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ORIGINAL ARTICLE

Is food self-sufficiency possible for Reunion Island?

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Abstract

In the context of political and economic instability, food self-sufficiency of countries and territories is becoming a burning issue. Reunion Island is a densely populated small French territory isolated in the middle of the Indian Ocean. The previously developed GRAFS model, allowing consistent balances to be established using nitrogen (N) as a common metric for all crops and foodstuffs, has been applied to Reunion Island, considering 11 sub-regions to account for landscape variety. Reunion Island dedicates 87% of its crop production in terms of harvested proteins to the exportation of sugar and tropical fruits, while it imports 67% of its food supply, 54% of livestock feed, and 57% of all fertilizing N inputs to agricultural soils. Overall, the supply of 1 tonne of N as food requires the import of 2.7 tonnes of N as food, feed, and fertilizers. The model also demonstrated that the simultaneous operation of three levers of change would make it possible to reach self-sufficiency in terms of food, feed, and fertilizer: (1) the generalization of agro-ecological crop rotations alternating grain and forage legumes, cereal, and other food crops; (2) the reconnection of livestock with crop farming and a better recycling of manure as well as of human excreta; (3) a drastic reduction of animal-based food in the Reunionese diet, down to 20% of animal products in the total per capita protein intake, instead of the 60% current share. The area dedicated to sugarcane cultivation should be reduced to 15–25% of its current value.

Keywords Reunion Island · Food self-sufficiency · Agro-food system · Agro-ecological scenarios · Sugarcane

Introduction

In the current context of increasing political and market instabilities, food self-sufficiency at national and territorial scale is becoming a major political issue, subject to heated debates (Clapp 2017). Food self-sufficiency of a territory is defined by the Food and Agriculture Organization (FAO 1999) as the extent to which the particular territory can satisfy its food needs from its own domestic production. This definition differs from that of food security, which involves commercial imports and food aid as possible sources of food supply, and refers to stability of supply and access to food by the population. The concept of food sovereignty (Windfuhr and Jonsen 2005), on the other hand, refers to the possibility of democratic control that the population can exercise over its own food supply, either domestic or not.

Centuries of colonialism and economic policies based on the Ricardian concept of comparative advantages led to the specialization of agro-food systems around the world and their opening to international markets (Kraussman and Langthaler 2019; Billen et al. 2019). The current specialization in export crops from many countries or territories in the Global South is often the legacy of a colonial history that locked them into the production of agricultural commodities now facing declining terms of trade in inherently unstable international markets, preventing these regions from controlling their own development (FAO 1999).

The issue of food self-sufficiency is particularly acute in the case of isolated islands, because of the inherent risks of supply disruption. For the smallest and most populated of these, obvious biophysical barriers simply make it impossible to achieve self-sufficiency. For others, depending on the ratio between their population and the available farmland, the question of food self-sufficiency can be raised, all

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the more so when self-sufficiency was achieved at a certain stage in their history. The case of Reunion Island, a small (2512 km^2) volcanic island in the Indian Ocean, 680 km east of Madagascar, is quite illustrative of these debates, and this also applies to other islands in the Indian Ocean (e.g., Mauritius) as well as to Caribbean islands (Martinique, Guadeloupe, etc.). A major factor here is the ratio between population and available agricultural land, which is 21 people per ha in Reunion Island, compared to 2.3 in Metropolitan France, and respectively 16, 12, and 18 in Martinique, Guadeloupe, and Mauritius, making Reunion Island an extreme example. Some commentators in the opinion press go so far as to assert that the goal of food self-sufficiency of these islands is nothing more than an *ideologically driven chimera* (Nol 2021). Clapp (2017), in her lucid discussion of the issue of food self-sufficiency, advocated that the stake is not autarky per se, but rather the aim to avoid the risks associated with excessive reliance on trade for food supply. She also highlights the lack of an agreed and common metric for measuring the degree of self-sufficiency (or conversely import reliance) of regional agro-food systems.

Here, we intend to provide an objective assessment of the current agro-food system of the specific example of Reunion Island, using an original biogeochemical approach based on the description of material fluxes associated with agriculture, livestock farming, and human food supply, allowing to assess its degree of openness and related fragility. This diagnosis is then the starting point for the development of a series of agro-ecological scenarios aimed at moving the system closer to food self-sufficiency, based on operating the same levers as those previously activated for designing similar scenarios at the scale of metropolitan France and Europe (Billen et al. 2018, 2021, 2024). Our approach is purely biophysical: It aims at assessing the current situation in terms of territorial metabolism (Barles 2010; Singh et al. 2020; Buclet 2021) and exploring hypothetical alternative agro-food systems. We are aware that the obstacles to change are often of a social, economic, and political nature, but we believe it is useful to the debate to assess the biophysical feasibility and the limits of such a target of food self-sufficiency.

Site description

A brief history of food supply on Reunion Island

Reunion Island was long a deserted volcanic island formed by the eruption of a hot spot 2–3 million years ago. The first human settlement dates back to its annexation by France in the 1640s and was first exploited for producing subsistence food to supply the ships in transit to India, later for growing coffee and then sugar for export (Leguen 1979). Massive imports of slaves from Africa and Madagascar were organized from the end of the seventeenth century, until slavery was abolished in 1848. A policy of semi-forced recruitment of Indian workers was then implemented until the beginning of the twentieth century, when the total population of the island reached 200,000 inhabitants (see SM1). Since the early nineteenth century, sugarcane has become the main cultivated crop while massive imports of food crops have been in place, foremost among which is rice as the basis of the diet of people of Asian origin. The highlands, where sugarcane cultivation is not possible, were populated by people of diverse ethnic origins at odds with the plantation's socio-economic system (Benoist 1983) dominating in the lowlands and who were living mostly in autarky. In the beginning of the twentieth century, the cultivation of Geranium developed on forest or savannah highlands for the purpose of exporting its essence. During World War II, the island, which remained under the authority of the pro-German Vichy regime, was subjected to a blockade by the British navy for almost 2 years. A severe food shortage ensued, forcing planters to replace sugarcane cultivation with staple food such as maize and manioc (Guèzé 1946; Corral-Broto 2021) and leading to the cessation of Geranium cultivation in the highlands. Owing to these radical changes in land use, the population could be fed using domestic food resources. After the war, Reunion Island, together with the other "oldest" French colonies in the West Indies, became a French administrative unit—*département*. This integration, rather than independence, was ardently desired by the left-wing parties representing the Creole working population, less so by the small minority of large planter-owners who at the time controlled 60% of the territory and the entire sugar industry. The political and social compromise was that sugarcane cultivation and sugar production were given priority in the state planning of the island's development (Valy 2000) rather than a search for a more diversified economy geared toward meeting local needs. Today, the historic planter-owner class has divested of their ownership of the industrial processing apparatus; only two giant sugar factories are left in the north and south of the island, bought out by Tereos Océan Indien, a subsidiary of the cooperative group Tereos, a major stakeholder in the international sugar sector. As a result of successful land policies aimed at redistributing land, sugarcane is cultivated by 2700 planters, on parcels of 8 ha on average. National and European public aid to the sugar sector currently amounts to 140 million euros per year (Agreste 2023), i.e., more than 6000 €/ha.

