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ABSTRACT

Reunion Island, a French overseas region in the Indian Ocean, has endorsed policies targeting food and electricity self-sufficiency. This objective implies balancing different land-uses (food, feed, bioelectricity, urbanisation, etc.) which we explore in a set of scenarios towards 2035. Through participatory structural analysis, we modelled drivers of change as processes using Ocelet, a spatially explicit and dynamic modelling platform. We built a detailed land-use map for our initial state and calibrated relevant processes through four scenarios ranging from "business-as-usual" to "implementation of ambitious territory planning policies". To improve local self-sufficiency, our results support the need for large-scale land planning policies, suggesting partial sugarcane conversion into food crops, urbanisation control, farmlands expansion onto fallows and photovoltaic increase. Our context-specific approach addresses food and electricity self-sufficiency as a whole and understands its inner dynamic and spatial processes from stakeholders' viewpoint. Moreover, our model recognizes small-scale spatial heterogeneity and contributes to mediate controversial issues related to territory foresight and land-use planning.

1. Introduction

Reunion Island is a French overseas department located in the Indian Ocean. It was formerly close to self-sufficiency: probably until the 19th century for food (Piccin et al., 2019) and until the 80′s for electricity (Selosse et al., 2018). Nevertheless, dependency towards imported food and fossil fuels has skyrocketed over the last decades: henceforth, local electricity sources only cover about 30% of electricity consumption (SPL Horizon Réunion, 2020) while the share of imported food keeps increasing (DAAF Réunion, 2017). This dependency makes the region highly vulnerable in case of import disruptions. With new "global and systemic risks" (Reghezza-Zitt, 2017) such as the Covid-19 pandemic and its consequences on supply-chains (Carlsson-Szlezak et al., 2020), these disruptions can no longer be considered as fantasies. To tackle this vulnerability, Reunion Island has endorsed public policies aiming at improving its food and energy self-sufficiency, mainly: a multiannual energy plan ("*Programmation Pluriannuelle de l'Énergie*", hereafter referred as *PPE*) (Région Réunion, 2022) and a co-elaborated agricultural action plan ("Plan AGRIPéi 2030″, hereafter referred as *AGRIPéi*) (Département de La Réunion, 2020a).

In literature, food self-sufficiency corresponds simultaneously to a degree and to a state: the extent to which a country can fulfil its food requirement from local production (FAO, 1999) and a situation where local food production equals or exceeds 100% of food consumption at the scale of a country (Clapp, 2016). In this study, we will use food self-sufficiency as a degree, at the scale of the island. Similarly, energy self-sufficiency is defined as the extent to which energy consumption of a system is satisfied by exploiting local primary energy sources (Al Katsaprakakis and Voumvoulakis, 2018). Scientific literature usually focuses exclusively on either food or energy self-sufficiency issues, mainly at local scale (Brand et al., 2017; Yalçın-Riollet et al., 2014), but sometimes at national or global scales (Noorollahi et al., 2021; Clapp, 2016). Few studies explicitly merge food and energy self-sufficiency issues. For example, this has been done at local level with material or energy flows (Barles, 2014; Gasparatos, 2011), or by considering a nexus of interrelated processes (Bazilian, 2011). Even fewer studies question simultaneously food and electricity self-sufficiency from a land-use perspective (Kim et al., 2015). Our approach in this paper belongs to that category, since agricultural land in Reunion may contribute to both food and electricity production.

On the island, bioelectricitiy (biomass to power) represents about 7–9% of the electricity mix, and nearly 40% of all renewable,

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synchronous and non-intermittent power systems, along with hydropower (SPL Horizon Réunion, 2020). Such power systems are also an essential asset for reaching electricity independence since they contribute to the overall inertia of the electricity grid (Makolo et al., 2021). The major source of bioelectricity is bagasse, the fibrous by-product resulting from the processing of sugarcane, which is by far the main cultivated crop (54% of all farmlands according to DAAF Réunion, 2020). This is therefore a typical situation where farmlands may contribute to both food and electricity self-sufficiency. These two issues may induce direct or indirect competition for land-use, as highlighted in literature (Muscat et al., 2020). This predicament gets even worse when land is a resource under pressure, which is a common feature for Small Island Developing States (SIDS) (Batra and Norheim, 2022). Although not a state, Reunion Island shares many drawbacks with SIDS, affecting self-sufficiency and land competition: limited resources to exploit, natural disasters, land degradation, unique but fragile biodiversity, a high pressure from the population, and above all, limited land. Being aware of these difficulties, Reunion Island's policies officially foster a balanced food and energy self-sufficiency that avoids land-use conflict: an increase in local food production with minimal competition against sugarcane (as stated in *AGRIPéi* and PPE) and urbanisation via a land-planning plan ("Schéma d′Aménagement Régional", hereafter referred as SAR) (Région Réunion, 2020).

However, several factors keep the territory away from this balanced objective. For example, food production is currently developing at the expense of bioelectricity due to sugarcane diversification towards food crops and pastures. In addition, new lands for agriculture such as fallows remain a scarce resource for a 2500 km^2 insular system (DAAF Réunion, 2020), and existing potential farmlands are continuously decreasing due to urbanisation accompanying population growth (Agorah, 2017). At the scale of Reunion Island, these interrelated processes and stakeholders constitutes a territory (Boiffin et al., 2014). The territory is a complex system (Leloup, 2010), for which modelling is a useful tool to offer a communicable representation in order to understand its mechanics and anticipate its evolutions (Le Moigne, 1977). In parallel, exploring scenarios is necessary regarding the uncertainty and complexity of our studied system. Foresight studies aim precisely to "systematically explore, create and test both possible and desirable futures to improve decisions" (Giaoutzi and Sapio, 2013): at territorial scale, they allow designing scenarios with local stakeholders in order to better anticipate, analyse and debate around complex topics (Fourny and Denizot, 2007).

In practice, on the one hand, previous modelling studies in Reunion Island have described the electricity system (Selosse et al., 2018; ADEME, 2018) and land-use changes were mostly related to urbanisation (Lajoie and Haken-Zanker, 2007; Lagabrielle et al., 2010; Lestrelin et al., 2017). In the latter case, spatial modelling proved to be particularly adapted to account for heterogeneity of the territory (Degenne and Lo Seen, 2016). Ultimately, bridging modelling and scenarios from foresight studies remains under-explored in literature. Examples include simulated scenarios of food system (Poux and Aubert, 2018), energy system (McDowall, 2014) and land-uses (Lestrelin et al., 2017; Jahel et al., 2018; Camara et al., 2019). In our situation, these topics are merged through several questions: Which major forces are influencing the insular transition towards improved food and electricity self-sufficiency? How to anticipate their mid-term evolution? Does food and electricity self-sufficiency seem plausible considering the current trends?

In this article, we propose an innovative method to simulate plausible futures by combining spatial dynamics modelling with participatory foresight approaches. Its development was motivated by the need to mediate between sometimes entrenched positions over controversial issues related to land use within complex landscapes. To the best of our knowledge, such a combined approach with a focus on transition towards an improved food and electricity self-sufficiency, hasn't been reported in the literature. The method was applied to the specific case of Reunion Island. We first identified the drivers of change that influence the current situation and the possible futures of the territory. This step consisted in semi-directive interviews with local stakeholders. As used in foresight studies, a structural analysis guided us to rank the identified drivers according to their relative influence on the system. Secondly, we modelled some of these essential drivers using Ocelet, a spatially explicit and dynamic modelling platform. To perform such modelling, we built a detailed land-use map for our initial state and calibrated the modelled processes through different land-use scenarios, using primary data from interviews as well as existing secondary data from literature and local administrations.

