A Water-Energy-Food Nexus Approach to Assess Land Use Trade-Offs in Small Islands

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Keywords: Geographic Information System, Land Use Trade-Offs, Thresholds Identification, Optimization.

Abstract: Due to their isolation, limited resources and high population density, small islands are particularly vulnerable to multi-sectoral crises. The study of the sustainability of small island social and environmental development raises among others the challenge of balanced uses of local resources, including water, food and energy. Aspects of this are currently investigated through so called models of the Water-Energy-Food (WEF) nexus. In this paper we propose a novel approach of the WEF nexus through the optimization of scenarios that make use of Geographical Information Systems (GIS) integrated with robust optimization models coined in Operations Research. Our contribution allows the identification of trade-offs between future land use potentials and thresholds by maximizing a food Self-Sufficiency Ratio (SSR) by 2035. We show a case study of our approach on Reunion island, based on real data. Our results show through different scenarii of land use dynamics, the potential of this model as a decision-support tool.

1 INTRODUCTION

Small islands are characterized by significant economic, climatic and demographic vulnerabilities (Briguglio and Nurse, 2001) as well as food and energy vulnerabilities, through the dependence of these islands on fossil fuels (Genave et al., 2020) and food imports (Teng, 2020). Additional land vulnerabilities emerge from a combination of biophysical, socio-economic and demographic factors (Birch-Thomsen et al., 2010). To cope with the various vulnerabilities they face, small islands need to adopt a posture of resilience through water management improvement (Holding et al., 2016) and through greater empowerment, harnessing local resources (Kim et al., 2015) by the development of renewable energies and local food systems to support energy self-sufficiency process (Weir and Kumar, 2020) and food self-sufficiency process (Guell et al., 2022). Nevertheless, land-use is a core issue to tackle multiple resource management and planning, especially if an objective is to maximize local resources usage in a highly spatially constrained territory (Samara et al., 2015). A suitable and promising approach to address the multiple and interdependent challenges is the integrated WEF (Water-Energy-Food) nexus. This approach explores the connections between water, energy and food resources to better understand their interdependence in the context of sustainable development (Lotfi et al., 2020).

To the best of our knowledge, few studies have combined different approaches to explore the interdependencies between multiple resources through the WEF nexus at a small island scale. (Rodríguez-Urrego et al., 2022) provide a decision support-tool through scenarios production to analyze future trends in energy consumption and greenhouse gases emissions on the island of Tenerife (Spain), based on projections of demand for water and energy resources. The approach developed by (Chen et al., 2020), for its part, consists in a material flow analysis to assess the risks associated with the WEF nexus and gives us important information on the impact of population growth and industrial development on securing

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Authier, R., Pillot, B., Guimbretière, G., Broto, P. and Gervet, C.
A Water-Energy-Food Nexus Approach to Assess Land Use Trade-Offs in Small Islands.
DOI: 10.5220/0012556900003696

In *Proceedings of the 10th International Conference on Geographical Information Systems Theory, Applications and Management (GISTAM 2024)*, pages 26-38
ISBN: 978-989-758-694-1; ISSN: 2184-500X

WEF resources in an island environment. These studies provide a systemic vision of the issues linked to the WEF nexus and the levers to be taken into account to improve the WEF nexus sustainability from an economic and environmental point of view. However, they do not aim at addressing land use challenges linked to the use of local resources. Land use challenges are depicted by (Lin et al., 2019) through a decision support tool based on a user-friendly nexus platform with GIS in Taiwan: GREAT for FEW. This tool, based on a life cycle assessment, aims at investigating the influences of food security on land-use change dynamics and to study the trade-offs between bioenergy production, food supply and environmental benefits. Finally, (Russeil et al., 2023) proposed a spatio-temporal modelling of drivers of change that influence food and energy self-sufficiency through semi-directive interviews in Reunion (French overseas department). Land use maps are generated following different land use scenarios for 2035. If these studies illustrate land use competition, land use scenarios do not search for thresholds linked to resource self-sufficiency process.

In summary, existing WEF nexus approaches do not explore thresholds to resource self-sufficiency process when investigating land-use trade-offs.

In this paper, we address land uses issues through the specific framework of thresholds to food self-sufficiency process, that is to say, to what extent can local production meet food demand in a small island subject to multiple constraints ? The key challenges we identified to analyse food self-sufficiency process through the WEF nexus are threefold: 1) a need to integrate multi-source and spatial data, 2) the definition and specification of heterogeneous spatio-temporal constraints reflecting the WEF nexus, and 3) a comprehensive model to derive insightful decision support scenarios. From a systemic modelling point of view, these challenges require innovative approaches that bring together the collection of data, the specification of the constraints at hand, and an optimisation module to derive insightful scenarios. Our main goal is to derive a generic methodology, that contributes a cartography of existing land use for each cadastral parcel based on real data, the specification of geographical constraints (land use, topography...), to extract potential alternative land usages of these parcels to be determined in the optimization process. Another element to be accounted for when optimizing cost functions in the context of spatial assignments, is the need to digitalize the contextual data (population, resource demand). The optimization approach will aim at deriving scenarios that seek the optimal future land uses per parcel on a 10 years time projection (by 2035) while satisfying the various spatio-temporal constraints linked to the WEF nexus. In this paper, we present our integrated Geographical Information System (GIS) and robust optimization methodology as a comprehensive decision-support tool that models the WEF nexus to assess land use trade-offs and identify thresholds for small islands territories.