The island, currently populated by 860,000 inhabitants, imports most of its food consumption, except for fresh vegetables and fresh meat. The risk of supply disruption was acutely felt during the COVID-19 crisis. A number of citizens' associations are now campaigning for food sovereignty on the island. One of the most active, Oasis-Reunion (www.oasis-reunion.bio/), has compiled a highly detailed inventory of the island's agro-food situation, and produced a manifesto, signed by over 40,000 persons, claiming the objective of feeding Reunion Island through "100% local, organic and peasant agriculture, at a fair price for all." The issue of food self-sufficiency is also taken up in official reports at both national (Thibault and Bastock 2021) and regional level (DAAF Réunion 2019); these latter reports, however, cautiously avoid calling the current agro-food system into question.

Landscape diversity

In spite of its small size, Reunion Island displays a large diversity of landscapes and climatic conditions, because of the a East-West gradient of pluviometry (mainly controlled by east trade winds and cyclonic episodes and varying from more than 2000 mm to less than 1000 mm/year) and altitude (varying from sea level to more than 2000 m in the center of the island). Based on these two factors, eight sub-regions can be considered by intersecting the official North, East, South, and West administrative micro-regions, often distinguished for their pluvial regime, with the contour line of 800-m altitude, which is about the higher limit of sugarcane cultivation. Two of the three cirques surrounding the Piton des Neiges—Salazie and Cilaos—represent official administrative entities in their own right (*communes*). We consider them as separate entities in our analysis because of their specificities. The third one, Mafate, inaccessible by road, belongs to two other communes and only counts approximately 800 permanent inhabitants. Although detailed information on this territory is difficult to obtain from conventional statistical sources, we nevertheless considered it as a distinct sub-region, because of its emblematic history and its situation of quasi-autarky. The 11 resulting sub-regions are shown in the map in Fig. 1a and b, which also displays the contours of the central protected zone of the National Park, created in 2007 and occupying 42% of the island surface area (see region characteristics in Table SM1).

Methods

In order to describe the current agro-food system of Reunion Island, we adopted the GRAFS approach (Generalized Representation of Agro-Food Systems) previously developed by Billen et al. (2014) and Le Noë et al. (2017, 2018) and applied at different scales from global (Lassaletta et al. 2016) to national and regional (Rodríguez et al. 2023; Garnier et al. 2016; 2023; Billen et al. 2021, 2024). The GRAFS approach is based on precisely accounting for fluxes of agricultural commodities and foodstuffs along the chain from cropland and grassland to livestock and the human population. Nitrogen (N) is chosen as a suitable common metric for three reasons. (1) N is the main constituent of proteins, a major and essential component of foodstuffs, alongside carbohydrates and lipids which do not contain N. Because proteins are primarily required for tissue build-up and renewal, a rather constant per-capita protein requirement of ca. 3.6 kgN/cap/year can be defined (taking into account ca. 20% unavoidable losses before final intake) (WHO 2007; Grizzetti et al 2013), while the requirement in terms of kilocalories is much more variable according to lifestyle and professional activity (WHO 1985, 2007). Supplying this required N protein ration to each inhabitant is the first condition for food security, and for most diets, the other necessary nutrients are provided in sufficient quantities if the ration contains enough protein (Willet et al. 2019). (2) N is also the main limiting factor of agricultural production (Galloway 1998; Le Bauer and Treseder 2008), so that N inputs to the soil (whether as synthetic fertilizers, manure, symbiotic fixation, or atmospheric deposition) determine crop yields. Domestic availability of adequate N fertilization resources is therefore key to food self-sufficiency. (3) N is a very mobile element in the environment, subject to important losses to water and atmosphere, which cause major pollution problems when excessive inputs occur (Galloway et al. 2003).

The GRAFS approach described in details by Billen et al. (2024) can be applied for two purposes. To diagnose the current functioning of the agro-food system, GRAFS is used as an accounting tool for nitrogen flows between arable land, grasslands, livestock, and human final consumption. This involves collecting data on agricultural production, imports, exports, and human food consumption and converting them into N, e.g., using the coefficient assembled by Einarsson et al. (2021) (SM1). From this, a complete and consistent picture can be assembled, which clearly reveals, well beyond the nitrogen cycle itself, many characteristics of the biophysical functioning of the agro-food system. Beyond this descriptive and diagnostic use, GRAFS can be operationalized to model future scenarios involving profound structural changes in the agro-food system. This requires additional assumptions on how land and livestock productivity depend on inputs.

Lassaletta et al. (2014) demonstrated that in a given pedo-climatic context, the harvested yield (Y) at the scale of the full crop rotation observes a simple hyperbolic relationship with total fertilization (F, i.e., the total of N inputs to the soil) of the form: $Y = Y\text{max}\ F / (F + Y\text{max})$. Anglade et al. (2015) and Billen et al. (2018, 2024) showed that the same relationship (i.e., with the same Ymax) holds whatever the source of fertilization, either conventional