2. Material and method

2.1. Methodology overview

Firstly, we set a spatial model with land-uses producing different resources at the scale of the island and calculated several food and electricity self-sufficiency indicators. In parallel, we gathered information on the drivers of change that are likely to influence the state of food and energy self-sufficiency at the scale of Reunion Island through a first round of semi-directive interviews with local stakeholders. We analysed the interview material to identify a list of drivers of change and proceeded to a structural analysis to assess the most influential of these drivers, referred to as "essential drivers". This stage led to a first conceptualization of the system as interrelated drivers and then to a first dynamic and spatially explicit modelling on Ocelet. In addition, we elaborated four scenarios ranging from "business as usual" to a mix of strategies currently on stakeholder's agenda. The "business-as-usual" trend was calibrated as a benchmark for all scenarios, using spatial analysis on a reference period prior to 2019 and dedicated specific interviews. Finally, we performed a second round of interviews where the first simulation results were discussed with local stakeholders to identify potential improvements which were further implemented in the final modelling and scenarios design. Fig. 1 displays a graphical overview of the methodology developed in this article.

2.2. Presentation of study area

Located in the Indian Ocean, Reunion Island is a French overseas department and an ultra-peripheral region of the European Union. Its population was 861,210 in 2019, increasing at a rate of 0.5% per year since 2013 (INSEE, 2023). The study area covers 2520 km^2 and is densely populated ($\sim$ 342 inhabitants/km^2). However, this volcanic island is composed of narrow littoral plains framing two mountain massifs (3070 m for the highest), surrounded by three deep calderas and a succession of slopes and gullies mostly covered by native forests (Caubet, 1934). Thus, more than half of the island is almost uninhabited, publicly owned and recognized as Natural Park and UNESCO World Heritage Site while 80% of the population is concentrated below an altitude of 400 m (Jauze, 2019) where urban spaces take up almost 15% of the territory and land tenure is mostly private and small-sized with, for example, an average 6.2 ha per farm (DAAF Réunion, 2020).

Furthermore, due to its steep relief, Reunion Island is characterized by numerous microclimates and habitats, ranging from tropical dry forests to rainforests and even subalpine grasslands (Cadet, 1977). This allows for a diversity of crops to be grown with agricultural lands occupying almost 20% of the island: sugarcane is the first cultivated crop, taking up around half of the farmlands, followed by pastures and other crops such as vegetable farming (starchy and non-starchy vegetables, legumes) and orchards (fruits) (DAAF Réunion, 2020).

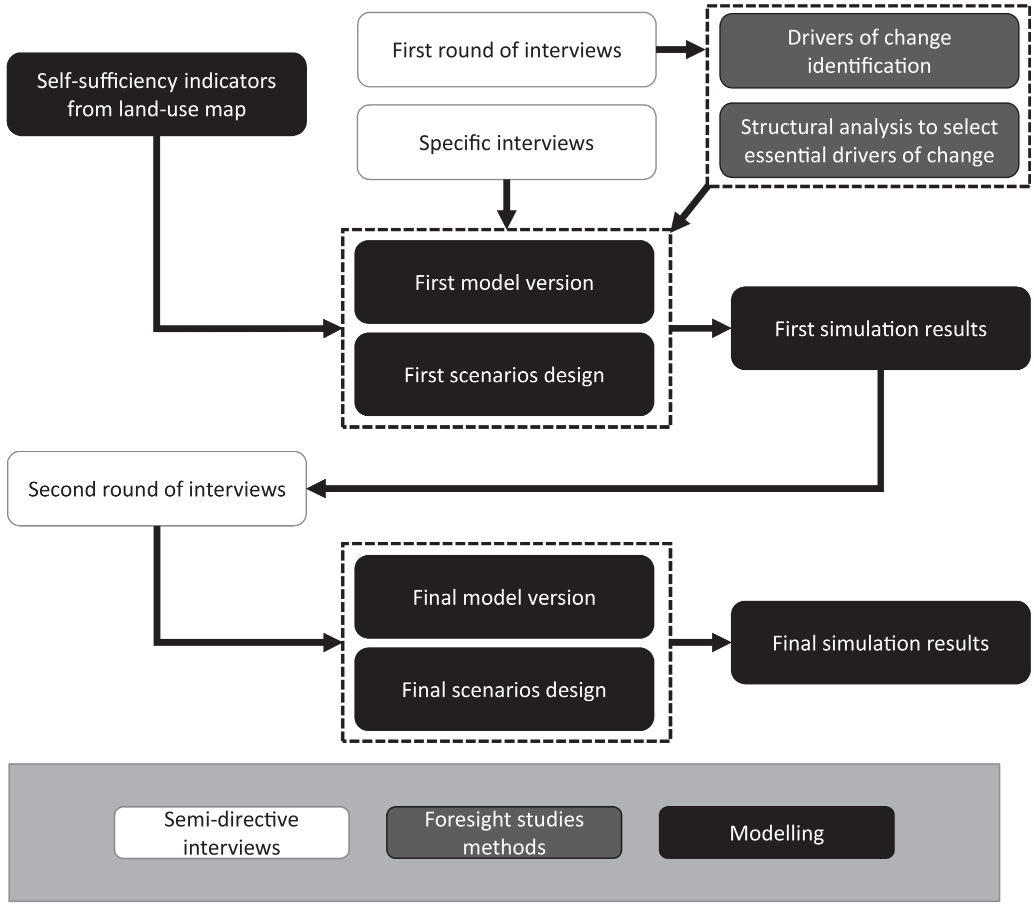

Fig. 1. Methodology overview: linkage between semi-directive interviews, foresight studies methods and modelling.
Source: authors.

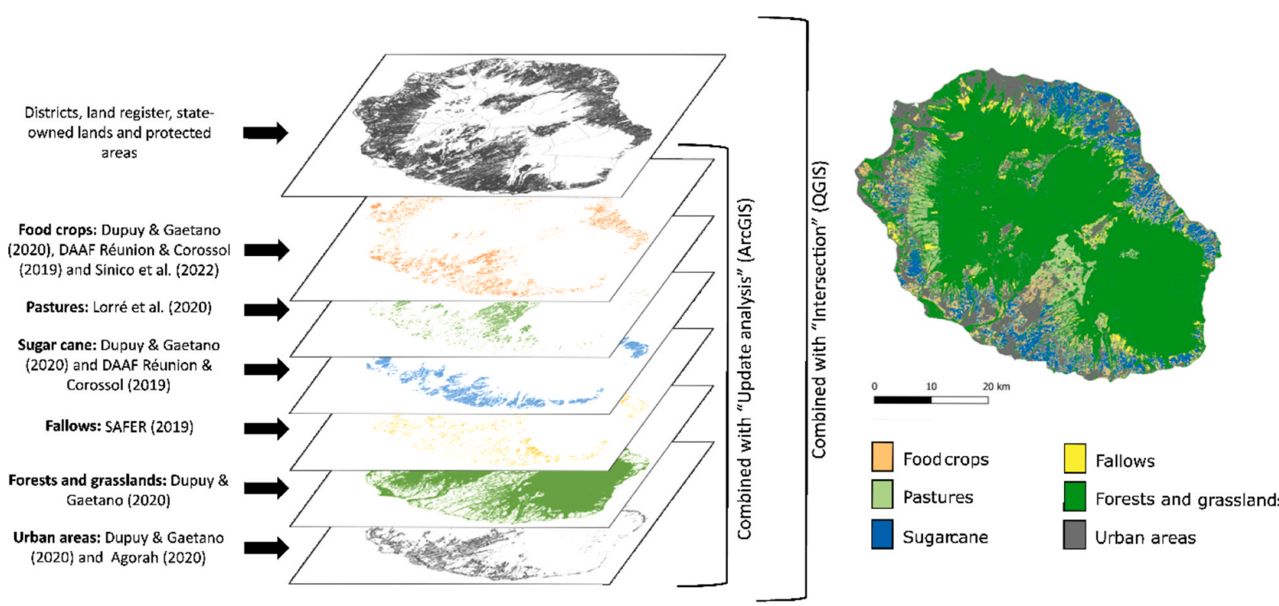

Fig. 2. Design of the initial 2019 land-use map. Six land-uses (food crops, pastures, sugarcane, fallows, forests and grasslands, urban areas) plus one administrative layers were combined (Agorah 2020; DAAF Réunion and Corossol 2019; SAFER 2019).
Source: authors.