Summary of Contributions. Our main contributions can be summarized as follows: 1) the identification of land use trade-offs to determine thresholds to food self-sufficiency process in small island territories within a WEF nexus approach and 2) through the combination of a GIS and optimization model that integrates a wide range of data and constraints specific to the nexus in small islands such as constraints on urban sprawl, energy and food production/demand so that the food self-sufficiency ratio is maximized. Our integrated approach enables the modelling of land use competition in order to determine the thresholds to food self-sufficiency process. Quantifying land use impacts linked to the WEF nexus is one of the key aspect of our approach.

The paper is structured as follows. In Section 2 we present the overall methodology, including the extraction of GIS data to characterize the specific features of the territory (topography, land use, cadastral parcels) and also the WEF resources (energy resource, rainfall, irrigated perimeters, crop yields); the optimization module that consists in maximizing a food self-sufficiency ratio under different geographical and supply/demand balance constraints related to the nexus. Section 3 illustrates our approach by applying our model to the case of the French Reunion island. It shows how our model can provide a framework for land-use pathways policies respecting local resource limits. This integrated model is thought as a simple decision-support tool to policy makers concerned by the objective of land use management to enhance food self-sufficiency process.

2 OUR NEXUS MODEL

2.1 Overall Methodology

The integrated modelling approach is depicted in Figure 1. It allows to model both the spatial land use, and its optimization paying particular attention to (1) the consideration of land use competition to enable trade-offs identification and (2) the search for thresholds linked to food self-sufficiency process. Our modelling framework is divided into two steps. Geographical data layers input the step 1 which consists in land use potential(s) allocation for each parcel based on values taken by the constraints specified upstream. These geographical data layers are in ESRI shapefile format (cadastral parcels layer, land use layer, irrigated perimeters layer, and crop yields layer) and raster format (topography layer, energy resource layer, and rainfall layer). The land use potential allocation model generates a map of land use potentials. We undertake a generic pre-processing step to transform the map into a set of lists of attributes corresponding to parcels (such as surfaces, crop yields...) to feed the optimization module. Quantitative temporal data also input the optimization module. At the end, the optimization module returns a map of optimal land uses for each time step. Each step is described in the subsections below.

2.2 Step 1: Land Use Potential Allocation

In our approach, the identification of land use trade-offs requires to divide the territory into cadastral parcels, and specified the land use constraints to allocate land use potentials for each parcel. The land use potential for a parcel corresponds to the parcel's potential for transitioning from its current land use to another; it reflects the evolution of land use within the framework of the WEF nexus. In the current version of the model, three specific land use potentials are defined: (i) crop production potential, (ii) urban development potential, and (iii) electricity production potential. Land use potential allocation relies on several geographical and resource constraints, as specified in Figure 1, including (i) topographic land use restrictions, (ii) surface area, (iii) land use type, (iv) neighborhood distance between parcels, and (v) water requirements. The constraint processing will filter out inconsistent potentials, leading to those that satisfy all constraints for each parcel. The nexus approach in small islands implies that some parcels are open to many uses, while others are not, depending on their current land use. The constraints specify that (i) natural and protected parcels do not change their land use, (ii) agricultural parcels can remain agricultural, become urban, or become energy-producing parcels, and (iii) urban parcels cannot change their land use but can be opened up for energy use (through solar self-consumption).

Land Use Potential Allocation Model: The Contribution of the *OCELET* Language

With all land-use potentials defined, and the associated constraints specified, we allocate one (or several) potential(s) for each parcel. The specification of constraints and the necessity for spatialization require the collection of the corresponding set of geographical data (refer to Figure 1). The initial step consists in assigning an average value of each layer feature to each parcel. Average values of slope (in %), altitude (in m), energy resource (in kWh/m^2) and monthly rainfall (in mm) are calculated for each parcel by spatially overlapping pixels (in raster format) with cadastral parcels (in ESRI shapefile format). Average values for crop yields (in ton/ha) are also assigned for each parcel. Given the sufficiently small average surface area of the parcels (with an average value of 5586 m^2 and a standard deviation of 91239 m^2), this method of assigning average values is deemed realistic. Note that the allocated actual land use for each parcel is the one with the largest area within that parcel. Subsequently, this step enables the comparison of the computed average values with predefined constraints values obtained from literature and field data for potential allocation.

The main challenge of potential allocation lies in allocating urban development potential to characterize urban sprawl. Indeed, it is considered that urban sprawl takes place close to urbanized parcels (Lajoie and Hagen-Zanker, 2007). Neighborhood relations between parcels must, therefore, be defined. These relationships can be modeled through an interaction graph linking neighboring parcels. A powerful language for processing land-use dynamics using interaction graphs is the domain-specific language *Ocelet* (Degenne and Lo Seen, 2016). We generate an interaction graph between urbanizable parcels and urban parcels. Urbanizable parcels must comply with maximum slope and distance thresholds from urban parcels as well as specific land use criteria. We then apply an interaction function to the graph that assigns a urban development potential to each urbanizable parcel on the graph. Finally, the assignment of other land use potentials must satisfy constraints linked to minimal surface area, maximal altitude, maximal slope, and specific land use for the allocation of electricity production potential, and additional constraints such as water requirements for the allocation of crop production potential. To satisfy the water requirements constraint, the parcel must be located within irrigated perimeters or receive an adequate amount of rainfall to support crop production.