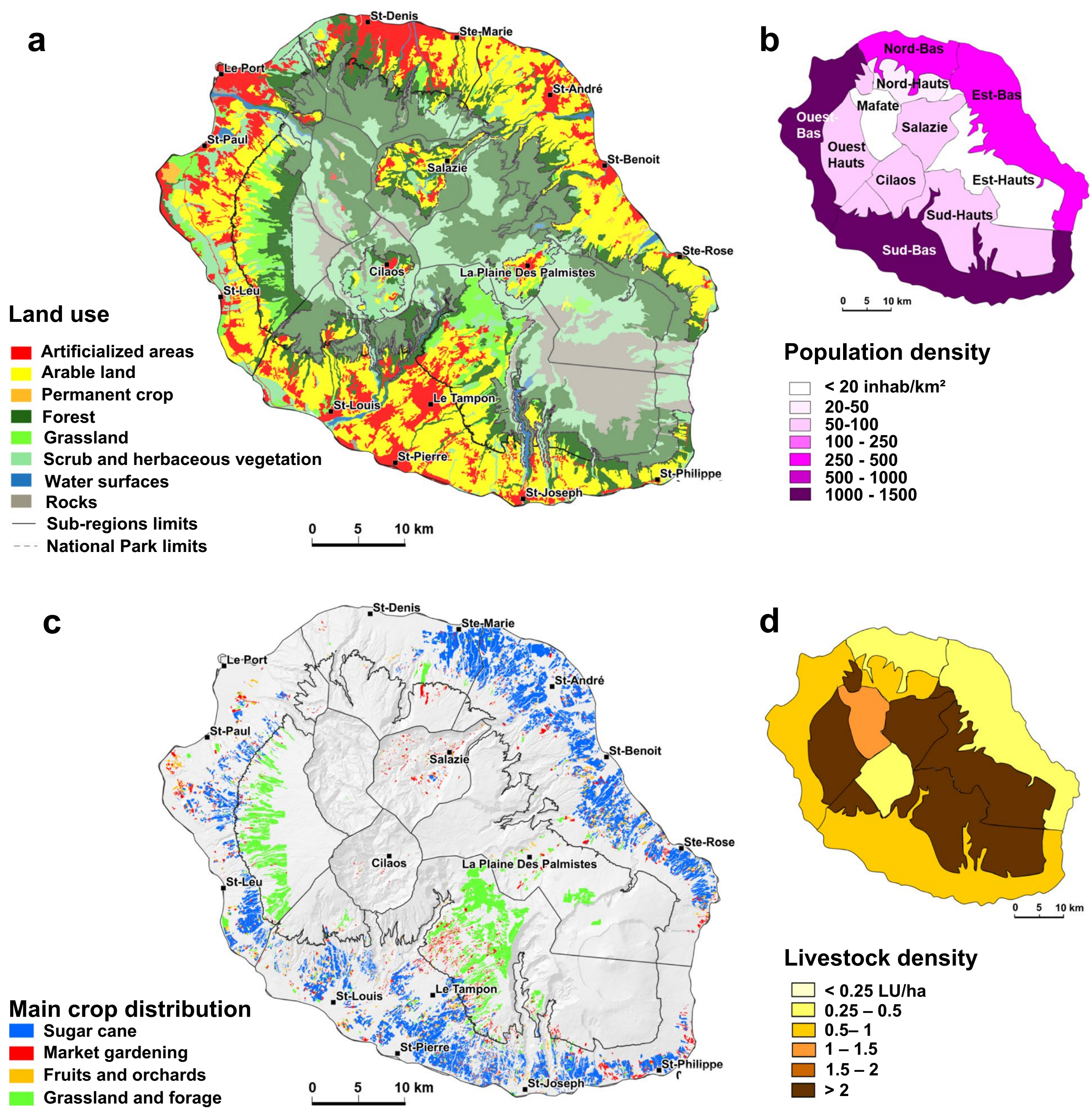

Fig. 1 **a** Land use in 2018 (Corine-Land Use data, www.data.gouv.fr/fr/datasets/corine-land-cover-occupation-des-sols-en-france/) in the 11 sub-regions considered in this study and limits of the National Park. **b** Population density per sub-region. **c** Main crop distribution over the period 2018–2020, from the analysis of RPG data (Registre Parcellaire Graphique 2021). **d** Total livestock densities (in livestock unit (LU) per agricultural area) in each region during 2018–2019 (see SM1 for details). LU is defined as the number of animals excreting 85 kgN/year (Le Noë et al. 2017; Billen et al. 2021)

or organic. This relationship, calibrated on data from current cropping systems, is used in the prospective GRAFS model application to calculate crop production from available fertilization resources. Regarding livestock, the prospective GRAFS model distinguishes between ruminant (cattle, sheep, goats) and monogastric (pigs and poultry) livestock, and calculates the edible production of each group based on the available feed resources, using a conversion efficiency (the ratio of edible production to total protein ingestion) calibrated for existing livestock systems. This coefficient is generally much lower for ruminants than for monogastrics, but the former can be fed on crop products not edible by humans, while monogastrics compete with human food.

Table 1 Agricultural production and trade data for Reunion Island during 2018–2019. Cultivated areas and crop production figures (see SM1 for details)

Crop areas and production				
Crop	Cultivated area (ha)	Fresh weight prod (tonnes/year)	N production (tonnesN/year)	N production (kgN/ha/year)
Sugarcane	22,095	1,645,000	2056	98
Cereals and food crops	647	5225	45	84
Vegetables	9864	52,750	107	11
Fruits	2586	35,100	30	10
Grassland	9814	108,500*	2088	213

*Dry matter

Table 2 Agricultural production and trade data for Reunion Island during 2018–2019. Edible production by ruminant and monogastric livestock in terms of protein N (see SM1 for details)

Livestock number and production		
Type of livestock	Number of livestock units (LU)	Edible production (tonnesN/year)
Ruminants	25,900	139
Monogastrics	22,900	737
Total	48,800	876

Results

Current agro-food system of Reunion Island

Spatially explicit data on agricultural land use are available from farmers' registered declarations to the EU (Registre Parcellaire Graphique 2021) (Fig. 1c). These data were analyzed from 2018 to 2021, allowing us to detect either crop rotations or changes in land use over the period. Crop rotations were quite infrequent as most of the cultivated land (except for market gardening) is occupied by monocultures. During the study period, 3.3% of sugarcane area was converted into another crop. Yet sugarcane remains by far the largest crop in terms of dedicated area, representing 56% of total utilized agricultural land (39,768 ha), followed by permanent grassland (24%), market gardening and fruits (together 19%) (Tables 1, 2, and 3) (see SM1 for details). Regarding market gardening and fruits together, DAAF (2019) provides the figure of 7000 ha exploited officially by declared farmers, plus 5500 ha (= 44% of the total) by informal, not declared, operators (e.g., in private Creole gardens). Average crop production figures over the 2018–2019 period for the whole island (Tables 1, 2, and 3) were assembled from different sources (see SM1). The distribution of crop production among the different sub-regions was estimated pro rata of the cultivated crop areas.

The resources for agricultural land fertilization include recycled organic material and imported synthetic fertilizers. Kleinpeter et al. (2019, 2023) estimated the reuse of organic material for soil fertilization (excluding livestock excretion at grazing) to be 1550 tonnesN/year from collected livestock effluents, 755 tonnesN/year from composts from urban wastes and wastewater treatment plants, and to a lesser extent 185 tonnesN/year from sugar industry residues (SM1). The import of mineral fertilizers amounts to

Table 3 Agricultural production and trade data for Reunion Island during 2018–2019. Import and export fluxes (see SM1 for details)

Import export of agricultural goods					
Commodity	Import (tonnes/year)	Export (tonnes/year)	%N	N import (tonnesN/year)	N export (tonnesN/year)
Sugar	4500	168,000	*0*	-	-
Cereals	53,199	-	*1–2*	635	-
Vegetables	17,339	-	*0.1–0.35*	45	-
Fruits	20,361	-	*0.03–018*	28.9	1.0
Spices, coffee, tea	93	-	*0.2–1.6*	-	1.7
Meat, milk, eggs	120,670	-	*0.5–2.8*	1337	1.6
Animal feed	222,000	6610	*1.6*	3500	130
Synthetic fertilizers	32,000 RM	-	*19*	5600	-

RM, raw material

32,000 tonnes/year (Kleinpeter et al. 2019), including 5600 tonnesN/year nitrogen fertilizers (mainly urea), by far the largest contributor to N fertilization.

Except for ovine and caprine rearing, for which informal independent activity still exists to a significant extent, animal breeding activities in Reunion Island are closely organized by professional organizations such as SICALAIT (for dairy cows), SICAREVIA (for bovine meat), OVICAP (for sheep and goats), CPPR (for pig farming), ARIV (for broiler poultry farming), and SPOR (for egg production).

The livestock distribution among the different regions of the island is quite heterogeneous (Fig. 1d), reflecting their strong specialization. Estimations of livestock edible production (meat, milk, eggs) in terms of N at the scale of the whole island are presented in Table 2. Apart from direct grassland grazing by ruminants, livestock is mainly fed by concentrated feed. A single cooperative firm, URCOOPA, created and controlled by several other agricultural and livestock breeding cooperatives, produces animal feed from imported primary material (cereals, oilseed, soybean, etc.) as well as some residues from agro-food industries including molasses from the sugar industry. We estimated the net amount of imported feedstuff to 3400 ktonnesN/year (see Table SM12).