2.3. Setting the spatial model: a map composed of several land-use types produces different resources for the island self-sufficiency

2.3.1. Overview of modelling land-uses to calculate self-sufficiency indicators at the scale of the island

In order to build an initial 2019 land-use map for our spatially explicit model, we needed to combine in one single map, data from different geographic information systems (GIS) as presented in Fig. 2. Each polygon of this initial 2019 land-use map contains two key attributes: a calculated surface area (m^2) and a land-use code. Specific land-uses corresponding to crops (sugarcane, fruit crops, vegetable crops, pastures) produced dedicated resources that contribute to certain final uses as presented in Fig. 3. By associating average annual yields to each land-use, it is possible to estimate global production for corresponding resources. Then, by assessing global population food and electricity needs as well as livestock's feed need, it becomes possible to calculate several indicators of share of local resources in final uses.

2.3.2. Calibration of crops yields, population needs and livestock needs

Regarding crops, yields firstly showed spatial variation for feed produced by pastures since they are highly dependent on local climate and agricultural practices (Lorré et al., 2020). Secondly, bioethanol yields were considered homogeneous on the island since bioethanol total contribution to electricity generation is minor compared to bagasse (SPL Horizon Réunion, 2020). However, bagasse yields were assessed (see Appendix A) by combining data from a map of predicted sugarcane yields (Martiné and Todoroff, 2002) with fibrous ratio samples from sugarcane delivery centres (CTICS, 2019). Moreover, predicted sugarcane yields depend on the existence of irrigation. Finally, average yields with spatial variations for food crops ("fresh fruits and vegetables", "starchy food" and "protein plants") were calibrated from Sinico et al. (2022).

In terms of population's needs, we first calculated average food consumption per person in 2018 for seven different food categories: "eggs and meat", "fish and seafood", "dairy products", "fruits and vegetables", "oil", "starchy food", "protein plants". We took our data from official sources for non-professional agriculture estimations (INSEE, 2014), professional agriculture productions (DAAF Réunion, 2020), food importations (Reunion Island Customs Services, 2019) and food waste (ADEME, 2016). Finally, individual electricity consumption and global population count were based on official estimates (EDF, 2019; SPL Horizon Réunion, 2020).

The model monitored nine types of animals for livestock: dairy cows, meat-type cows, pigs, meat-type chicken, laying hen, rabbits, sheep/goats, cervids and horses. We systematically converted the number of animals into livestock units with calibrated feed consumption, at the scale of the island, using existing research material (Magnier, 2019).

2.3.3. Calculated indicators to reflect on self-sufficiency

As outputs, the model calculated a feed coverage ratio, an electricity coverage ratio and a food coverage ratio, inspired by similar quantitative indicators used when assessing food and/or energy self-sufficiency at the scale of territories (Shreiber et al., 2020; Praene et al., 2012). Moreover, we specifically monitored the share of bioelectricity from bagasse and bioethanol in the electricity mix since this resource is the predominant source of bioelectricity, with the strongest influence on land-uses. We also monitored the share of asynchronous electricity in the electricity mix (e.g. share of electricity from windfarms and solar panels) since there are uncertainties about the maximum possible ratio of asynchronous electricity without undermining the stability of the electricity system (interviews: groups A and C).

2.4. Our model is also dynamic: modelled processes influence the evolution of the territory through scenarios

2.4.1. Overview of dynamic modelling approach on Ocelet

Our modelling approach aims to simulate potential future evolutions and support stakeholder's decision-making similarly to other studies (Schubert et al., 2015; Zhang et al., 2018). Our model was built using the Ocelet dynamic and spatially explicit modelling software (Degenne and Lo Seen, 2016). In this modelling approach, the studied system was composed of interaction graphs. On the nodes of the graphs were spatial entities (e.g., plots of land, urban areas), interconnected with edges holding interaction functions potentially activated during a scenario to change the state of the system (e.g. land-use type). From an initial land-use map (see Fig. 2), relevant processes were modelled to induce

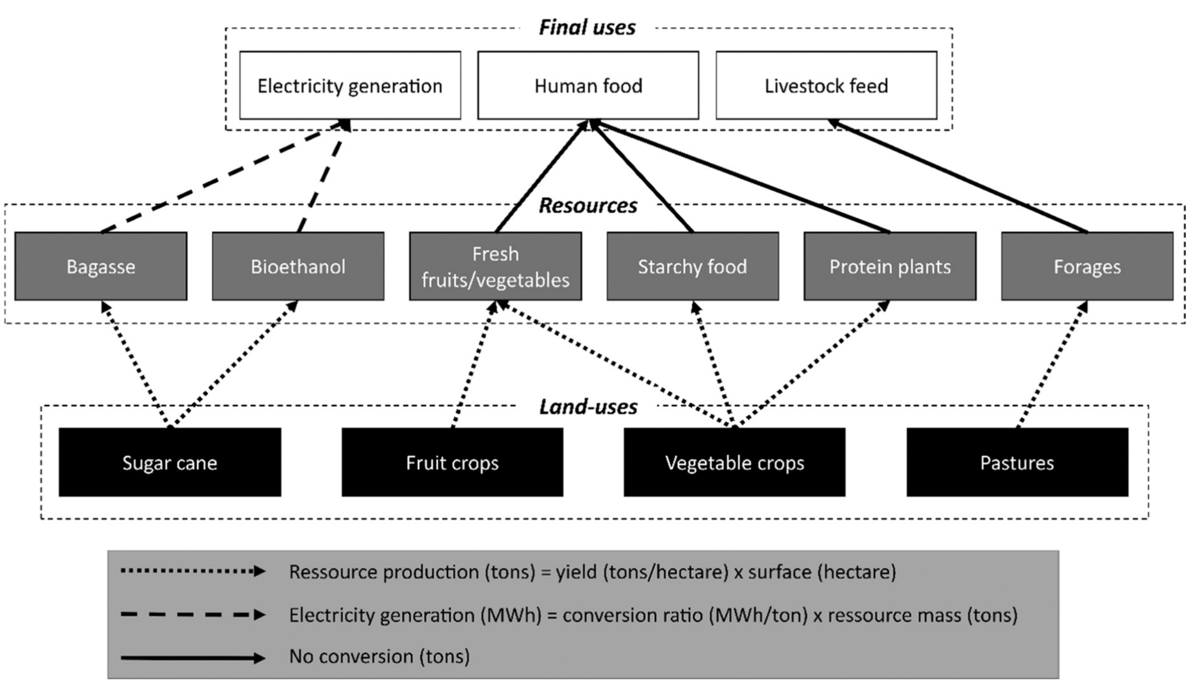

Fig. 3. Modelled resources production from land-uses.
Source: authors.

land-use changes every year. In turn, these changes affect how local food and electricity self-sufficiency evolves over a time span. In order to implement relevant processes in our model, we conducted a four-step analysis of the studied territory: (i) with a structural analysis, identification of "essential drivers of change" which are the most influential forces in the system, (ii) visualization of interrelations between drivers of change, revealing an interconnected system of "processes" to be modelled, (iii) calibration of some of these processes by assessing contextual variables and (iv) design of different scenarios in order to run simulations of plausible futures.

2.4.2. Identifying "essential drivers of change" from a structural analysis

In a foresight study context, "drivers of change" refer to factors causing change, affecting or shaping the future, thus influencing the constitution and evolution of the system (Zahraei et al., 2020; Bourgeois and Jesus, 2004). When describing a complex system with many quantitative and qualitative variables, structural analysis is a common method foresight studies, and requires three steps: inventory of drivers, description of relationships between drivers and identification of essential drivers (Arcade et al., 2009).

Firstly, an inventory of drivers was conducted based on semi-directive interview material from 72 experts out of 30 organizations (see Appendix B). Four relevant types of experts were identified: (i) administration, (ii) agricultural and agrifood industry, (iii) electricity industry and (iv) civil society. As recommended in Bourgeois et al. (2017), we focused on "internal drivers of change", which are under potential local stakeholder's influence.