A map of land use potentials is then generated by the land use potential allocation model and transformed into a set of parcel attribute lists to feed the optimization model.

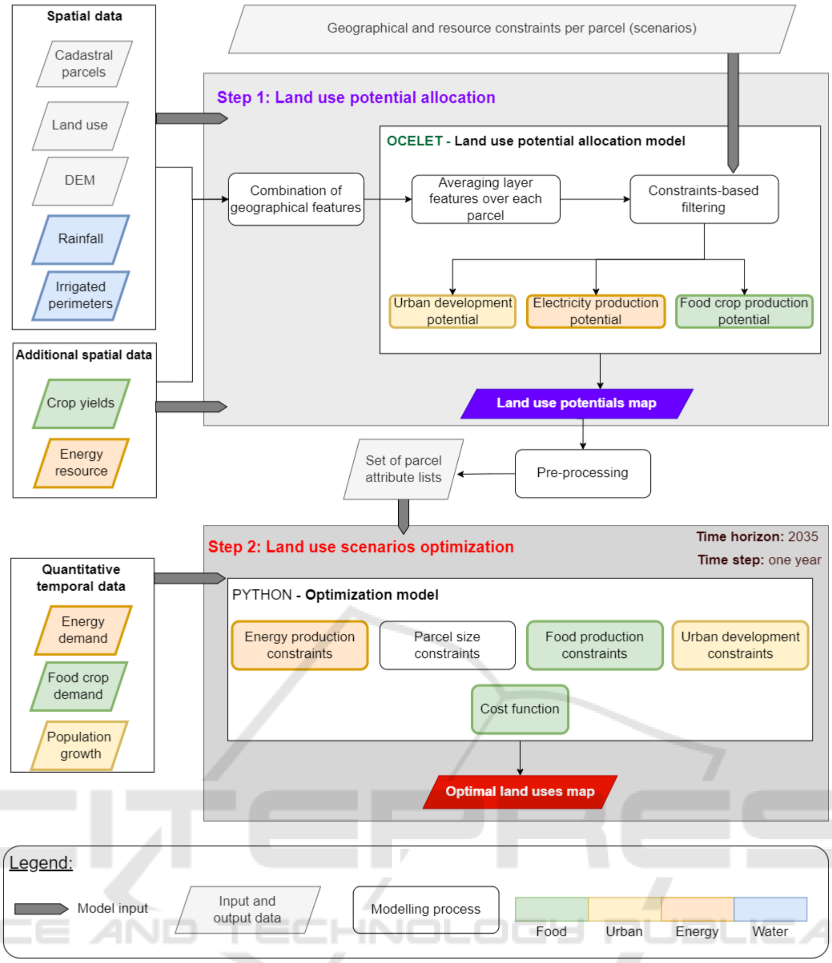


Figure 1: Integrated modelling framework.

2.3 Step 2: Land Optimization

As shown in Figure 1, the optimization model takes as input a set of parcel attribute lists and temporal data such as projected population growth, electricity and food crop demand by 2035. These projections are derived from estimates provided by institutes and companies. For each time step, it selects optimal land use(s) for each parcel from among all its potential land uses, considering WEF-related constraints and the objective function for the time horizon 2035. At the end of the optimization process, a parcel can therefore have several concomitant land uses. The goal of the optimization, here, is to maximize a food Self-Sufficiency Ratio (SSR), expressed in *kcal*. The robust modelling approach relies on the creation of deterministic intervals to enclose uncertainties within robust extreme values, specified by a low and high robust limit values (ex: $Value = [\ \underline{Value}, \overline{Value}\ ]$) as mentioned in (Chinneck and Ramadan, 2000) and (Ben-Tal and Nemirovski, 1999). This approach allows the planning of best and worst case scenarios. The specifications of the optimization problem are given in Table 1.

Variables. The decision variables are designed to highlight land use competition among all the defined land use potentials, i.e. electricity production, food crop production, and urban development. Hence, the area variables depicts the surfaces allocated to (1) *urban development*, (2) *food crop production* and (3) *electricity production from a specific energy source* within each parcel and for each time step. These variables range across a real interval and are increasing over time.

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

Food Production Constraint. The initial set of constraints pertains to annual crop production, ensuring that it does not exceed the projected annual de-

Table 1: Optimization problem specifications.

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 $e \in E = \{set\ of\ primary\ energy\ sources\}$	
Set of parcels with a potential of production of crop c	P_c
Set of parcels with a potential of production of electricity from source e	P_e
Set of parcels with urban development potential	P_u
Total electricity demand for a year t (GWh)	$d_t^{elec} = [\underline{d_t^{elec}}, \overline{d_t^{elec}}]$
Existing electricity production (GWh)	P^{elec}
Surface of parcel p (ha)	S_p
Number of households for a year t	$h_t = [\underline{h_t}, \overline{h_t}]$
Urban extension area per new household for a year t $(ha/household)$	Su_t^h
Surface energy density from a primary source e for a parcel p (GWh/ha)	p_p^e
Total demand for crop c for a year t (ton)	$d_t^c = [\underline{d_t^c}, \overline{d_t^c}]$
Calories per kg of crop c $(kcal/ton)$	$kcal_c$
Yield of crop c for a parcel p (ton/ha)	$Yield_p^c$
Find:	
The optimal land use(s) for a parcel among all its potential land uses	
The surface areas allocated to urban development, food crop and electricity production	
Objective function:	
Maximize food self-sufficiency ratio	
Such that the following constraints hold:	
Local food crop production is less than or equal to the food crop demand	
Total annual electricity production meets demand	
Fossil fuels imports are decreasing	
Limit on intermittent Renewable Energies (RE) existing and new production	
Limit on urban sprawl	

mand regarding food crop for both the best case scenario (lowest projected demand) and the worst case scenario (highest projected demand) for each time step. The objective is to fulfill local population requirements, while simultaneously preventing surplus food exports for the considered food crops, in order to delineate the thresholds to food self-sufficiency process.

