcane parcels will need to be converted for alternative agricultural, energy, or urban uses depending on the urban planning scenarios. Thus, sugarcane emerges as a major lever for addressing the combined challenges of urban growth and the uses of local resources. Nevertheless, as depicted in Figure 4.15, at least 9,000 hectares of sugarcane parcels are preserved across all scenarios, maintaining 38 % of current production. This suggests that the sugarcane sector remains active, regardless of the scenario.

Imports of biomass. We now gradually integrate imported biomass into electricity production to limit the expansion of ground-mounted PV systems. We observe a similar impact on the food SSR as when no biomass imports are considered. This is attributed to the fact that, even though fewer parcels are converted into parcels for ground-mounted PV systems, the available space freed up by the ground-mounted PV systems does not allow for crop production, while optimized urban areas compete directly with potential areas for crop production. One benefit of importing biomass is the preservation of more sugarcane surfaces compared to scenarios without biomass imports. However, it involves an increased dependence on external energy sources, making the island more reliant on imports.

4.6.3 Decision support elements

Overall, the modeling framework serves as a powerful decision support system offering a spatial analysis that illustrates future urban areas by considering both food and energy factors across various urban planning scenarios. It also provides medium-term projections of the impact of urban planning scenarios on agricultural and electricity production. By simulating various urban development dynamics, we underscore the necessity of implementing urban planning policies focused on high-density development of existing urban areas, as recommended by regional guidelines (SAR, 2011). Such policies not only optimize land use but also help increase the uses of local food and energy resources.

4.7 Summary

In summary, Reunion Island faces significant challenges in strengthening its food system resilience, largely due to its historical reliance on imports, which has triggered multi-sectoral crises during supply chain disruptions. To address these issues, we developed a multifaceted approach tailored to Reunion's specific context. This approach incorporates (1) agricultural practices, (2) electricity production sources, (3) dietary behaviors, and (4) urban development dynamics into comprehensive scenarios grounded in field interviews and historical context. These scenarios provide decision support for land use management and the promotion of alternative dietary behaviors that support the food self-sufficiency process. Specifically, insights from the scenario analysis require making trade-offs between supporting a more resilient food system and maintaining current levels of sugarcane production.

CHAPTER 5

Conclusion

In this thesis, we conducted a comprehensive analysis of food system resilience by identifying multidimensional thresholds related to food self-sufficiency resulting from land use competition between the uses of local WEF resources and urban development. We demonstrated that addressing challenges related to food system resilience requires a holistic approach, where resource uses are interconnected. This highlights the relevance of employing a WEF nexus approach, with a specific focus on assessing the impacts on land use change driven by resource uses and urban development, especially in territories where land availability is a critical concern.

We introduced a GIS and robust optimization model designed to analyze the impacts of comprehensive scenarios on the dynamics of land use change and their combined effects on crop and electricity production. The model enables the integration of comprehensive data and constraints, offering flexibility to generate diverse scenarios. It captures the intricate interconnections between resource uses and identifies trade-offs by maximizing of local food production while adhering to constraints related to resource uses and urban development. These scenarios are informed by historical data and field interviews, accounting for urban development dynamics, dietary behaviors, agricultural practices, and electricity production sources.

This modeling framework serves as a generic tool applicable to small islands facing multi-sectors vulnerabilities, as demonstrated through a case study on Reunion Island. However, its applicability extends beyond this context; the insights gained can be applied to larger regions, thereby broadening the research's impact. For example, the framework could be tailored for regions seeking to optimize local resource use while contending with land constraints that induce competition between resource uses and urban development. The methodology we developed is adaptable to various territories by selecting relevant food crops, incorporating energy-related constraints that align with local conditions, and considering specific urban development dynamics. Additionally, it accounts for existing agricultural practices and regional characteristics such as topography and protected areas. This flexibility enables its application across a broad spectrum of geographical contexts.