Secondly, we conducted the description of relationships based on literature and interview material, using the Micmac software (Arcade et al., 2009), dedicated to structural analysis. Such a description of relationships between drivers of change takes the form of a matrix of direct influences (MDI): a cross-impact matrix where each element (a^{ij}) equals 1 if an influence exists from the driver in row (i) over the driver in column (j) (Appendix C). By summing all values in row (i) or in a column (j), we calculated the influence and dependence scores for each driver. We also calculated a matrix of indirect influences (MII) from MDI to encompass mid and long-term propagation of indirect influences between drivers of change (Delgado-Serrano et al., 2015).

Thirdly, drivers of change with the highest influence on the system dynamics were identified as "essential drivers of change". Driver's position on a combined influence-dependence map generated with Micmac reflected its influence on the system dynamics. On this map, each driver took the form of a vector that represents the transition between MDI and MII. Coordinates of each vector depend on its influence and dependence scores.

2.4.3. Visualizing interrelations between drivers of change, revealing an interconnected system of "processes" to be modelled

In order to design our first model version, we finally mapped all essential drivers of change in one interconnected system, based on qualitative material from the first round of interviews and several specific interviews. This visualization helped us to identify different "processes" to be modelled, each corresponding to a single or group of essential drivers. Later, first simulations results were discussed with stakeholders as "boundary objects" (Lestrelin et al., 2017). They fostered exchanges by illustrating land-use trade-offs between food and electricity self-sufficiency objectives. This constituted a second round of interviews to collect feedbacks from experts to improve our definitive model design (see Fig. 1).

2.4.4. Design and set up of four plausible scenarios

We designed our scenario building from a method called "co-elaboration of scenarios" (Bourgeois et al., 2017). However, we adapted the method to limit participation to two rounds of interviews in our study (see Fig. 1). Two reasons motivated this change: (i) most stakeholders had full agenda and gathering them for several days was impossible and (ii) land-use issues are highly sensitive on Reunion Island and some stakeholders would probably not have expressed themselves freely nor felt comfortable in presence of other actors.

In practice, we combined several coherent hypotheses concerning processes' plausible evolution from stakeholders' opinions. These hypotheses are translated into constraint variables which are pre-set (and mostly evolutive) parameters for the simulation period (e.g., population size, electricity consumption per inhabitant, surface conversion objectives for processes, etc.). Each set of constraint variables then defines a scenario.

We designed four scenarios on the 2019–2035 period, each set to explore a unique configuration of land-use changes at the scale of the island: (i) "business-as-usual" used as a reference trend, (ii) "food + " with priority given to land-use changes favouring food production, (iii) "bioelectricity + " with priority given to sugarcane protection to maintain bioelectricity production potential, and (iv) "planning + " which combines ambitious strategies set by local administration and agricultural organizations in terms of urbanisation, food production, and electricity planning.

2.4.5. Calibration of some modelled processes based on contextual variables

Contextual variables were used to distribute land-use changes for two processes regardless of the scenario. They were assessed by mapping recent land-use changes on the 2017–2019 period (Dupuy and Gaetano, 2019; Dupuy and Gaetano, 2020). Firstly, for sugarcane diversification, we sampled altitude and slope on converted sugarcane areas. Secondly, for urban sprawl, we sampled average slope, distance to road, distance to closest urban area and distance to closest urban sprawl. Calibration of these two processes related to their contextual variables is detailed in Appendix D.

3. Results

3.1. Essential drivers of change identified

Table 1 displays 12 out of 20 drivers identified as relevant for our

Table 1
Relevant drivers of change for our study. "Essential drivers" are in bold.

Drivers of change	Code	Description
Fallow conversion back to agriculture	FALCO	Net gain of agricultural lands by conversion of fallow lands back to agriculture
On-ground photovoltaic	SOLAR	Ratio of photovoltaic capacity installed on non-urban area
Food crop systems	FOSYS	Spatial distribution of major food crops and average yields
Pasture systems	PASYS	Spatial distribution and yields of pastures
Sugarcane systems	CASYS	Spatial distribution and yields of sugarcane systems
Urban sprawl	URBAN	Urbanisation beyond planning at the expense of agricultural and natural lands
Land protection for nature conservation	NATCO	State of protection on certain lands, forbidding most of agricultural uses (example: inside the National Park)
Natural ressources for agriculture	NATRE	Soil quality and water availability for agriculture
Consumers behaviour	CONSO	Individual average consumption for electricity, food preferences and food waste
Population growth	POGRO	Global population growth on the study area
Electricity mix except for bioelectricity from sugarcane	ELMIX	Share of local electricity sources (other than bioelectricity from sugarcane bagasse and bioethanol) in the mix and global electricity consumption
Livestock systems	LISYS	Global livestock size and its characteristics: species composition, feed needs, manure production, etc.

study. The remaining 8 drivers are listed in Appendix E. These lesser drivers are left aside because we chose to focus on quantitative drivers in the model and because they often appear to have low influence in the system dynamics. As introduced in 2.4.2, conclusions on a driver's role in the system dynamics is based on its position on a combined influence-dependence map (Fig. 4). In practice, each driver of change is associated to one of the five possible roles in the system dynamics: "input" drivers are located in the top-left corner, "stakes" in the top-right, "regulators" around the centre, "autonomous" in the bottom-left or "output" in the bottom-right (Delgado-Serrano, 2015).

Drivers of change ranked as "Input" and "Stakes" should bear the strongest influence (Bourgeois et al., 2017) but "Regulators" can also leverage influences across the system (Delgado-Serrano, 2015). Therefore, these constitute "essential drivers of change". Exceptions correspond to drivers with little or no evolution in our scenario design (see 2.4.4) and are therefore not considered as essential: NATCO, NATRE and LISYS.

3.2. Visualizing drivers' interconnections allows for identification of processes to be modelled

To design our model, we elaborate in Fig. 5 one final interconnected system of the drivers listed in Table 1. This way, several processes are identified to be modelled in Ocelet. Four key processes appear to bear a more important role in the system, as they encompass several essential drivers.

The first key process is "sugarcane diversification towards pastures and food crops". Mostly due to economic pressure and insufficient labour supply, more and more sugarcane farmers enrol in diversification on their farmlands. These are partially converted from sugarcane to other crops (mainly food crops but also pastures). In the model, random plots of sugarcane turn into "vegetable crops", "fruit crops", "other crops" or "pastures" in order to reach a global diversification surface objective, while distributing those newly diversified plots according to contextual variables (see 2.4.5).

Secondly, the process "urban sprawl and its competition with agricultural lands" is split in 3 phases to satisfy the required number of new accommodations per year for each of the five inter-municipalities of the island. During phase 1, urban density from existing urban areas increases which creates new accommodations without extending urban areas. Then, during phase 2, a defined number of urban extensions are built with optimal urban density in areas classified as priority urbanisation areas. Finally, accommodations left to build after phases 1 and 2 constitute the urban sprawl objective. In phase 3, the model distributes as many new houses-sized polygons (650 m^2 in average) as necessary to reach the urban sprawl objective, according to contextual variables (see 2.4.5). Phase 3 occurs on privately owned plots; often agricultural lands having undergone fragmentation followed by land reclassification (interviews: groups A and B).

Thirdly, fallows are abandoned lands that were previously cultivated, and constitute a potential source for new farmlands if recovered. Thus, the process "net gain of agricultural lands from fallow conversion" turns random plots identified as fallows into farmlands (food crops, pastures and/or sugarcane) until a conversion surface target is reached. Fallow conversion may happen on privately owned plots as well as on some pre-identified public owned lands with low biodiversity status according to National Park and Department (interviews: group A).

Fourthly, "on-ground photovoltaic competing against agricultural lands" consists in solar panels being installed directly on-ground. In the model, on-ground photovoltaic can only replace privately owned fallows, below 600 m. Such converted plots produce electricity. The area converted to on-ground photovoltaic each year correspond to a fraction of all photovoltaic production in the electricity mix.

Lastly, "evolution of population needs", depends on individual behaviours regarding food preferences and electricity consumption as well as the number of inhabitants on the territory.