The largest share of the Reunionese population is concentrated in the coastal lowlands, where densities of more than 1000 inhab/km^2 are reached (Fig. 1b). Asal et al. (2022) summarized the most recent data regarding the average diet of the population. The figures are well in line with the historical data provided by Guèzé (1946) and Allirot et al. (2006). The diet of the population has evolved considerably since the beginning of the twentieth century, as shown in Fig. SM1. The current diet is characterized by a large consumption of rice as the main cereal. The consumption of starchy roots and grain legumes, although remaining characteristic of traditional Creole cuisine, has decreased considerably. Consumption of meat, particularly of poultry and pork, has increased substantially in the past 50 years; animal-based proteins now represent 60% of the total protein intake. The connection rate of the population to the collective sewage network is 56% (Office de l'Eau 2023). Wastewater treatment plants produce about 8900 ton (dry weight) sludge annually which, after composting, are mostly recycled on agricultural land, corresponding to an input of 310 tonN/year, the rest being lost (see SM1).

Reunion Island exports sugar, rum, and pineapple. Most other agricultural products are imported in large amounts to cover the domestic demand not met by local production (Table 3). The disequilibrium is particularly striking in terms of N.

The data assembled and discussed above allow us to describe the nitrogen metabolism of Reunion Island according to the GRAFS accounting method (Fig. 2a, and SM2; see SM1 for a comparison with an analogous representation proposed by Kleinpeter et al. 2023).

Particularly striking in this representation is the importance of overseas imports. Compared to domestic food consumption, the degree of reliance on overseas imports of total N (i.e., how much N as fertilizer, food, and feed must be imported to supply 1 tonne N as food) is 2.7. The dependence on food and feed import for human food supply (excluding fish) (i.e., how much food and feed are imported to supply 1 tonne of food) is 1.4. The dependence of livestock feeding on imported feed is 54%. In terms of food self-sufficiency, the coverage of domestic food needs by domestic production (irrespective of the origin of the resources required for this production, as imported feed or fertilizers) is 33%. The dominance of sugarcane production for the export of sugar and the lack of cereal production explain the high dependency on food imports. The same indicators can be calculated for the different regions considered here (Fig. 2b, c, d). The population density (much higher in the lowlands), the main cultivated crop (sugarcane in the lowlands, market gardening in the highlands), and the type of livestock farming activity (ruminants mainly fed on grass, monogastrics on cereals) are the main factors explaining the distribution of these indicators. Unsurprisingly, the cirque of Mafate appears to be the least import-dependent territory of the island, while the cirque of Salazie is more dependent on N imports than most of the other highland regions, because of the high concentration of monogastric livestock there.

The figures discussed above are derived from a budget of production and consumption in each of the 11 sub-regions analyzed, summed up to provide the overall figure for the island. As an independent check, this sum can be compared with the data provided by the Customs Administration (Table 3). The same comparison can be made for Mafate, with the estimates by the National Park Authorities of the amounts of food, feed, and fertilizers brought into the cirque by helicopter. Although obviously not perfect, the agreement of the two independent estimates of input fluxes lends credence to the GRAFS approach (SM1, Fig. SM2).

The GRAFS analysis also reveals the importance of environmental N losses to the atmosphere and the hydrosphere (Garnier et al. 2019, 2023). Losses through NH_3 volatilization, denitrification, N_2O emission, soil leaching, and wastewater release together represent as much as 60–80% of the total new N resources mobilized by the agro-food system (imported N as fertilizer, food, and feed plus symbiotic fixation, i.e., 13,600 tonnesN/year) (see SM1 and SM2 for details).

Alternative scenarios

In order to explore the possibility of reaching food self-sufficiency in Reunion Island, possibly together with a

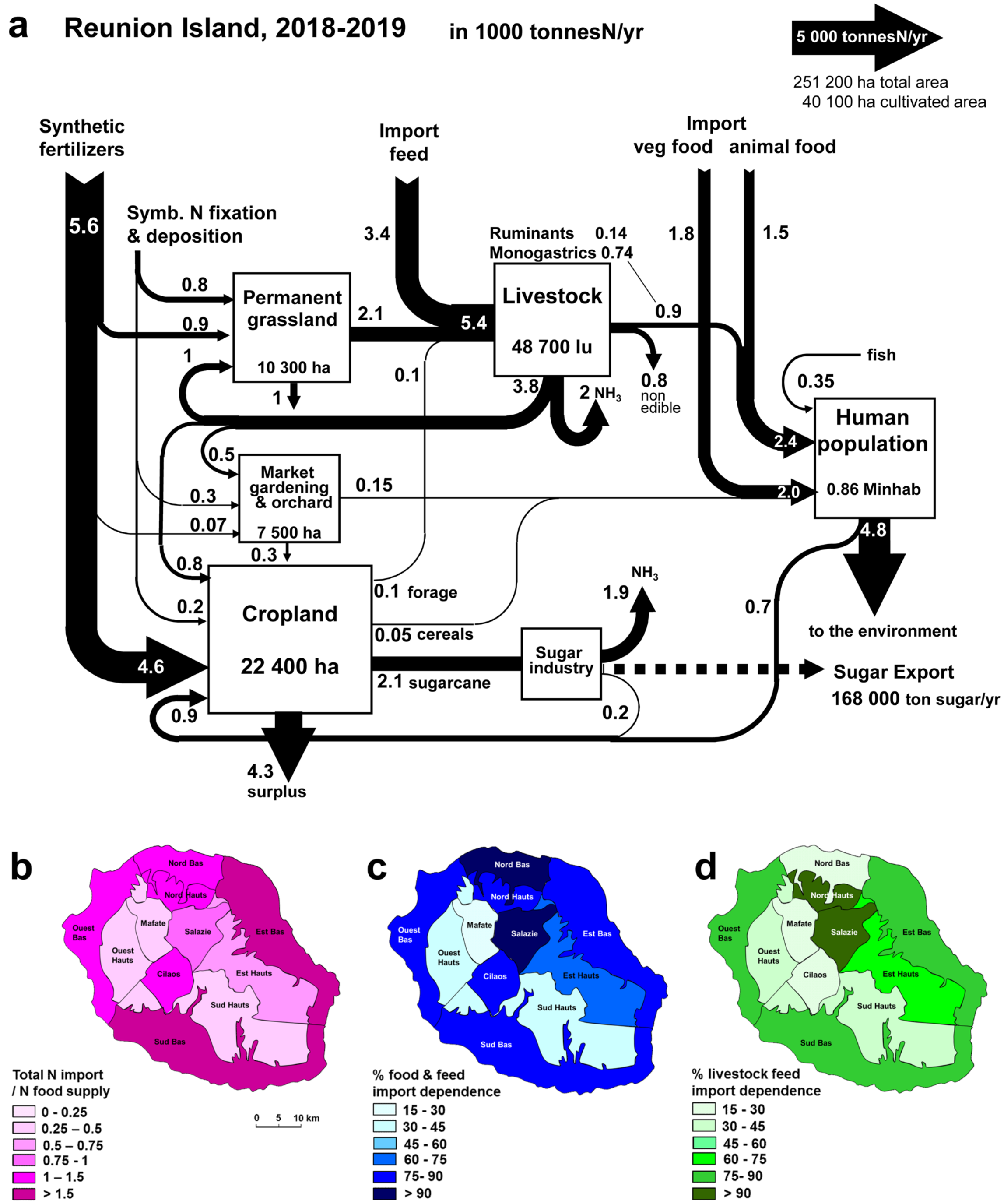

Fig. 2 **a** GRAFS representation of the N fluxes characterizing the functioning of the Reunionese agro-food system during 2018–2019 (see the corresponding figures at regional scale in SM2). Dependence of the agro-food system on N imports. **b** Ratio of total N imports (fertilizers, food, and feed) to total food supply. **c** Dependence of food supply on imported food and feed. **d** Dependence of livestock feeding on imported feed