The model is intended as a decision support system that provides spatial analysis capabilities to identify potential and optimal areas for crop production, electricity production, and urban development. It also offers medium-term projections on how comprehensive scenarios will impact crop and electricity production. Through the case study of Reunion island, we underscore the critical importance of integrating land use management for elec-

tricity, agricultural, and urban planning to effectively address challenges related to the uses of local resources. The key elements we have identified for decision support include: (1) optimizing land use by promoting solar self-consumption and the controlled expansion of ground-mounted PV systems, while also limiting biomass imports; (2) shifting agricultural practices towards subsistence farming by converting suitable sugarcane parcels, (3) promoting incentives to encourage dietary shifts towards high-value crops such as fruits and vegetables, and (4) implementing robust urban planning policies aligned with regional guidelines, as outlined in (SAR, 2011), which can lead to benefits such as land optimization and enhanced use of local food and energy resources.

5.1 Further developments

Some issues are still open with respect to what we did not implement and remains to be done. We have focused our approach on identifying multidimensional thresholds related to food self-sufficiency, deliberately setting aside economic factors. Instead, we concentrated on land use competition, which influences those thresholds. A further development involves integrating economic indicators into the model, such as macroeconomic projections that consider growth, inflation, wages, and unemployment. This requires expertise in economic modeling to assess how these factors impact these thresholds.

Another room for improvement involves integrating stakeholders -such as policymakers, farmers, and local communities- more directly in the modeling process. This is particularly valuable for designing comprehensive scenarios by engaging more deeply with stakeholders during field interviews, particularly on sensitive topics like the conversion of agricultural land for urban or energy purposes. Such an approach necessitates more extensive field investigations, allowing for the development of intermediate scenarios that strike a balance between preserving existing agricultural production with converting areas dedicated to export crops. In addition, this integration could help address challenges related to scaling data. Currently, spatial data are aggregated at the island scale to fit the nexus approach. By integrating the knowledge of a broad panel of farmers into the modeling process, it would be possible to generate more accurate crop yield estimates at the parcel scale, ensuring that the model reflects localized variations more precisely and allows for the inclusion of additional agricultural practices, such as organic farming. Such an approach would require finer-scale data collection and analysis to ensure accuracy.

Furthermore, a further development would involve incorporating local urban development plans in the model to refine the identification of future urban areas. This step requires significant time and resources to ensure that all the plans are integrated effectively.

5.2 Future work

Future research will include incorporating new data from other small islands to enable comparative assessments. This would require more field interviews and a deeper understanding of the territorial specificities to select relevant resources. Another challenge is expanding the range of crops and incorporating livestock breeding into the model to simulate the land use competition between them. This process is currently time-consuming, and addressing the associated computational costs will be necessary.

It would also be valuable to consider the connections between a specific small island and neighboring countries or islands to prioritize geographically proximate supplies (for imported food and energy sources). By doing so, the environmental impacts associated with imports could be reduced, particularly by minimizing greenhouse gas emissions through a

cost-function approach. For instance, in the case of Reunion, this could involve considering connections with Mauritius and Madagascar. Such analysis would require a detailed investigation into various modeling scales, focusing on the entire food production chain (e.g., chemical inputs, food processing, transportation) or the electricity production chain.

We chose to set aside the impacts of climate change in our approach due to the short projection time frame of 10 years. In that regard, future work will focus on exploring the impacts of climate change on agricultural yields, potential photovoltaic production, and rainfall by extending the analysis to long-term scenarios.

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Appendix

Table 1: Static optimization parameters.

Parameters	Values	References
Electricity production from hydropower in 2022 (GWh)	634.2	(OER, 2023a)
Electricity production from oil in 2022 (GWh)	1327	(OER, 2023a)
Electricity production from coal in 2022 (GWh)	581.1	(OER, 2023a)
Electricity production from PV in 2022 (GWh)	266.3	(OER, 2023a)
Electricity production from wind in 2022 (GWh)	3.489	(OER, 2023a)
Electricity production from local biomass in 2022 (GWh)	181.4	(OER, 2023a)
Electricity production from imported biomass in 2022 (GWh)	50.6	(OER, 2023a)
Domestic electricity production in 2022 (GWh)	1313	(OER, 2023b)
Non-domestic electricity production in 2022 (GWh)	1507	(OER, 2023b)
Calories for rice (kcal/kg)	2800	(FAO, 2001)
Calories for vegetables (kcal/kg)	248.6	(CIRAD, 2021)
Calories for fruits (kcal/kg)	570.9	(CIRAD, 2021)
Rice consumption (kg/household)	113	(AGRESTE, 2023)
Fruit consumption (kg/household)	120	(Chambre d'agriculture, 2023)
Vegetable consumption (kg/household)	153	(Chambre d'agriculture, 2023)
Urban development surface per new household (m^2/household)	234	(AGORAH, 2016)
Urban development surface for non-residential areas (m^2)	290,000	(SAR, 2011)
Bagasse yield per ton of harvested sugarcane (%)	30	(OER, 2023c)
Ratio of electricity production per ton of bagasse (GWh/t)	0.00047	(OER, 2023c)
Rice yield (ton/ha)	[2.8, 3.3]	*Association Riz Réunion*