3.3. Contrasted constraint variables define four different scenarios

The first scenario (S1: "extrapolation") constitutes a business-as-usual trend and used linear extrapolation of observed trends as specific calibration. The second and third scenario are opposite variations of the first scenario: S2 ("food +") increased diversification and fallow conversion for local food production, whereas S3 ("bioelectricity +") stopped diversification and increased fallow conversion towards sugarcane to maintain local bioelectricity production. Finally, S4 ("planning +") grouped the most ambitious stakeholders' hypotheses still deemed to be possible and compatible, both for increasing food self-sufficiency while maintaining a large surface of sugarcane for bioelectricity, all with an additional strict supervision over urban

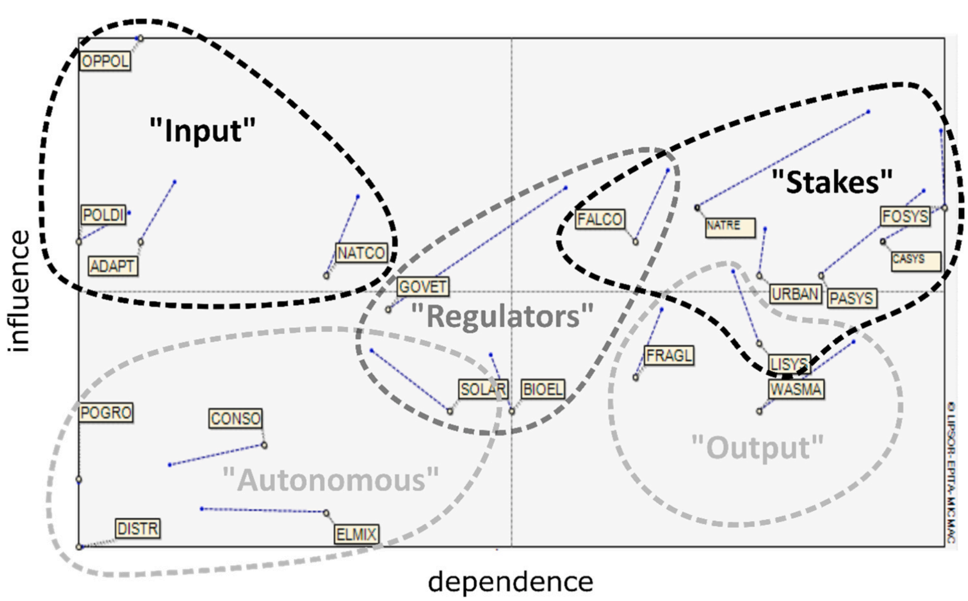

Fig. 4. Clusters of drivers of change according to their role on the combined (direct and indirect) influence-dependence map. Tags refer to drivers' codes indicated in Table 1 and Appendix E.
Source: authors.

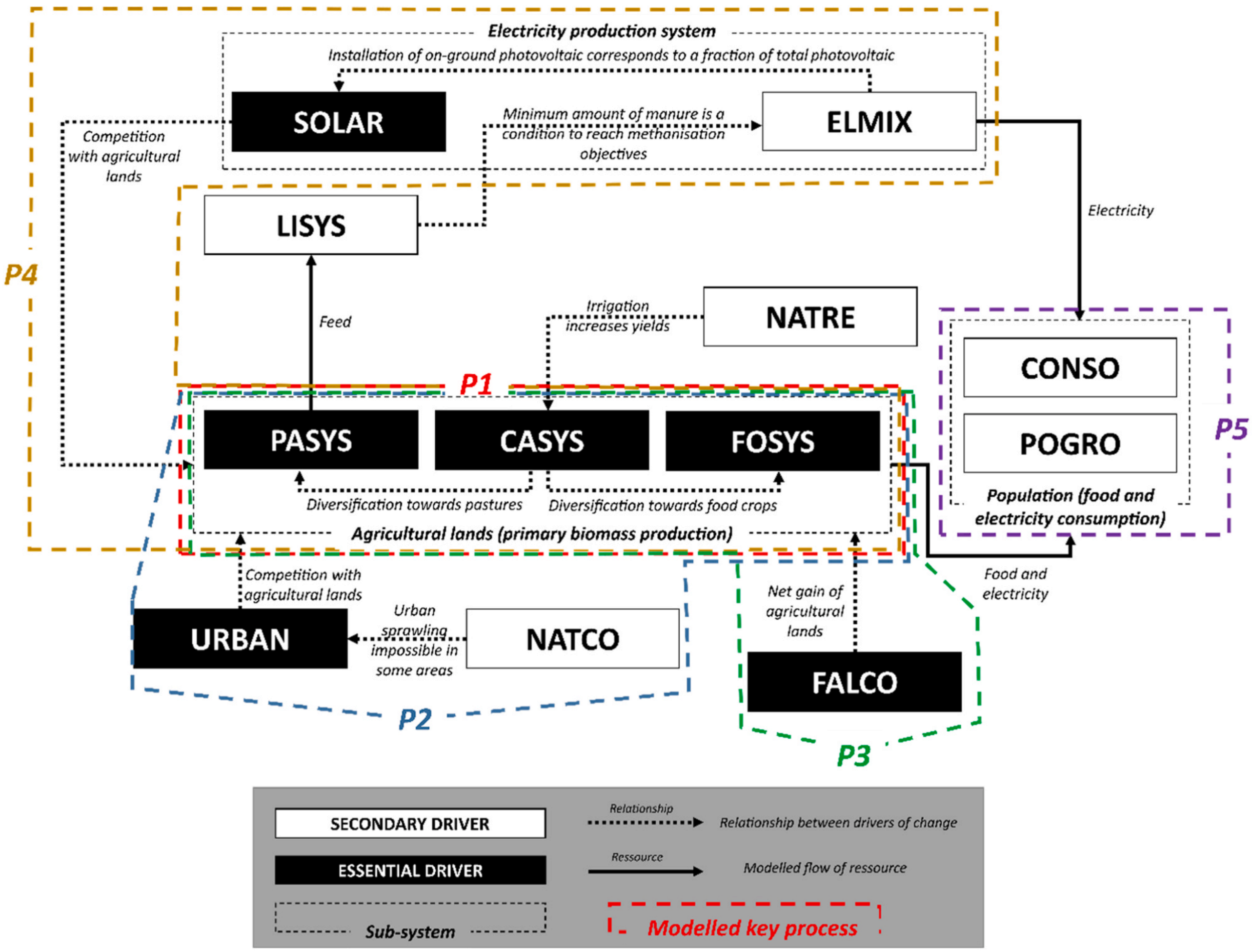

Fig. 5. Conceptualization of the modelled system as interconnected drivers reveals key processes to be modelled. P1: Sugarcane diversification towards pastures and food crops; P2: urban sprawl and its competition with agricultural lands; P3: net gain of agricultural lands from fallow conversion; P4: on-ground photovoltaic competing against agricultural lands; P5: evolution of population needs.
Source: authors.

Table 2
Main hypotheses setting up the four simulated scenarios on the 2019–2035 period. Key process codes refer to the conceptualized system in Fig. 5.

Parameter (key process code)	S1: Extrapolation	S2: Food +	S3: Bioelectricity +	S4: Planning +
Sugarcane diversification rate per year (P1)	Constant based on 2017–2019 assessment	Sharp increase compared to S1	No diversification	Identical to S1 but no less sugarcane than 22 000 ha according to AGRIPéi
Diversification crops (P1)	Based on 2017–2019 assessment: mostly fruit crops then pastures and vegetable crops		No diversification	Identical to S1
Contribution of urban densification per year (P2)	Densification increases extremely slowly as observed in recent years			Densification increases rapidly according to SAR
Contribution of urban extensions per year (P2)	Constant surface area based on 2017–2019 assessment			Constant percentage according to SAR
Net gain of farmlands from fallow conversion per year (P3)	Inactive process (gain equals loss)	Lowest ambition according to AGRIPéi		Highest ambition according to AGRIPéi
Crops cultivated on converted fallows (P3)	Inactive process (gain equals loss)	Food crops and pastures	Sugarcane	Sugarcane, food crops and pastures
Share of on-ground in total photovoltaic production (P4)	Constant based on 2019 assessment	Photovoltaic only in urban areas	Constant based on 2019 assessment	Photovoltaic only in urban areas
Electricity mix apart from bioelectricity from sugarcane (P4)	Linear extrapolation from the 2010–2019 period	Objectives set by local PPE until 2028 then linear extrapolation of trends until 2035		
Evolution of consumers' diet (P5)	Linear extrapolation from the 2011–2017 period			
Evolution of electricity consumption (P5)	Linear extrapolation from the 2010–2019 period	Efficiency and sobriety decrease electricity consumption according to PPE		
Population size (P5)	Official projections (corrected based on most recent population census)			
Livestock size (other)	Linear extrapolation of trends from the 2010–2019 period			Agrifood industry plans

sprawling. Moreover, we considered that this fourth scenario was the closest to a shared compromise amongst official stakeholders by combining strategic objectives from *AGRIPéi*, PPE and SAR (see Introduction). Table 2 gives a summary of the main hypotheses for the four scenarios. Translation of these qualitative hypotheses into constant parameters and constraint variables' quantitative set-up is detailed in Appendix F.