reduction in environmental N losses, three levers can be operated, representing deep structural changes of the whole agro-food system along the principles of agro-ecology, as shown by previous work carried out for Europe (Billen et al. 2021, 2024). The first lever requires a full reshaping of the cropping systems as well as a redistribution of land use, generalizing agro-ecological crop rotations and operating without synthetic fertilizers. The second lever entails that livestock farming is reconnected with local cropping systems, thus excluding long-distance transport of feed and allowing for efficient reuse of manure in cropland. The third lever of change consists of readjusting the human diet and reducing the share of animal-based products in the total ingested proteins. We address these three aspects in the following paragraphs.

The first lever: alternative cropping systems and their performance

The GRAFS analysis of Reunion Island considered separately three land use classes: market gardening and orchards, arable cropland, and permanent grassland. For each of them, the agronomical performance can be assessed in terms of their yield–fertilization relationship. Arable croplands are currently mostly occupied by sugarcane, most often cultivated as a permanent crop. A typical example of the current functioning of a sugarcane field is presented in Figure SM2, based on the work of Mika-Nsimbi Poultney (2021). Yet, sugarcane is not intended to be cultivated as a monoculture. The traditional agricultural practice alternated cultivation of sugarcane with manioc and peas (Dubuisson 1890). Dadant (1974) described a large number of crop rotation systems well adapted to the different Reunionese climate conditions, involving (or not) sugarcane as well as cereals, other food crops, and forage (see SM1). The yield–fertilization relationship of all these systems at a given altitude range is quite similar, as shown in Fig. 3a and b, thus indicating that the productive capacity of all these crop rotation systems is similar to that of sugarcane at the same fertilization rate, with *Y*max in the range of 1000–1500 kgN/ha/year in the well-irrigated lowlands, and 750–1000 kgN/ha/year in the highlands. Permanent grasslands show similar yield–fertilization relationships, with about the same range of *Y*max: 1000–1500 kgN/ha/year in the lowlands and 750–1000 kgN/ha/year in the highlands (Fig. 3c and d). Market gardening systems and orchards differ from arable land and permanent grassland by a much lower N yield, as their harvested products have a considerably lower N content (Fig. 3e and f), albeit with a large diversity in production, particularly in the emblematic Creole gardens. A bulk of literature data suggest that combined tree and herbaceous production in agro-ecological management performs as well as the separate crops in terms of yield per ha (Simon et al. 2017; Ivezic et al. 2021), so that the productivity of the combined systems may be considered as additive. The functioning of an example private Creole garden is provided in SM1 (Fig. SM3). On the basis of all this information, an average *Y*max value of 75 kgN/ha/year (cf. Fig. 3e and f) has been used in the present study for combined vegetable and fruit production.

In the scenarios below, the distribution of land use between cropland, market gardening, and permanent grassland is reconsidered for each sub-region. There is an intense debate on the island about the possibility of cultivating existing derelict land and fallow agricultural land. A census by the SAFER in 2015 led to a maximum estimate of 5800-ha wasteland (ARP/BRL 2016), distributed about equally between EST, NORD, and SUD micro-regions and only 7% in OUEST. Legal difficulties exist regarding the objective of using these lands for agricultural production, namely, because of real estate speculation. The AGRIPéi Plan (DAAF Réunion 2019) foresees the recultivation of 2000–3000-ha fallow land. We have considered a total extension of cultivated areas by 2500 ha.

The second lever: crop-livestock reconnection

Reconnecting livestock to cropping systems involves adjusting the number of ruminant and monogastric heads in each sub-region to the locally available specific feed resources, namely, grass and forage legumes inserted in crop rotations for ruminants, and cereals and grain legumes in excess over human requirements, or food wastes, for monogastrics. We assume no structural long trade of feed neither from outside nor between sub-regions.

The third lever: population and diet

The prospective estimate for the total population of Reunion Island in 2050 is 1,022,000 inhabitants (a range of 915,400–1,075,600) according to INSEE (Dehon 2022), with the rate of change expected to be slightly higher in the north and slightly lower in the western regions (see SM1).

The traditional Reunionese meal is composed of rice, grain legumes (*grain*), green vegetables (*brèdes*), and meat in a spicy sauce (*cari*). The observed changes in diet over the last 50 years (Fig. SM1), namely caused by the introduction of globalized fast food, largely correspond to an increase in the share of cari at the expense of grain (Allirot et al. 2006; Méjan et al. 2020; Grangé 2021). The prevalence of obesity, diabetes, and cardio-vascular diseases, known to be related to diet rich in animal-based products, is a serious public health concern on the island (Allirot et al. 2006; Asal et al. 2022). This calls for a healthier diet, similar to that proposed by the Eat Lancet Commission (Willett et al. 2019). Here, we will consider reducing the total protein ingestion from 5.6 to 5 kgN/cap/year, with a strong reduction in the share of animal proteins, down to 15% of the total. The effect of such reduction on the appearance of the typical Reunionese meal is illustrated in Fig. SM4.

A spectrum of biophysically possible scenarios

A series of scenarios, simultaneously operating the three levers discussed above, have been constructed, according to the following rules. The different scenarios vary according to the diet of the population, in particular the share of animal-based food in the total protein ingestion set at 5 kgN/cap/year in all scenarios. We considered fish and shellfish