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

$$\sum_{p \in P_c} s_{t,p} * Yield_p^c \leq \underline{d_t^c} \tag{1}$$

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

$$\sum_{p \in P_c} s_{t,p} * Yield_p^c \leq \overline{d_t^c} \tag{2}$$

Electricity Production Constraint. The second set of constraints relates to additional and existing electricity production matching the projected electricity demand for both the best case scenario (lowest projected demand) and the worst case scenario (highest projected demand) for each time step. It demonstrates the impact of electricity generation on land use based on the primary energy source used.

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

$$\sum_{e \in E} \sum_{p \in P_e} s_{t,p} * p_p^e + P^{elec} = \underline{d_t^{elec}} \tag{3}$$

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

$$\sum_{e \in E} \sum_{p \in P_e} s_{t,p} * p_p^e + P^{elec} = \overline{d_t^{elec}} \tag{4}$$

Energy Imports Constraints. The nexus approach developed here involves increasing the use of local renewable energy resources. Hence, the third set of constraints refers to energy imports and is built in such a way that electricity generation from imported fossil fuels is gradually decreasing to zero throughout the planning horizon.

Intermittent RE Production Constraint. The maximum share of intermittent renewable energies (wind and photovoltaic without storage) that can be injected into the grid at a given time has to be limited in island systems due to high variability of these energy sources that may affect the stability of the power grid (EDF-SEI, 2023). Thus, a maximal threshold is set for ground-mounted PV and wind power production.

Solar Self-Consumption Constraint. This set of constraints depicts the will to preserve land surfaces and to limit the development of ground-mounted PV due to the low power density of solar energy (Trainor et al., 2016). It is assumed that some urban parcels are equipped with photovoltaic panels on their roofs for solar self-consumption. This enables industrial or domestic consumers to utilize their own electricity directly without relying on the power grid, constituting a decentralized system.

Urban Sprawl Constraints. This set of constraints pertains to the extent of urbanization, which is influenced by economic development and expected population growth for both the best case scenario (lowest population projections) and the worst case scenario (highest population projections).

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

$$\sum_{p \in P_u} s_{t,p} = Su_t^h * (\underline{h_t} - h_0) \tag{5}$$

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

$$\sum_{p \in P_u} s_{t,p} = Su_t^h * (\overline{h_t} - h_0) \tag{6}$$

Land Use Conversion of Potential Areas. At each time step, a maximum surface area is established for the conversion of potential food crop areas into effective food crop production areas, preventing the conversion of all potential surfaces from the initial time steps. The specified surface limit depends on the food crop.

Maximize Food SSR. The objective function is the food SSR (where d_t^c can take the best or worst case value). What we call food SSR corresponds to the specific SSR for the crops considered in the modelling. Then, the function to maximize is:

$$\sum_{c \in C} \sum_{p \in P_c} \frac{s_{t,p} * Yield_p^c * kcal_c}{\sum_{c \in C} d_t^c * kcal_c} * 100 \tag{7}$$

Finally, an optimal land uses map is generated for each time step under different land use scenarios.

3 CASE STUDY: AGRICULTURAL PRACTICES SCENARIOS FOR REUNION ISLAND

The proposed framework illustrated in Figure 1 is applied to Reunion island. Reunion Island is an overseas french department located in the Indian Ocean, around 200 km southwest of Mauritius and 900 km east of Madagascar. Small in size and particularly vulnerable to natural hazards, to land pressure linked to urban sprawl (INSEE, 2018) and to any disturbance linked to imports (fossils fuels and foodstuffs), Reunion Island is a relevant laboratory to study the issues related to land use trade-offs within the framework of WEF nexus. These issues are reinforced by the will of the French government to move towards food and energy self-sufficiency by 2030 (CIRAD-AFD, 2021). In Figure 2 is represented the land-use map for Reunion, delineated by cadastral parcels according to three main areas: agricultural areas, artificial areas, and natural areas and forest plantations. What is referred to as *'Excluded areas'* in the legend corresponds to areas between parcels, such as roads or waterways, as well as the volcano. At first glance, most of the natural areas and forest plantations are contained within the national park, covering 42 % of the territory, while agricultural and artificial areas tend to coexist predominantly near the coast. The Utilised Agricultural Area (UAA), totaling 42 000 ha, is composed of sugarcane (54.4 %), livestock breeding (29 %) and other crops, mainly fruits and vegetables (16.6 %) in 2018 (CIRAD, 2021).