Table 2: Food crop consumption for two dietary behaviors: *Traditional (Trad)* and *Mediterranean (Med)*.

Parameters	Values	References
Trad profile - Rice consumption (kg/household)	123	(INSEE, 2015)
Trad profile - Fruit consumption (kg/household)	88.4	(INSEE, 2015)
Trad profile - Vegetable consumption (kg/household)	125.5	(INSEE, 2015)
Med profile - Rice consumption (kg/household)	67.8	(INSEE, 2015)
Med profile - Fruit consumption (kg/household)	252.7	(INSEE, 2015)
Med profile - Vegetable consumption (kg/household)	263.4	(INSEE, 2015)

Table 3: Specifications of urban planning scenarios.

Scenarios	Specifications	References
S1 (highly planned)	$\delta_{S_1} = 234\ m^2/new\ household$ $\alpha_{S_1} = 290{,}000\ m^2$	(SAR, 2011)
S2 (continuity planning)	$\delta_{S_2} = 833\ m^2/new\ household$ $\alpha_{S_2} = 290{,}000\ m^2$	(DEAL, 2017)
S3 (unplanned)	$\delta_{S_3} = 2300\ m^2/new\ household$ $\alpha_{S_3} = 500{,}000\ m^2$	*(author)*

Résumé étendu

Contexte thématique

Les vulnérabilités spécifiques aux petites îles mettent en évidence l'importance cruciale de renforcer leur résilience dans divers secteurs (Weir and Kumar, 2020) (Guell et al., 2022). Cela passe notamment par la valorisation des ressources locales (Kim et al., 2015), avec une attention particulière portée au développement des énergies renouvelables et des systèmes alimentaires locaux, afin de promouvoir l'autonomie énergétique (Weir and Kumar, 2020) et alimentaire (Guell et al., 2022). Cependant, la gestion de l'utilisation des terres demeure un enjeu central dans ces territoires aux espaces limités, surtout dans un contexte de forte exploitation des ressources locales (Samara et al., 2015).

Dans ce contexte, bien que relever les défis liés à la résilience dans les petites îles soit indispensable, il est légitime de se demander quelles sont les implications sur l'utilisation des terres. Une compréhension approfondie des impacts sur l'utilisation des terres s'avère nécessaire. C'est pourquoi nous nous inscrivons dans le cadre du nexus Eau-Énergie-Alimentation. Pour les petites îles, cette approche est particulièrement pertinente, car elle permet de mieux appréhender les dynamiques de changement dans l'utilisation des terres (Lin et al., 2019) (Russeil et al., 2023). En effet, une gestion inadéquate des ressources au sein de ce nexus peut avoir des conséquences négatives sur les terres agricoles, les espaces naturels protégés, ainsi que sur les zones urbaines.

Ainsi, une approche globale et systémique est nécessaire pour l'évaluation des multiples impacts du nexus sur l'utilisation des terres. Il est également crucial d'analyser les effets de la croissance urbaine sur ces ressources ainsi que sur les dynamiques de changement d'utilisation des terres. Parmi les outils de modélisation pertinents pour l'étude de ces dynamiques, le langage de programmation *Ocelet* permet de modéliser différents types d'interactions (spatiales, fonctionnelles, sociales, hiérarchiques) au sein d'un même modèle, grâce au concept de graphe d'interactions (Castets, 2015).

Pour relever les défis liés à la résilience de manière plus systémique, il est donc essentiel de combiner ces approches de modélisation de la croissance urbaine avec celles du nexus Eau-Énergie-Alimentation. Dans cette thèse, l'accent est mis en particulier sur l'étude de la résilience des systèmes alimentaires.