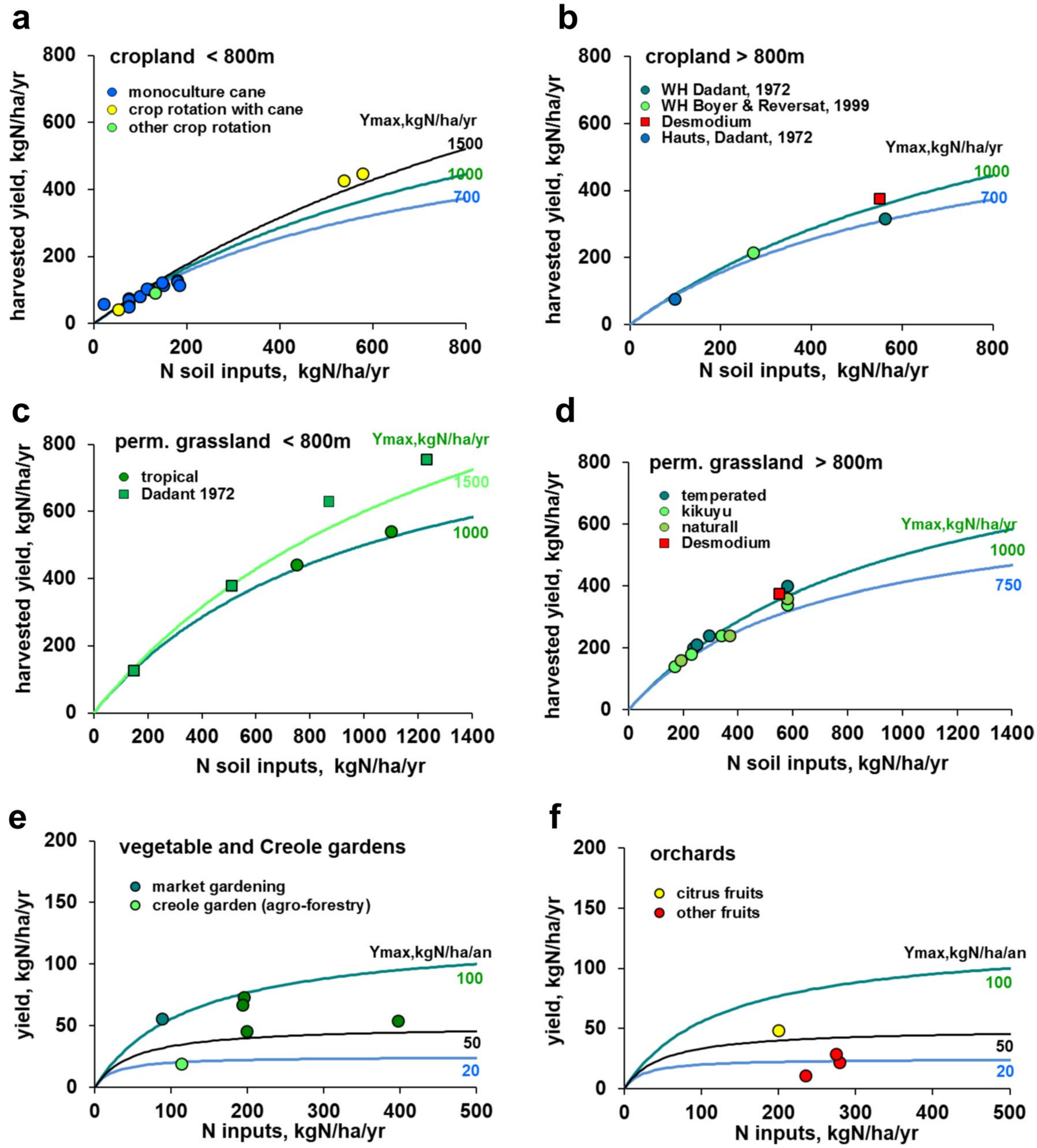

Fig. 3 Yield–fertilization relationships in cropland, permanent grassland, and market gardening systems from the lowlands (<800 m) and the highlands (>800 m) of Reunion Island (source of data in SM1)

consumption to be the same as the current value (0.4 kgN/cap/year) for all scenarios. What varies between the scenarios is, therefore, the overall consumption of meat, eggs, and milk, which amounts to 1.6 kgN/cap/year in the *40% animal protein* scenario and to only 0.1 kgN/cap/year in the *10% animal protein* scenario. Consumption of fruits and vegetables is set at a constant value of 0.6 kgN/cap/year. Cereal consumption is 2.4 kgN/cap/year and grain legumes vary from 0.3 to 1.5 kgN/cap/year (Fig. 4a). From the total available agricultural land in each region, market gardening and orchard areas are affected by priority in order to fulfill the requirements of the population, up to a maximum of 80% of the total agricultural area. Considering a typical productivity of market gardening/orchard systems of 55 kg/ha/year, this represents an area of 0.011 ha/capita. The required area cannot be found in the most populated sub-region of the island (Nord-Bas), which is compensated by imports from additional areas in other sub-regions able to produce surpluses. Permanent grassland area is taken to be identical to the current value, up to a maximum of 10% of the total agricultural

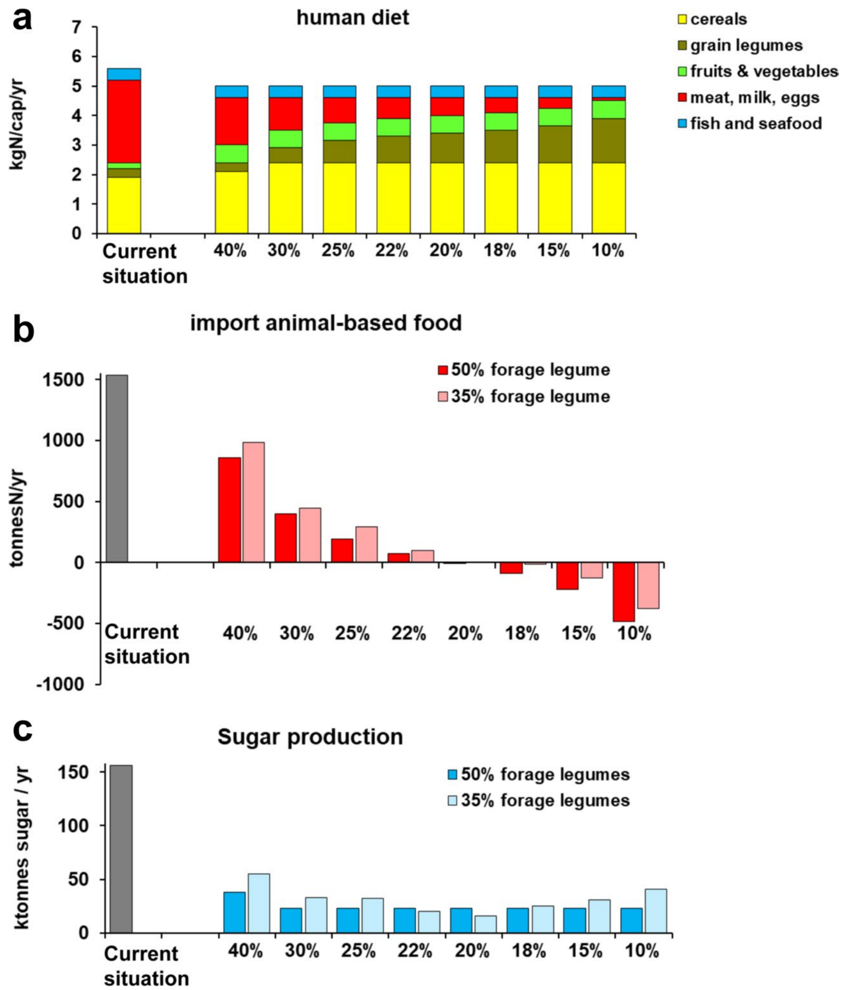

Fig. 4 Food self-sufficiency scenarios for Reunion Island at different levels of animal-based food consumption. Current situation is 60% of animal protein in the diet. Full self-sufficiency can only be reached with diets lower than 20% of animal-based food. **a** Diet composition. **b** Import (or export when negative) of animal-based products required for meeting human domestic consumption. **c** Maximum level of sugar production possible after meeting human plant-based food needs