Geographical Data Collection. As input for step 1 (refer to Figure 1), we gathered geographical data from diverse sources. Monthly rainfall data (in mm) are sourced from *Meteo France*. The irrigated perimeters layer is from Department of Reunion. The land use layer for 2021 is extracted from (Le Mézo et al., 2022). The altitude map and the slope map were obtained from (CGIAR-CSI, 2008), while the cadastral parcels layer is sourced from (Etalab, 2023). Yearly data of practical photovoltaic power potential (expressed in kWh/m^2) are obtained from (World Bank Group, 2020). Crop yields (in ton/ha) were estimated based on a map produced by (Russeil, 2023). The national park layer is derived from the data provided in (PEIGEO, 2021).

Land Use Potential Assessment. In this paper, we considered all the energy sources contributing to electricity production in Reunion island (OER, 2023a): coal, oil, wind, PV, hydro, local and imported biomass but we only consider the future direct land-use impact

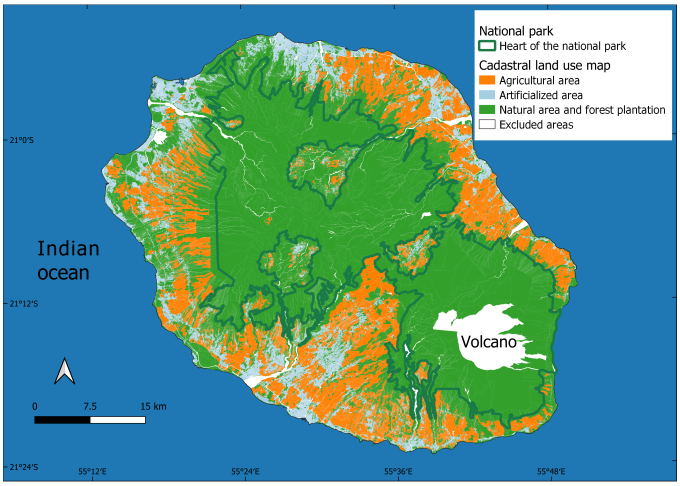


Figure 2: Land use map delineated by cadastral parcels.

of ground-mounted solar PV (DEAL, 2020). We focus on three key food items which are part of the local creole diet: fruits, vegetables and rice. We examine the future direct land-use impact associated with these food items. The future direct land use impact of water resource and facilities is considered negligible (CESER, 2017). Finally, the future direct land use impact of urban development is taken into account. Hence, four land use potentials are defined within the framework of the WEF nexus in Reunion island: (1) potential for electricity generation from ground-mounted PV systems, (2) rice production potential, (3) fruit and vegetable production potential and (4) urban development potential.

Scenarios. We explore two different agricultural practices scenarios:

- **Scenario A (Sugarcane Conservation)**: current surface areas dedicated to each crop are maintained, constraining future crop production (rice, fruits, vegetables), ground-mounted PV production and urban development in agricultural wastelands or in rotation with vegetable crops in the case of rice cultivation *(Association Riz Réunion)*.
- **Scenario B (Subsistence Farming)**: agriculture intended for the local population is preserved to the detriment of sugarcane, which is the primary crop for exports. It illustrates the commitment to support food self-sufficiency process through the promotion of subsistence farming.

The specifications of constraints for each land use potential (scenario A and B) are summarized in Table 3 in the appendix. The scenarios differ in the constraint specifications for land use types. The different constraints make use of data collected from different sources: (1) communication with *Association Riz Réunion* and (Makungwe et al., 2021) for slope values related to rice production potential areas (we consider only one production cycle per year, lasting four months between November and February), (2) (Lajoie and Hagen-Zanker, 2007) for slope values related to urban development potential areas, (3) (Nebey et al., 2020) for slope values related to ground-mounted PV potential areas, (4) (Le Mézo et al., 2022) for the maximal altitude value and (DAAF, 2017) for the maximal slope and water requirements values regarding fruit and vegetable production potential areas. We define a maximum neighborhood distance for urban development based on the width of a road, as well as a minimal surface area value for ground-mounted PV potential areas.

Input Data and Constraints for Optimization. As input for step 2, temporal data refers to population growth as well as electricity and food crop demand (refer to Figure 1). We assume that the increase in electricity demand in the future will depend on population growth (number of households on the island) according to INSEE's low population projection scenario (best case scenario) and high population projection scenario (worst case scenario) (INSEE, 2018) as well as the development of the electric vehicle fleet (DEAL, 2020). The increase in food demand will be exclusively linked to population growth, in line with INSEE's low and high population projection scenarios (best and worst cases)(INSEE, 2018). Some constraints implemented in the optimization model (refer to Figure 1) need to be specified in the case of Reunion. Regarding the electricity production constraint (refer to Equation 3 and Equation 4): we consider that electricity production from wind power is set to increase until 53 GWh by 2035 (OER, 2023c);

the electricity production from hydro is considered to be stochastic, following a uniform distribution within a specified range, which is determined based on hydropower data spanning from 2000 to 2021 (OER, 2023c); the electricity production thanks to local biomass depends on the amount of sugarcane residues (bagasse) collected (OER, 2023c) and the electricity production is reduced to zero for coal and projected to be reduced to zero by the end of 2030 for oil. Concerning the urban development constraints (refer to Equation 5 and Equation 6), we take a constant urban extension area per new household based on recommendations from Reunion Regional Development Plan throughout the time horizon. Values for the time-related maximum surface area of conversion from potential to effective food crop production areas (refer to *Land use conversion of potential areas* constraint defined in subsection 2.3) have been assessed by the author due to the absence of existing data.

Data related to the static parameters of the optimization model are summarized in Table 4 in the appendix.