Approche thématique et méthodologique

Notre approche thématique et méthodologique se concentre sur la résilience des systèmes alimentaires dans les petites îles à travers l'élaboration d'un modèle spatio-temporel. Ce modèle met en lumière la compétition pour l'utilisation des terres et permet d'identifier des seuils critiques multidimensionnels liés à l'autonomie alimentaire à travers sa structure intégrée, qui combine un modèle SIG avec un modèle d'optimisation.

À cela s'ajoute le développement de scénarios holistiques intégrant les sources de production d'électricité, les dynamiques de développement urbain, les pratiques agricoles et les comportements alimentaires. Notre méthodologie, volontairement holistique et générique, est conçue pour être applicable à différentes petites îles présentant des caractéristiques communes.

Le modèle développé a pour objectif de soutenir les décideurs et autres parties prenantes, qu'il s'agisse de responsables politiques, d'élus locaux ou d'associations, dans la promotion de nouveaux comportements alimentaires et dans la gestion de l'utilisation des terres, en lien avec le développement urbain et à la production agricole et énergétique.

La structure générale du modèle intégré est représentée en Figure 1.

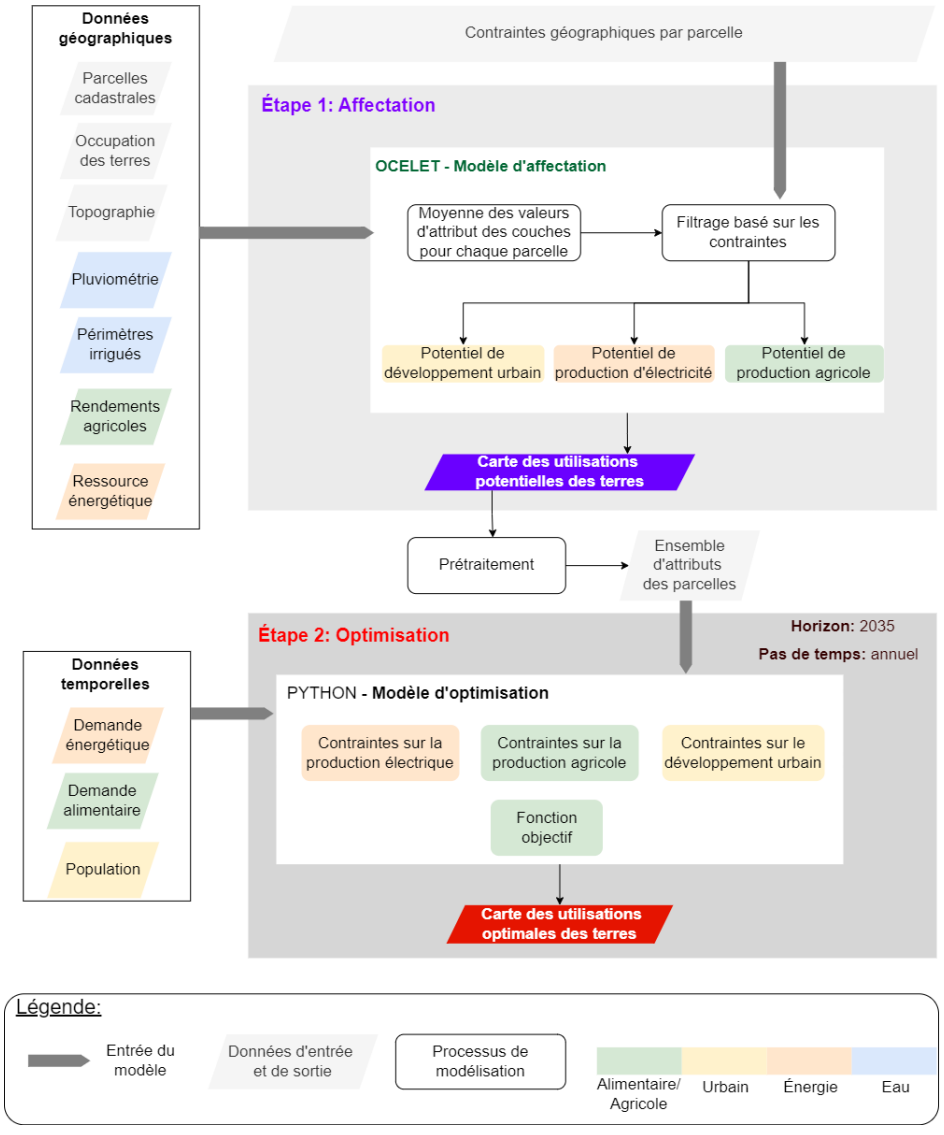

Figure 1: Structure générale du modèle intégré.