3.4. Scenario comparison: land-use dynamic monitoring and self-sufficiency indicators

Fig. 6 illustrates with a detailed map in southern Reunion Island how modelled processes influence land-uses during simulations between 2019 and 2035. The disappearance of sugarcane fields, replaced by food crops and pastures is visible except in scenario S3. The land-use changes towards food production appears massive for S2. Dots of urban sprawling appears in all scenarios along roads and existing urban areas: the east of the map seems particularly favourable for establishment of new settlements in all scenarios, which compete directly with farmlands. Only scenario S4 visibly manages to control urban sprawling, simulating stricter urban policies.

As shown in Fig. 7, the simulated scenarios lead to a wide range of land-use changes between 2019 and 2035: from − 12,212 ha to + 990 ha for sugarcane, from + 324 ha to + 2773 ha for pastures, from + 305 ha to + 11,566 ha for food crops and from + 1797 ha to + 5465 ha for new urban sprawl areas. However, sugarcane surfaces

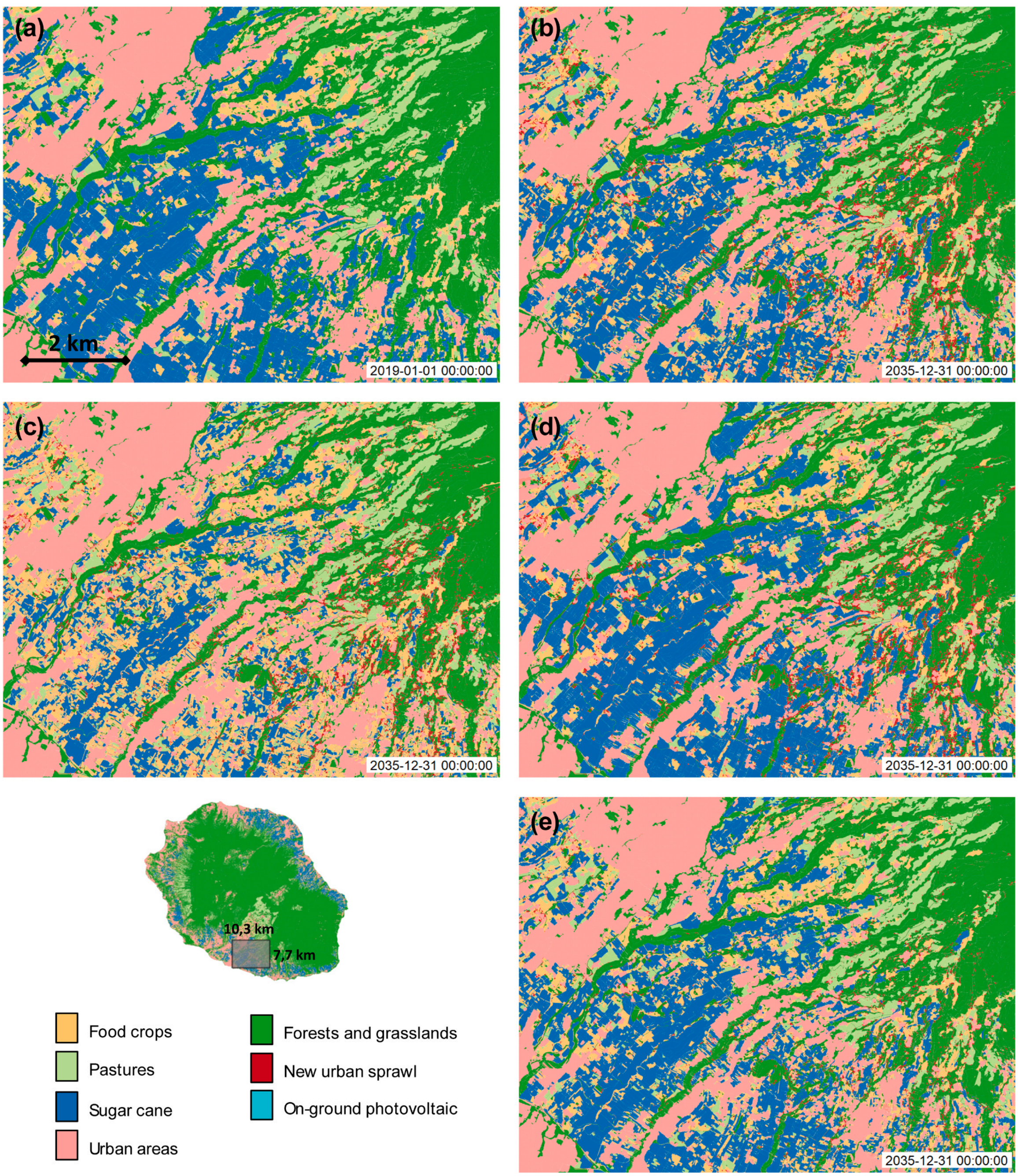

Fig. 6. Sample of simulated land-use changes in scenario S1 "extrapolation", in southern Reunion Island. From the initial land-use map set in 2019 (a), four scenarios are simulated and the resulting land-use maps in 2035 are presented: S1 "extrapolation" (b), S2 "food + " (c), S3 "bioelectricity + " (d) and S4 "planning + " (e) Source: authors.

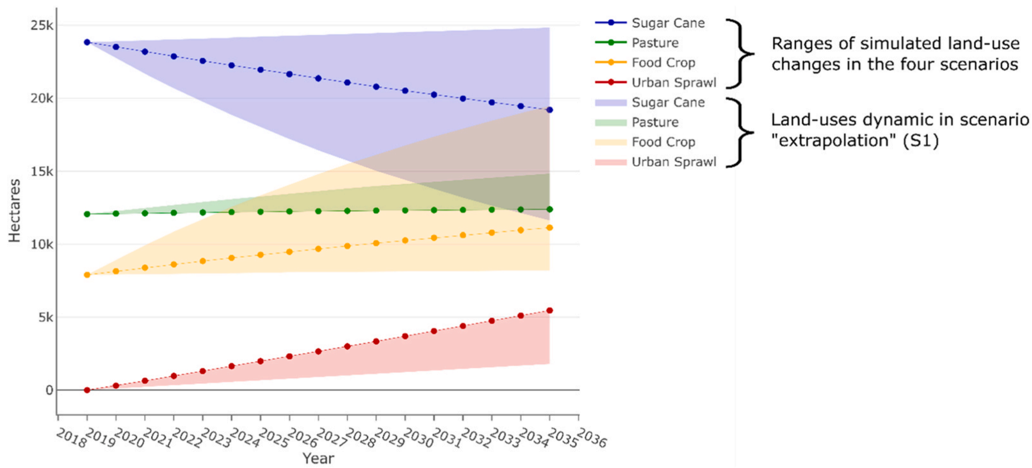

Fig. 7. General land-use trends (sugarcane, pasture, food crops and new urban sprawl) through the four simulated scenarios. Solid lines correspond to scenario S1 whereas coloured areas show for each year the difference between scenarios with maximum and minimum values.
Source: authors.

seem globally to decline (except in S2), essentially replaced by food crops but also some pastures, while urban sprawls keep rising and pressuring on all farmlands.