3.1 Results and Analysis

The main output results presented here to support future decision-making are (1) the identification of potential areas on the island for two agricultural practices scenarios and (2) the determination of thresholds to food self-sufficiency process for both scenarios, considering various electricity mixes. These findings can serve as guidance for policymakers in making informed decisions regarding land use management.

3.1.1 Land Use Potential Areas

Land use potential areas are depicted on land use potential maps at the output of step 1 (refer to Figure 1). Land use potential maps are shown for rice production potential areas (Figure 3a), ground-mounted PV potential areas (Figure 3b), fruit and vegetable production potential areas (Figure 3c) and urban development potential areas (Figure 3d) for both scenario A (sugarcane conservation) and scenario B (subsistence farming). Firstly, we can see that the potential surface areas in Figures 3a, 3b and 3c are significantly greater for scenario B compared to scenario A due to the conversion of some sugarcane areas for alternative purposes (in this case energy and agriculture).

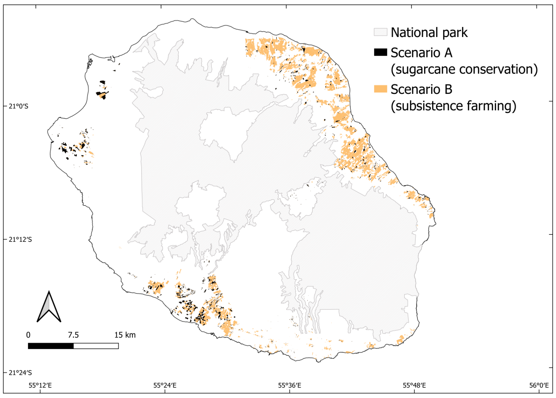
Secondly, we observe that the potential areas for rice production and ground-mounted PV (Figure 3a and Figure 3b) are concentrated around the same sites: mainly in the north-east of the island with a smaller portion in the south-west for scenario B, and mainly in the south-west for the scenario A. This illustrates the potential future land use competition between agriculture and energy. Note that, for scenario B, the absence of rice production and ground-mounted PV potential areas in the west is explained by the fact that many surgarcane parcels have excessively steep slopes (> 10 %). Conversely, as depicted on Figure 3c, fruit and vegetable production potential areas are more scattered along the coast for scenario B. In the eastern region, we identify areas that directly compete with rice and ground-mounted PV, 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. For scenario A, we identify the same locations for fruit and vegetable, rice and ground-mounted PV potential areas (mainly in the south west).

Finally, Figure 3d illustrates artificial areas as well as potential areas for urban development for scenario A (same map for scenario B). We can see here that urban development potential areas are located in the north-west, very close to the coast (where the 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 land use potential areas.

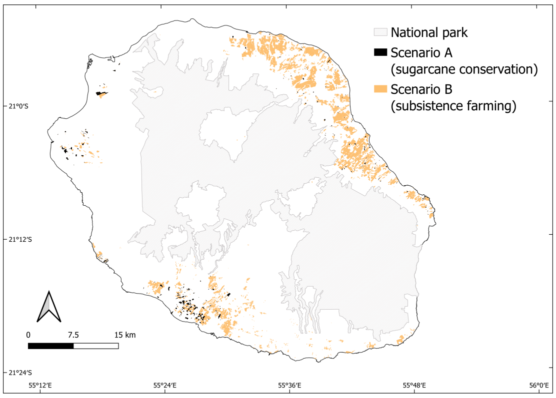
3.1.2 Identifying Thresholds to Food Self-Sufficiency Process

Among its various potential outputs, the optimization model provides a maximum food SSR (as expressed in Equation 7) for each time step. Here, thresholds to food self-sufficiency will be studied in the light of Reunion's electricity mix. Specifically, we will emphasize the impact of electricity production on food production in terms of land use. Three distinct electricity mixes are analyzed for the 2035 time horizon and specified in Table 2.

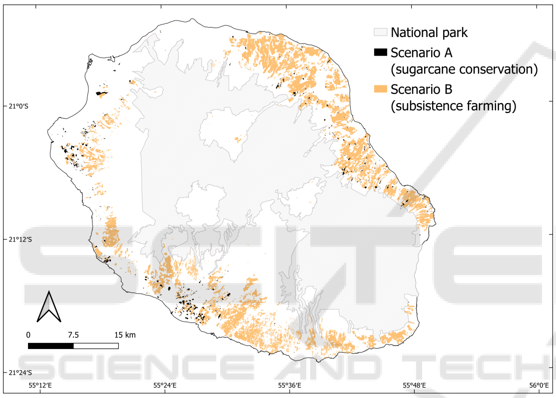
For scenario B (subsistence farming), none of the electrical mixes has an impact on the food SSR. Indeed, if potential areas for rice production and ground-mounted PV appear to be in the same locations (refer to Figure 3a and Figure 3b), some areas only have the potential for ground-mounted PV, and these areas are sufficient to host ground-mounted PV systems regardless of the mix. As a result, areas with both potentials will not be converted. In the absence of land use trade-offs, decision makers can orient policies towards what they identify as an optimal electricity mix. If the criteria for selecting an optimal mix prioritize the reduction of the energy land use footprint and minimizing energy imports, an electricity mix with a high share of solar self-consumption,



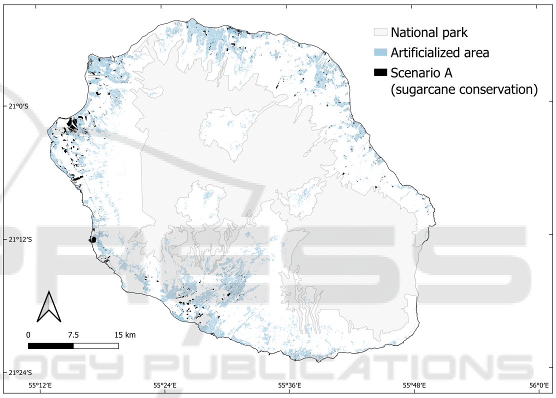
(a) Rice production potential areas.