Modèle d'affectation. Trois types d'utilisations potentielles des terres sont définis: (i) un potentiel de production agricole, (ii) un potentiel de développement urbain, et (iii) un potentiel de production d'électricité. Pour chaque parcelle cadastrale, l'affectation de ces utilisations potentielles repose sur une étape de filtrage tenant compte de contraintes spécifiques, qui élimine les utilisations incompatibles pour chaque parcelle et ne conserve que celles respectant l'ensemble des contraintes. Les contraintes incluent : (1) le type d'occupation du sol, (2) la topographie, (3) les relations de voisinage entre parcelles, (4) les besoins en eau des cultures, et (5) la taille des parcelles. Cette étape d'affectation est réalisée à l'aide du langage de programmation *Ocelet*, qui permet d'intégrer les différents scénarios holistiques.

Modèle d'optimisation. Par la suite, à chaque pas de temps annuel, une (ou plusieurs) utilisation(s) optimale(s) des terres est sélectionnée au cours du processus d'optimisation pour chaque parcelle parmi l'ensemble des utilisations potentielles. Le modèle intègre des données de projections de population, de demande en électricité et en alimentation. Il prend également en compte les contraintes liées aux ressources alimentaires et énergétiques, ainsi qu'au développement urbain, et cherche à maximiser un ratio d'autonomie alimentaire (fonction objectif) à l'horizon 2035. Au terme de l'optimisation, une carte des utilisations optimales des terres est produite pour chaque pas de temps, intégrant les différents scénarios holistiques.

Cette approche a été testée spécifiquement sur l'île de la Réunion.

Cas de l'île de La Réunion

L'île de la Réunion, département français d'outre-mer, souffre d'une forte dépendance aux importations pour son approvisionnement alimentaire et énergétique, ce qui la rend particulièrement vulnérable à d'éventuelles ruptures d'approvisionnement (CIRAD, 2021). De plus, l'île subit une pression foncière croissante due à l'étalement urbain (INSEE, 2018). L'aménagement du territoire à La Réunion représente donc un défi majeur, compte tenu de sa superficie limitée de 2 512 km^2, de l'essor urbain et de la nécessité de préserver les zones naturelles. Dans ce contexte, notre approche systémique a été appliquée à l'île de la Réunion en suivant la méthodologie précédemment décrite. Nous avons commencé par identifier la compétition pour l'utilisation des terres à travers plusieurs scénarios holistiques. Ces scénarios ont été élaborés grâce à des entretiens menés avec divers acteurs des secteurs alimentaire, énergétique et urbain. En nous basant sur les informations recueillies lors de ces entretiens, tout en tenant compte du contexte historique de La Réunion, nous avons restreint les utilisations potentielles des terres aux quatre suivantes: (1) la production d'électricité à partir de systèmes photovoltaïques au sol, (2) la production de riz, (3) la production de fruits et légumes, et (4) le développement urbain.

Localisation des zones potentielles. Nous avons produit des cartes renseignant sur la localisation de ces zones potentielles (liées aux utilisations potentielles des terres). Ces cartes révèlent qu'il est prioritaire de convertir en premier lieu les parcelles présentant une utilisation potentielle unique, afin de minimiser les conflits entre développement urbain, production agricole, et production d'électricité. Elles constituent ainsi des outils d'analyse spatiale essentiels pour l'aide à la décision concernant l'aménagement du territoire à La Réunion. En outre, ces cartes mettent en évidence la compétition pour l'utilisation des terres, soulignant la nécessité d'opérer des compromis lorsque des conflits se manifestent.