Fig. 8 stresses that the more a scenario maximizes food and forage coverage ratios, the more it tends to undermine the bioelectricity share in the electricity mix, and vice versa. Regarding food self-sufficiency: in the best case (scenario S2), simulated food coverage ratio reaches 65% in 2035 (+23% compared to 2019) while the share of bioelectricity decreases to 3% of the electricity mix (−5%). Regarding global electricity coverage ratio, two categories appear: S1 is isolated from the other three scenarios, which show similar coverage ratio values since PPE is implemented in each of them. Similar trends are observed regarding shares of asynchronous sources in the global electricity mix.

4. Discussion

4.1. In an insular system such as Reunion Island, the lack of available land calls for ambitious land planning policies which in turn questions land tenure

Results in Fig. 8 highlight how increasing simultaneously food and bioelectricity production is challenging when land is a scarce resource. Scenario S2 favours food production but decreases the production of bioelectricity from sugarcane, whereas scenario S3 does the opposite. Only scenarios S1 and S4 manage to increase slightly food production without collapsing bioelectricity production from sugarcane. S4 does slightly better than S1, probably due to two of its simulated land planning policies: high conversion of fallows and strict urban sprawl control. But even this optimistic scenario remains far from self-sufficiency due to a structural lack of available land.

Indeed, land is recognized as one of the main constraints when aiming at improving food and/or electricity self-sufficiency for islands (Rahman et al., 2022; Halldórsdóttir and Nicholas, 2016; Kim et al., 2015). Our work supports this idea since several essential drivers are directly linked to land availability and competing uses (e.g., urbanisation, fallow conversion, land protection for nature conservation, etc.).

Furthermore, in Reunion Island, our work highlights how most of relevant land-use changes regarding self-sufficiency occur on a small portion of the territory: a low to medium altitude belt essentially composed of fragmented privately-owned lands. While our results illustrate the benefits of anticipative land-planning to improve self-sufficiency, this state of land tenure would therefore complicate any large-scale strategic planning policy. As a top priority, our paper advocates the implementation of measures to better protect vulnerable insular farmlands, especially considering how these are prone to land reclassification into urban sprawling in our study case as well as for most SIDS (Batra and Norheim, 2022).

4.2. Relevance of producing bioelectricity from crop is a controversial issue with uncertain outcome for insular territories

Bioelectricity has the potential to increase energy self-sufficiency, especially for non-interconnected islands where it often constitutes one of the only local sources of synchronous electricity (Chary et al., 2018; Kim et al., 2015). Results in Fig. 8 indicates that bioelectricity potential can be maintained rather than increased, at best, around 7–8% of the electricity mix in scenario S2. This share seems low but still it may play an essential role. Firstly, bioelectricity is a local synchronous source of electricity: it contributes to network stability, and thus to electricity security. Secondly, scenarios implementing PPE (S2, S3 and S4) may not be achievable if the share of asynchronous sources in the mix cannot exceed its current limit: 35% due to network limitations (interviews: group C). In addition, other limitations (mineral depletion, economic crisis) may also put a ceiling to the share of asynchronous sources such as photovoltaic. In this case, bioelectricity could contribute to provide this missing share of synchronous electricity (interviews: groups A, C and D). Furthermore, if bioelectricity is needed in the mix, producing it locally, at least partially, would secure the resource. Considering biomass production in terms of security is usually related to food security, but in times of geopolitical, economic and energetic turmoil, it may become necessary to rethink electricity security as well. For small islands, this could translate into securing biomass reserves for bioelectricity production.

On the contrary, some stakeholders think that bioelectricity production from sugarcane should be abandoned or at least gradually reduced, replaced essentially by photovoltaic (interviews: group A and D). Three arguments support this idea. Firstly, bioelectricity has limited production potential, mostly due to space constraint as stressed in other studies (Chary et al., 2018). Indeed, in our study, bioelectricity only holds a limited influence on "electricity coverage ratio" (see Fig. 8). Secondly, necessary technological advancements and funding, especially on storage and grid, has potential to raise the share of asynchronous sources in electricity mixes of islands (Al Katsaprakakis and Voumvoulakis, 2018). Thirdly, our results show that even an important development of on-ground photovoltaic (25% of installed capacity in S1 and S2) has a reasonable land conversion impact (around 200 ha in total by 2035) at the edge of farmlands (on fallows) which prevent from large scale land tenure conflicts.

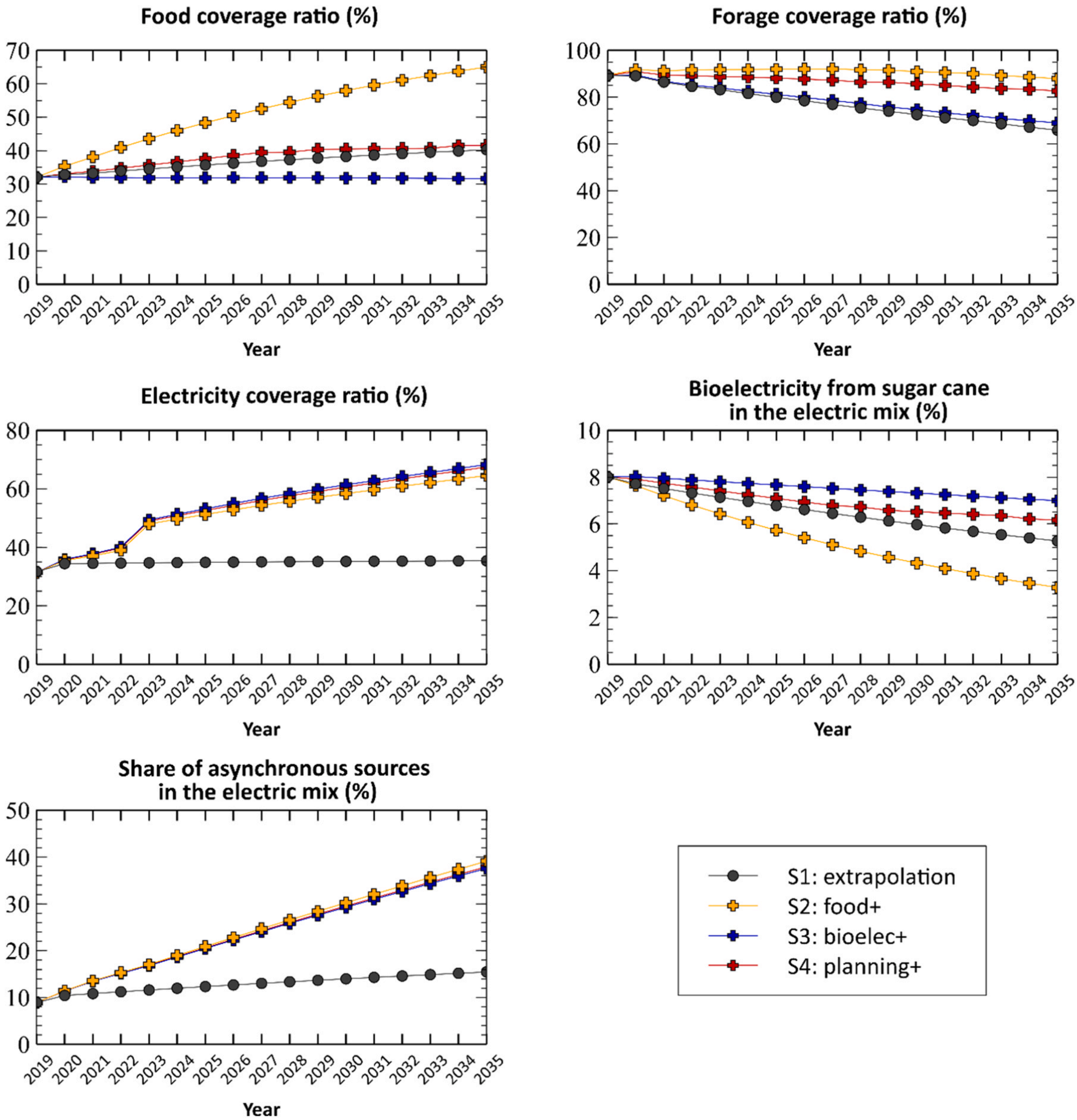

Fig. 8. Monitoring of food, feed and electricity in the four simulated scenarios. Coverage ratios express the percentage of local demand satisfied by local production. For "bioelectricity from sugarcane in the electricity mix", percentages correspond to the share of electricity produced from bagasse and bioethanol compared to the global electricity demand. (a) Similarly, for "share of asynchronous sources in the electricity mix" (e.g., share of electricity from windfarms and solar panels), percentages are related to the global electricity demand. (b) Sharp evolution for "electricity coverage ratio" in 2023 indicates the start of a garbage incinerator generating around 220 GWh per year (as planned in the PPE).
Source: authors.