(b) Ground-mounted PV potential areas.



(c) Fruit and vegetable production potential areas.



(d) Artificial and potential areas for urban development.

Figure 3: Land use potential maps.

Table 2: Characteristics of potential future electricity mixes.

Electricity mix	Specifications
Mix 1	The RE intermittent energy threshold is set to 32 % (EDF-SEI, 2023). Substantial biomass imports limit ground-mounted PV deployment, with up to 77 % of future electricity production relying on biomass during the planning horizon.
Mix 2a	The RE intermittent 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 solar PV is on the rise during the planning horizon, with considerations for solar self-consumption in urban parcels less than 100 m^2 (from 11.1 % to 12.3 % of total electricity production).
Mix 2b	Same as mix 2a but solar self-consumption considered for urban parcels less than 70 m^2 (from 5.9 % to 6.6 % of total electricity production).
Mix 3	Same as mix 2a but solar self-consumption is not considered.

such as mix 2, appears to be the most preferable.

However, electricity mixes influence the food SSR for scenario A (sugarcane conservation) as illustrated in Figure 4 up to 2035 for mixes 1, 2a, 2b and 3. These curves can be segmented into four phases. The initial phase, characterized by a sharp increase, is attributed to the attainment of 100 % SSR for fruits and vegetables with few additional surfaces converted due to high yields per hectare and existing production. After reaching this 100 %, we enter the second phase marked by a slight increase due to the time-dependent rate of conversion (refer to *Land use conversion of potential areas* constraint defined in section 2.3) from parcels with rice crop production potential to rice crop-producing parcels. With a low conversion rate of potential areas for rice production early in the simulation, the food SSR only marginally increase. It's worth noting that for mix 3 (with a high share of ground-mounted PV), the curve remains flat due to the conversion of rice and ground-mounted PV potential areas into ground-mounted PV areas. The third phase, characterized by an increase, corresponds to the multiplication of converted parcels into rice-producing parcels and the impact of the rising conversion rate. A threshold is then reached at different time steps depending on the mix. Note that the more we develop ground-mounted PV, the faster we reach a threshold. After reaching this threshold, a declining phase is observed. This is attributed to the impact of population growth on the demand for food crops. This phase follow a linear trend as dictated by the linear projections provided by (INSEE, 2018).

It can be noted that mix 1 (refer to the specifications in Table 2) has a more favorable impact on food SSR due to the limited expansion of ground-mounted PV (threshold set to 32 %) and the extensive use of imported biomass. Therefore, there is no land use competition between agricultural and energy production. Conversely, mix 3 (refer to the specifications in Table 2) appears to have the most detrimental impact on food SSR due to the substantial surface areas required by ground-mounted solar PV projects, creating competition with agricultural lands. Finally, increasing solar self consumption looks to contribute positively to the food SSR thanks to space savings (refer to the specifications of mix 2a and 2b in Table 2). These differences demonstrate the model's capability to depict conflicts of use between agriculture and energy.

As the differences between the curves are quite small between mix 1 and 2a (maximum 2.38 % food SSR loss for each time step), it may be valuable to identify thresholds to food SSR for scenarios A and B with mix 2a, which appears more preferable than mix

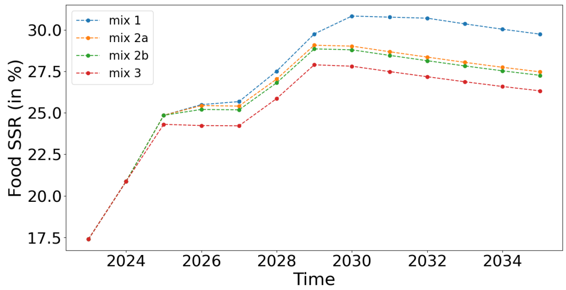


Figure 4: Influence of the electricity mix on the food SSR for scenario A for the worst case.

1 in terms of biomass imports (refer to the specifications in Table 2).

Thresholds to food self-sufficiency process are then depicted for each scenario with mix 2a in Figure 5. The intervals formed by the best and worst cases are proof of the robustness of our results for each scenario. By 2035, it is observed that the food SSR varies from 72 % to 90 % for scenario B (subsistence farming) and from 27 % to 32 % for scenario A (sugarcane conservation). These differences arise from replacing some sugarcane parcels with rice, vegetables, or fruit crops in scenario B.