Influence des sources de production d'électricité et des pratiques agricoles. L'intégration des sources de production d'électricité et des pratiques agricoles souligne l'importance d'une gestion conjointe des terres pour répondre aux besoins énergétiques et alimentaires. Parmi les recommandations clés pour la prise de décision, nous insistons sur la nécessité : (1) d'optimiser l'utilisation des terres en favorisant l'autoconsommation solaire dans les zones urbaines, (2) de développer des systèmes photovoltaïques au sol tout en limitant les importations de biomasse, et (3) de réorienter les pratiques agricoles vers l'agriculture vivrière en convertissant des parcelles de canne à sucre adéquates.

Intégration de divers comportements alimentaires. Nos scénarios holistiques révèlent que l'adoption de nouveaux comportements alimentaires, associée à des politiques d'aménagement du territoire efficaces, peut considérablement accroître le ratio d'autonomie alimentaire et soutenir les objectifs visant à accroître la résilience du système alimentaire. Toutefois, passer d'un régime alimentaire dit "Traditionnel", caractérisé par une forte consommation de riz et une faible consommation de fruits et légumes (suivi par 80 % de la population), à un régime de type "Méditerranéen", marqué par une moindre consommation de riz et une plus forte consommation de fruits et légumes (adopté par 20 % de la population), exige non seulement une sensibilisation aux nouvelles tendances, telles que la "déconsommation", mais aussi une prise en compte de l'accessibilité financière de ces pratiques pour les consommateurs (Pothin, 2017). Ces changements de comportements alimentaires sont souvent plus courants parmi les ménages aisés (Pothin, 2017), ce qui souligne l'importance des dimensions socio-économiques dans la conception de politiques visant à renforcer la résilience des systèmes alimentaires. En ce qui concerne la production de canne à sucre, la question n'est pas de savoir s'il faut abandonner complètement ce secteur, mais plutôt de préserver les niveaux de production actuels tout en ajustant la sélection des cultures pour se diriger vers l'agriculture vivrière, compte tenu des contraintes physiques de l'île et de l'objectif de soutenir l'autonomisation alimentaire.

Influence des dynamiques de développement urbain. Les résultats de notre modèle mettent en évidence l'identification de zones de développement urbain optimales, tenant compte à la fois des facteurs alimentaires et énergétiques. De plus, le modèle fournit des projections à moyen terme (2035) de l'impact des scénarios de développement urbain sur la production alimentaire et électrique. À travers ces résultats, nous soulignons l'importance de soutenir une politique d'urbanisation orientée vers une densification accrue des zones urbaines existantes. Ces politiques permettraient non seulement d'optimiser l'utilisation des terres, mais aussi d'accroître l'utilisation des ressources alimentaires et énergétiques locales.

Conclusion

Dans cette thèse, nous avons examiné la résilience des systèmes alimentaires sous le prisme de l'autonomisation alimentaire. Nous avons démontré l'importance d'adopter une approche holistique et globale, où les utilisations des ressources sont interconnectées. Cela met en évidence la pertinence d'une approche nexus Eau-Énergie-Alimentation, avec un accent particulier sur l'évaluation des impacts sur les changements d'utilisation des terres.

Nous avons introduit un modèle combinant SIG et optimisation, conçu pour analyser les impacts des scénarios holistiques sur les dynamiques de changement d'utilisation des terres ainsi que leurs effets sur la production agricole et électrique. Sa flexibilité permet de générer divers scénarios, capturant les interconnexions entre les utilisations des ressources et facilitant l'identification des compromis nécessaires pour maximiser la production à partir

de ressources locales.

L'adaptabilité du modèle le rend applicable aussi bien aux petites îles confrontées à des vulnérabilités multisectorielles, comme l'illustre le cas de La Réunion, qu'à des régions plus vastes cherchant à optimiser l'utilisation des ressources locales tout en gérant des contraintes foncières significatives.

Certaines questions demeurent ouvertes concernant ce que nous n'avons pas abordé et ce qui reste à explorer, notamment l'étude de l'influence d'indicateurs économiques sur les seuils liés à l'autonomie alimentaire, ce qui nécessiterait une expertise en matière de projections macroéconomiques. De plus, des travaux futurs pourraient inclure l'intégration du changement climatique et son impact sur les rendements agricoles, la production électrique à partir de PV au sol et les niveaux de précipitations.