area of each region. Croplands occupy the remaining cultivated areas and are cultivated according to a crop rotation scheme alternating cereals, forage, and grain legumes and possibly sugarcane. Their overall productivity depends on the total soil N fertilization input. Symbiotic N fixation by legumes plays a major role in N fertilization, besides manure recycling and atmospheric deposition. For this reason, the share of the cropland surface areas occupied by legumes in the rotations largely determines productivity. Two options regarding the share of forage legumes in the integrated crop rotation area have been considered: 50% in the most intensive option, and 35% in a less intensive option, with 20% dedicated to grain legumes in both options. The remaining part (30% and 45%, respectively) is occupied by non-legume crops, including cereals (and possibly other food crops) and sugarcane. The share of cereals is adjusted by priority to reach self-sufficiency for the whole island with respect to human needs, while sugarcane is only allowed to occupy the remaining share of the rotation in the lowland regions. Livestock (ruminants and monogastrics) is adjusted in each sub-region to the locally available resources that allow its population to be sustained, namely, grass from permanent grassland and forage legumes for ruminants, grain legumes and cereals in excess over human needs, as well as human food wastes, for monogastrics. The balance of animal production vs. human needs at the scale of the island in each scenario determines the magnitude of imports of animal products (or of possible exports) required.

The results (Fig. 4) show that self-sufficiency in animal products can only be achieved for a diet with less than 20% animal protein in total protein consumption, whatever the proportion of cropland area dedicated to forage legumes: above that level, substantial imports of meat and milk are required.

The possibility of cultivating sugarcane while still meeting the cereal requirements for human nutrition exists, but the total production of sugar would be lowered to 23–40 ktonnes (about 15–20% of the current value) because of the area competition between cereals and cane, on the one hand, and the nitrogen limitation of non-legumes (cereals and cane) production at a low share of legumes in the rotation, on the other hand (Fig. 4c).

The GRAFS representation of a scenario at 18% animal-based protein under the less intensive option is shown in

Fig. 5a at the scale of the whole island, together with the corresponding distribution of agricultural areas and livestock densities among the different sub-regions (Fig. 5b and c).

In this scenario, full self-sufficiency is achieved for food and feed supply as well as for crop fertilization. Ammonia emissions are halved with respect to the current situation and N_2O emissions are reduced to about 40% of the current value. Nitrate leaching is also considerably reduced (see SM1 and SM2).

Discussion

Reunion Island is highly dependent on overseas imports to ensure the food supply of its population. Analyzing this dependency in terms of N flows through the agro-food system makes it possible to objectify these dependencies and to define robust indicators. The dependency begins with crop fertilization: 57% of total N inputs to

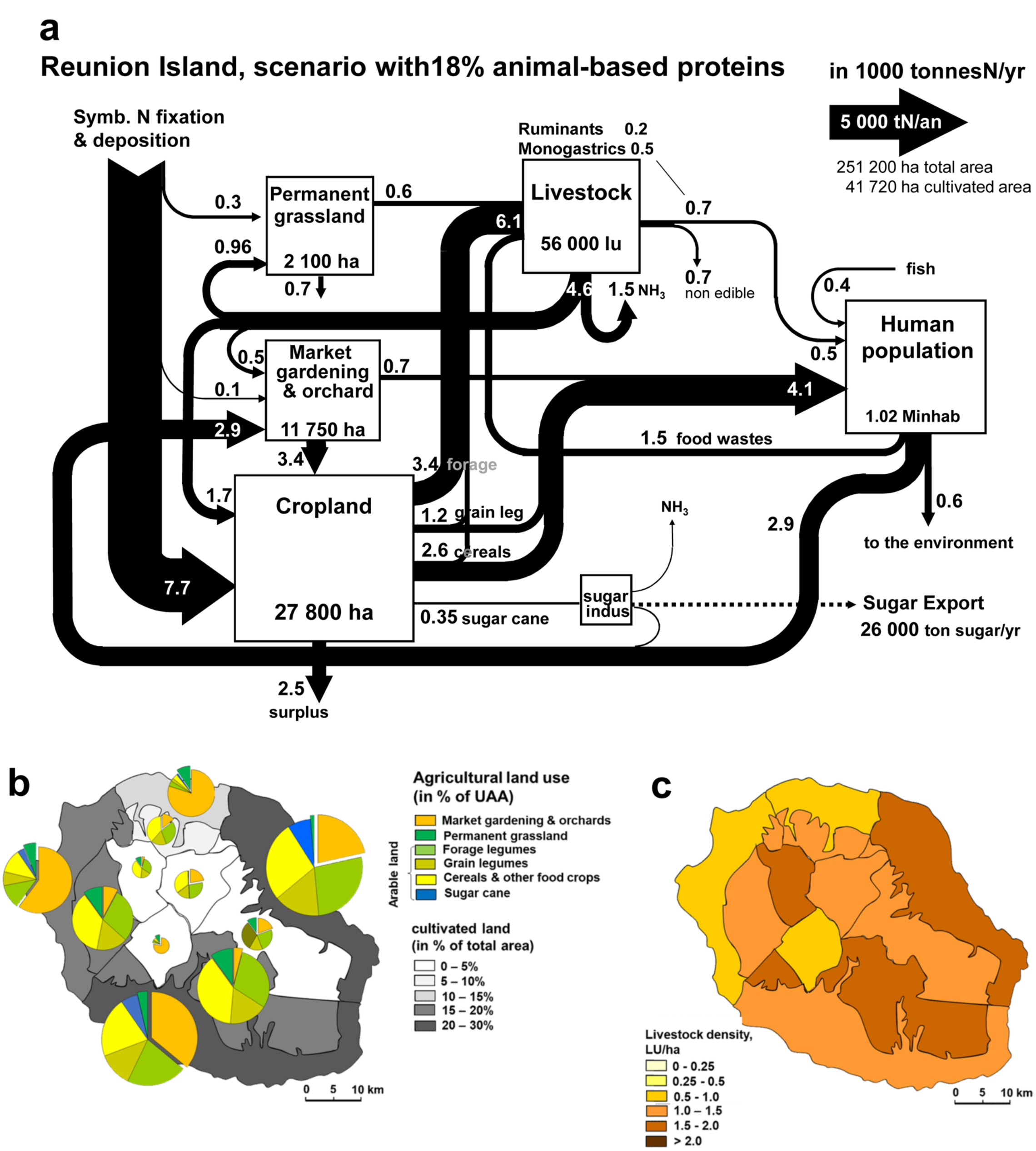

Fig. 5 **a** GRAFS representation of the N fluxes characterizing the functioning of the Reunionese agro-food system in an agro-ecological scenario for 2050, with a diet comprising 18% of animal-based food proteins. **b** Land cover (market gardening and orchards, cropland, and permanent grassland) in the different regions (colored pie charts) and % cultivated land per total area (range of grays). **c** Livestock density in LU/ha agricultural land

agricultural soils is based on imported synthetic fertilizers; 54% of livestock feeding depends on imported feed; 67% of food protein supply to the population relies on direct imports. Overall, the supply of 1 tonne protein as food for the Reunionese population requires the import of 2.7 tonnes of N as fertilizers, feed, and food. Such an extreme structural dependence creates serious risks of shortages in the event of an interruption of maritime supply and is experienced as a threat by many stakeholders. The high population density and the scarcity of agricultural land in Reunion Island represent major challenges to the goal of food self-sufficiency set by a number of stakeholders. Our calculations, however, show that this objective, far from being a pure chimera, does indeed belong to the realm of biophysical possibilities.