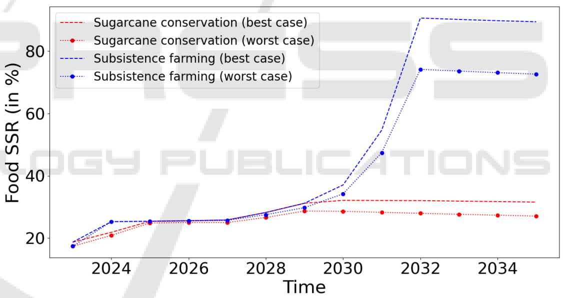


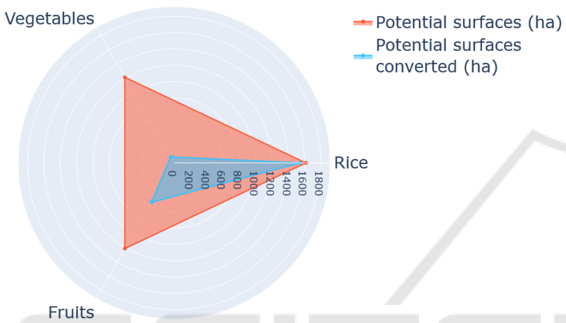
Figure 5: Evolution of the food SSR for both scenarios with mix 2a.

Finally, to understand how the food SSR reaches a peak, we plot the surfaces areas occupied by the three considered food crops at t = 2030 in Figure 6a for scenario A (sugarcane conservation) for the best case. We can see that the maximum threshold at t = 2030 is due to the conversion of all rice production potential areas into rice production areas. Then, rice becomes the limiting crop due to low yields per hectare (between 2.8 ton/ha and 3.3 ton/ha) and no current production. Conversely, local fruit and vegetable production can meet the population's total food requirements until 2030.

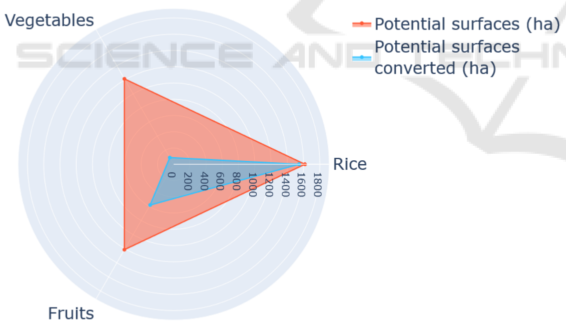
Few differences exist between the two diagrams (Figure 6a and Figure 6b) due to rice production on multiple potential surfaces (for example vegetables and rice production potential surfaces). Consequently, there are fewer surfaces available for fruit and vegetable production. However, the reduction in food self-sufficiency for fruits and vegetables is only 1 % between 2030 and 2035, decreasing from 100 % to 99 %.

For scenario B (subsistence farming), the same analysis is conducted, with the distinction that all rice production potential areas have been converted by t = 2032 due to a larger number of potential surfaces.

Land reserves for fruit and vegetable production can therefore fulfill a significant portion of the population's needs in scenario A. Thus, for scenario B (subsistence farming), sugarcane areas having only a fruit and vegetable production potential (13 473 ha) are globally preserved.



(a) t = 2030.



(b) t = 2035.

Figure 6: Potential surfaces converted vs potential surfaces for scenario A for the best case.

4 CONCLUSION

In this paper, we have presented an innovative integrated approach which consists in identifying land use trade-offs to determine thresholds to food self-sufficiency process in small island territories within a WEF nexus approach. The modelling approach allowed the integration of energy, food, water and population into a systemic approach based on GIS and robust optimization to deal with the challenges linked to food self sufficiency process. The *Ocelet* GIS model allowed us to model existing land use at the parcel level and extract various land use potentials within a single parcel. The link with the optimization model enables the identification of thresholds through the extraction of optimal land uses. Through this case study, we showed the importance of considering land use management for both energy and agricultural planning, and the need for an integrated approach in addressing issues related to the use of local resources. Current and future work involve fine-tuning food consumption by considering different dietary profiles (high rice consumption vs high fruit and vegetable consumption). A second aspect of future work would consist in exploring various urban growth scenarios to observe additional effects on land use competition.

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APPENDIX

Table 3: Constraints specifications for land use potential allocation per parcel in the Ocelet model.

Constraints	Rice	Urban	PV	Vegetables and fruits
Land use type **Scenario B** (Subsistence farming)	Agricultural wastelands, vegetable crops, sugarcane	Agricultural wastelands	Agricultural wastelands, sugarcane	Agricultural wastelands, sugarcane
Land use type **Scenario A** (Sugarcane conservation)	Agricultural wastelands, vegetable crops	Agricultural wastelands	Agricultural wastelands	Agricultural wastelands
Minimal surface area	240 m^2	/	3000 m^2	/
Maximal altitude	1200 m	/	/	1800 m
Maximal slope	10 %	30 %	10 %	30 %
Minimum water requirements	300 mm / cycle	/	/	300 mm / year
Neighborhood distance with urban parcels	/	20 m	/	/

Table 4: Static optimization parameters.

Parameter	Value	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)
Rice calories (kcal/kg)	2800	(FAO, 2001)
Vegetables calories (kcal/kg)	248.6	(CIRAD, 2021)
Fruits calories (kcal/kg)	570.9	(CIRAD, 2021)
Rice consumption (kg/household)	113	(AGRESTE, 2023)
Fruits consumption (kg/household)	120	(Chambre d'agriculture, 2023)
Vegetables consumption (kg/household)	153	(Chambre d'agriculture, 2023)
Urban extension area per new household (m^2/household)	247	(AGORAH, 2016)
Ratio of tons of bagasse per ton of sugarcane (%)	0.30	(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