In the end, our results suggest that the need for local bioelectricity sources such as bagasse and its consequent impact on land-use will also depend on the capacity for the electricity system to rely massively on renewable asynchronous sources. In such a scenario, bagasse would locally cease to be a strategic resource for the electricity mix, thus farmlands could be dedicated to food crops, massively replacing sugarcane (similar to scenario S2, see Table 2).

4.3. Originality of our method: food and electricity self-sufficiency integration in space and time, bottom-up context-specific modelling and small-scale heterogeneity

The first and main novelty of our approach lies in the integration of foresight with modelled spatial processes to translate the concept of self-sufficiency as a dynamic land-use trajectory. This supports the idea that food and electricity self-sufficiencies should also be seen as "processes". As such, this paper highlights how improving self-sufficiency (as a "degree") may appear harder and longer-term when considering its pace as a "process". For example, in the best case (S2), it takes 16 years to double the food coverage ratio in our simulated scenarios (see Fig. 8). Our approach goes one step further in terms of integration by underlining the benefits of merging food and electricity at territory scale not only in terms of physical flows (Barles, 2014; Gasparatos, 2011) but under dynamic spatial constraints.

Secondly, the use of the "drivers of change" concept from foresight studies, allows identifying context-specific dynamics from stakeholders' perspective. Then, our model is built from a selection of these drivers and their related processes, which leads to build an endemic bottom-up model able to simulate specific dynamics of our studied area such as (i) "diversification of sugarcane", a monoculture-exported cash crops losing field in favour of local food production whereas it is usually the opposite (Clapp, 2016) and (ii) "fallow conversion back to agriculture" ranked among essential drivers according to our study while it is uncommonly discussed in literature (Shreiber et al., 2020).

Finally, our work emphasizes the need to account for small-scale heterogeneity. In our model, this translates above all into: (i) spatially distributed land-use changes according to contextual variables (see 2.4.5) and (ii) mapped yields for pastures, sugarcane fields and food crops, which is uncommon when modelling agricultural production in small territories.

4.4. Identified lesser drivers pave the way for further scenario building

Another benefit of our approach being participatory lies in the interviews' content: its richness open interesting perspectives. Some identified drivers are ranked as lesser driver with our method (see Appendix E) but appear important for imagining future contrasted scenarios. Five of them constitute interesting perspectives while being disregarded in our model.

Firstly, although not being lesser drivers, alternative production systems (organic and/or traditional farming) are underexplored in our model but are recognized by stakeholders (interviews: groups A, B and D) and literature (Schmitt et al., 2017; Poux and Aubert, 2018) when aiming at food self-sufficiency. Furthermore, alternative livestock production systems often entail an increased ratio of locally produced feed which would lead to dedicated crops on the island whereas in current systems, feed concentrates are almost entirely imported (interviews: all groups).

Secondly, literature insists on including policies and governance in the scope of influential drivers for food or electricity self-sufficiency at territorial level (Cango et al., 2023; Shreiber et al., 2020; Al Katsaprakakis and Voumvoulakis, 2018). This was only partially implemented (e.g. by involving PPE, an energy policy in three scenarios). Governance aspects also affect scenario design, such as the strength asymmetry between local agricultural representatives, which hinders or favours certain crop production systems (interviews: group D).

Thirdly, nutrient dependency is a major limiting production factor, especially for islands aiming at food self-sufficiency (Halldórsdóttir and Nicholas, 2016; FAO and CDB, 2019). In our context, we identify "organic waste management" as a driver able to cycle locally produced nutrient flow in a circular economy, in order to increase local nutrient availability for crops (interviews: all groups).

Fourthly, water availability is identified as prominent in many situations for food and/or electricity self-sufficiency (Yuling Leung Pah Hang et al., 2016; FAO, 2016). In our study, we only considered the influence of irrigation for sugarcane yields, since water scarcity is not a critical issue for agriculture yet but it probably poses a serious challenge in the mid or long-term for all crops (interviews: group B).

Finally, we globally considered that improving food and electricity self-sufficiency equals increasing local production. However, further scenarios should also question consumer's behaviour evolutions: for example, some diets facilitate localizing food systems (Poux and Aubert, 2018) while others can limit consumption of local products (Halldórsdóttir and Nicholas, 2016). Although not being a lesser driver, "consumers' behaviour" could be subject to more ambitious hypotheses. Indeed, this driver is stressed among stakeholders for its great potential to tip food and electricity balance towards more self-sufficiency (interviews: all groups).

5. Conclusion

Food and electricity self-sufficiency receive increasing attention from policy makers at territorial level, especially in insular systems where the dependence towards imports is particularly acute. In Reunion Island, local stakeholders are committed to improve both food and electricity self-sufficiency over the next decades. However, in practice, local food and electricity production systems require farmlands, a scarce resource since the island is small and under pressure from urbanisation. Thus, increasing food and electricity self-sufficiency in the coming years is a matter of land-availability. In order to understand these land-use dynamics and anticipate potential evolution of food and electricity self-sufficiency at the scale of the island, we designed a new method combining a foresight study approach and dynamic spatial modelling. Firstly, we adapted the "co-elaboration of scenario" method from foresight studies. We identified essential drivers of change with a structural analysis based on semi-directive interviews and we combined these drivers and their related processes to create land-use scenarios. Secondly, we used the Ocelet platform to spatially model drivers of change and their related processes, to finally simulate their dynamics according to the four scenarios.

Our results confirm that land-availability is a critical resource for food and electricity self-sufficiency in small insular territories such as Reunion Island. In our context, there is limited potential for increasing simultaneously food coverage ratio and bioelectricity coverage ratio. Ambitious land planning policies supported by official stakeholders, such as massively converting fallows back to agriculture and restricting urbanisation, show a positive but limited effect on self-sufficiency. One way forward would be to enrol farmers into a larger-scale diversification towards food crops. In parallel, a local electricity mix relying heavily on asynchronous sources such as photovoltaic should be designed to safely phase out sugarcane bioelectricity. However, land tenure state, mostly private, complicates required large-scale land-planning policies. Moreover, the feasibility of such an electricity system in the future is still uncertain (due to mineral depletion, economic or technological factors) whereas maintaining bioelectricity production potential could represent an insurance for electricity security on the eve of global scale energy crisis.

Our innovative approach merges food and electricity self-sufficiency issues in space and time. Moreover, our bottom-up model is built from stakeholders' perspective, which in turn contributes to root science within heterogeneous territories. This contributes to mediate debate around controversial issues related to land-use planning.

Further scenario building and modelling are required to ensure continuation of stakeholders' commitment and policy planning towards a more self-sufficient territory. New scenarios should mobilise complementary drivers of change: involving changes in individual consumption (diet especially), innovative food and/or energy crop systems, allocating a share of local food crops to feed livestock, mobilising local nutrient sources for crop growth, etc. While our approach focuses on internal drivers of change, some external drivers may also complement such modelling work especially when they can deeply affect future trends such as climate change (especially its effects on extreme weather events and water availability), depletion of fossil fuels and minerals.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Most of the data used in this paper will be made available on request; however some data are confidential as stated in the References.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.landusepol.2023.106784.

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