This last conclusion depends on a number of assumptions, the uncertainty of which needs to be assessed. From an agronomic point of view, the most important of these assumptions lies in the productivity of crop rotations incorporating forage and grain legumes, which the scenario assumes to become widespread, returning to crop sequences and practices that were studied and documented through agronomic work in the 1970s (Dadant 1974; Boyer et al. 1999). Unfortunately, agronomic research over the past 50 years has focused on sugarcane and other export crops, while the performance of food crops has been scarcely documented by recent research. However, the few available data allow us to consistently evaluate the *Y*max of these crop rotations in the range of 700–1500 kgN/ha/year (Fig. 3a, b). The sensitivity of the model to this value has been calculated: a systematic reduction of *Y*max in all regions by 20% would lead to a reduction of the estimated total crop production by 15% and would not deeply affect our conclusions.

Although biophysically possible, achieving food self-sufficiency in Reunion Island would, however, entail profound structural changes in the current Reunionese agro-food system, for which there are considerable socio-technical and socio-political obstacles. First of all, our scenarios would involve a significant reduction of the area devoted to sugarcane cultivation, down to 15–20% of its current value, at the benefit of cereals and other food crops as well as market gardening. The current hegemony of sugarcane cultivation and industry, a legacy of the island's colonial past, is among the most serious obstacles to the transition of the agro-food system toward more self-sufficiency. Sugarcane monoculture occupies most of the best agricultural land. It is considered to be a crop particularly well adapted to the pedo-climatic conditions of tropical islands and often perceived as part of the Reunionese identity. Owing to substantial public aid to the entire sugar sector, it provides incomes to a large number of small farmers. For these reasons, most agronomical efforts since the middle of the twentieth century have been dedicated to improving the performance of this crop, at the expense of the development of other cropping systems including food crops. Changing this state of affairs will require political willingness and will take time and efforts, although diversification of sugarcane farms is claimed to be an objective by many stakeholders (DAAF Réunion 2019).

Second, in our scenarios, livestock should be closely connected to crops at the sub-region scale, allowing for efficient use of forage legumes and recycling of manure, as well as avoiding feed import. This implies that livestock numbers are limited by locally available feed resources that are either not edible by humans (grass, forage legumes, food wastes) or produced in excess of human requirements at the scale of the whole island (cereals and grain legumes). As a result of this principle, livestock would be much more homogeneously distributed among the different regions, and ruminants would tend to be favored over monogastrics, in spite of their lower conversion efficiency. The current distribution of livestock, concentrated in the highlands (Fig. 1d) where the climate is not suitable for sugarcane cultivation, is the result of development policies implemented since the 1970s that favored intensive livestock breeding based on imported feed (Marblé et al. 2018) and the establishment of grassland for grazing and mowing in the highlands (Barbet-Massin et al. 2005). The ruminant farming model locked down by a single professional organization is currently experiencing serious financial and social difficulties (Marblé et al. 2018).

Market gardening in Reunion Island is represented by a large number (>2600 registered producers) of very diverse small farms (<1 ha on average) with a much looser level of professional organization (Agreste 2019). Organic farming practices were adopted by 13% of these farms in 2019, a figure that has doubled since 2015 (Agreste 2019). It is probably among organic market gardeners that the greatest potential for change is found today, with the experimentation of new crop rotations. For example, two producer associations are currently actively working on the introduction of rice cultivation in Reunion Island. The shortening of supply chains is also an objective of many citizen associations, using the potentialities offered by collective catering to develop local diversified productions. Also, the development of small livestock breeding activities can easily complement market gardening activities.

The third condition of our scenarios toward food self-sufficiency would be the reduction of animal-based food consumption by at least a factor of 3 compared to the current Reunionese diet. Such dietary change, although drastic, would have considerable public health benefits, as it has the potential to reduce the risks of several pathologies, including cancer, cardiovascular diseases, and diabetes (Tilman and Clark 2014). Yet, diet is often the blind spot in public agro-food policies. In a recent PhD thesis, Russeil (2023), taking a completely different approach to ours, based on a spatialized model of land use dynamics and territorial participatory approaches, reached the conclusion that the highest rate of local coverage of food and feed needs achievable in 2040 in a scenario considered to be the most proactive toward food self-sufficiency would be 55%. This scenario considers a diet comprising a share of 50% of animal protein over a total protein ingestion of 5.2 kgN/cap/year. Russeil's results confirm that a much larger reduction in animal-based food ingestion is required if food self-sufficiency is to be reached. Our own calculations show that in a scenario with a share of 30% of animal protein in diet, which would be in line with the recommendation of the Barsac Declaration (2011), only some 520 tonnesN of animal food should be imported to Reunion Island to meet human consumption (Fig. 4), already bringing the overall self-sufficiency rate close to 90%, with the possibility of still exporting sugar at a rate close to 25% of the current value.

A recent paper by Kleinpeter et al. (2023) discusses the opportunities offered to reduce N losses from the Agro-Food-Waste system of Reunion Island without structural changes, i.e., without seeking to change economic activities or human dietary habits, but just by improving the efficiency of sub-systems and circularity between sub-systems. A multi-stakeholder dynamics is indeed ongoing in Reunion Island for moving toward a "zero biowaste" agenda, and proposing actions aimed at recycling unused secondary products. Implementing these actions is obviously more realistic in the short term than structural changes such as those discussed in the present paper. However, as stated by the authors themselves, the results, although beneficial for the environment, would not provide significant gain in terms of self-sufficiency of the Island.

Conclusion

The agro-food system of Reunion Island is a paradigmatic example of the level of dependence and structural fragility that a territory can reach through specialization and openness to international markets, following development policies inspired by the outdated Ricardian concept of comparative advantages (Billen et al. 2019). Even in such a densely populated island, our analysis based on the biogeochemical GRAFS model confirms that food self-sufficiency is biophysically possible but would require major structural changes at all levels of the system. The main obstacle to achieving this objective, if shared by the majority, lies in the socio-technical lock-in of the agro-food system, inherited from past development policies (Meynard et al. 2017). An integrative vision of the agro-food system is required, including the triptych of producers–consumers–local sales outlets, and a comprehensive strategy covering this entire system would have to be implemented to achieve such deep-rooted changes. Our approach can be easily adapted to study the case of other tropical Islands, in the Indian Ocean or the Caribbean.

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Data Availability All data and model code used in this study are available in the Supplementary Material SM1 and SM2.

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