LIVESTOCK BASED CIRCULAR FOOD SYSTEMS IN TROPICAL ISLANDS

GUIDELINES TO IDENTIFY OPPORTUNITIES TO IMPROVE CIRCULARITY

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CIRAD UMR SELMET (Mediterranean and Tropical Livestock Systems)

March 2022

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CIRAD AGRICULTURAL RESEARCH FOR DEVELOPMENT

GLOBAL RESEARCH ALLIANCE ON AGRICULTURAL GREENHOUSE GASES

ABSTRACT

Today, tropical islands are on the frontline of climate change and have to overcome many challenges to improve food security. Circular food systems are required to become more self-sufficient and to limit environmental impacts. Livestock have a crucial role to play in a circular food system by valorising co-products, waste and rangelands and converting them into valuable food and manure. To facilitate the transition towards more circular systems, we propose a metabolism-based methodology, which aims to identify livestock-based scenarios to increase the circularity of food systems. The methodology enables three levels of accuracy and investment to cover the wide range of tropical island contexts. The three levels have the same objective but can be applied depending on the available data, time, funds and human resources. Level 1 is based on a proto-metabolism using macro data, level 2 on an accurate metabolism using a material flow analysis (MFA), and level 3 is a participatory approach based on stakeholder involvement in the metabolism. The methodology was applied to two case studies, Madagascar and Reunion island, which have similar soil-climate conditions but very different food systems. Level 1 was applied to Madagascar and theoretical and global levers are proposed such as increasing the livestock stocking rate to provide more recycling opportunities and more organic matter to be valorised. Due to the large size of the island and the diversity of productions and systems, further research is needed at sub-regional scale to identify complementary levers. In Reunion Island, levels 1, 2 and 3 were applied. Specific and local levers are proposed that were co-designed with local stakeholders such as co-composting livestock manure with green waste to produce organic fertilisers for sale to market gardeners.

Key words:
Food systems, circularity, metabolism, livestock, tropical islands, Madagascar, Reunion Island

To cite this report:
Flipo B., Vigne M., Kleinpeter V., Vayssières J., 2022. Livestock based circular Food Systems in Tropical Islands - Guidelines to identify opportunities to improve circularity. CIRAD, La Réunion, 48 p.

PREFACE

To build our methodology, three seminars were held to discuss the proposed methodology, its transferability, and adaptability to other tropical islands. Webinars were also organised to create a network of partners working on circular food systems in different tropical islands in the Atlantic, Pacific and Indian Oceans.

- 1 seminar with French research institutes and organisations with a focus on the methodology, participants: INRAE, CIRAD, AgroParisTech and Oasis Réunion (Appendix 1).
- 2 seminars with research institutes and organisations from other tropical islands in the Atlantic, Indian and Pacific oceans) with a focus on the transferability of the methodology to other tropical islands, participants: Wageningen University, University of Aruba (Aruba and Curacao), Waterloo University (Barbados, Dominica, Grenada and Jamaica), INRAE (Guadeloupe), University of La Réunion, Ministry for Primary Industries (New Zealand), the Pacific Community-SPC (New Caledonia, French Polynesia, Fiji and Vanuatu) and the Regional Chamber of Agriculture in New Caledonia (Appendixes 2 and 3).

We thank all the participants of the webinars for their useful comments on the proposed methodology. We particularly thank Amber S. van Veghel, Eliel González-García, Carlos A. Mazorra Calero, Jean-Luc Gourdine, Audrey Fanchone, Marine Esnouf and Clément Gandet who contributed to the report by presenting the food system on the island they are studying and the initiatives implemented.

We also thank Wageningen University (WUR) which coordinates the Circular Food Systems Network and the Global Research Alliance on agricultural greenhouse gases (GRA) which funds the network.

SUMMARY

I. INTRODUCTION

Major stakes in tropical islands

Tropical Islands are isolated territories, with closed bounded systems, where resources and land available for agriculture may be limited. These islands often depend on imports for a large proportion of their needs and produce only a few key resources for export (e.g. sugar cane and banana). For instance, islands in the Caribbean region may import up to 90% of their food and energy needs. Tropical islands thus face crucial food security problems and concerns about their undiversified exports and their dependence on imports are growing (Deschenes & Chertow, 2007; Singh et al., 2020).

In addition, tropical islands are on the frontline of climate change. First, they are exposed to increasingly frequent extreme weather events that intensify problems of food security (Thomas et al., 2018). On average, almost 30% of the populations of Small Island Developing States (SIDS) live in the zone less than 5 metres above sea level (United Nations, 2015). Second, rising sea levels and higher sea and air temperatures are key challenges in these areas (Bell et al., 2016; Mendelsohn et al., 2012). To face those challenges, tropical islands Food System (FS) need to become more resilient, less dependent on imports, while at the same time, reducing their environmental impacts, in particular on climate change.

The challenge of sustainable food systems

According to (FAO, 2018a), a food system encompasses "the entire range of actors and their interlinked value-adding activities involved in the production, aggregation, processing, distribution, consumption and disposal of food products that originate from agriculture, forestry or fisheries". Figure 1 is a representation of a food system proposed by van der Wiel et al., (2020) which includes five subsystems, animal production, crop production, food and feed processing industry, food consumption and waste management.

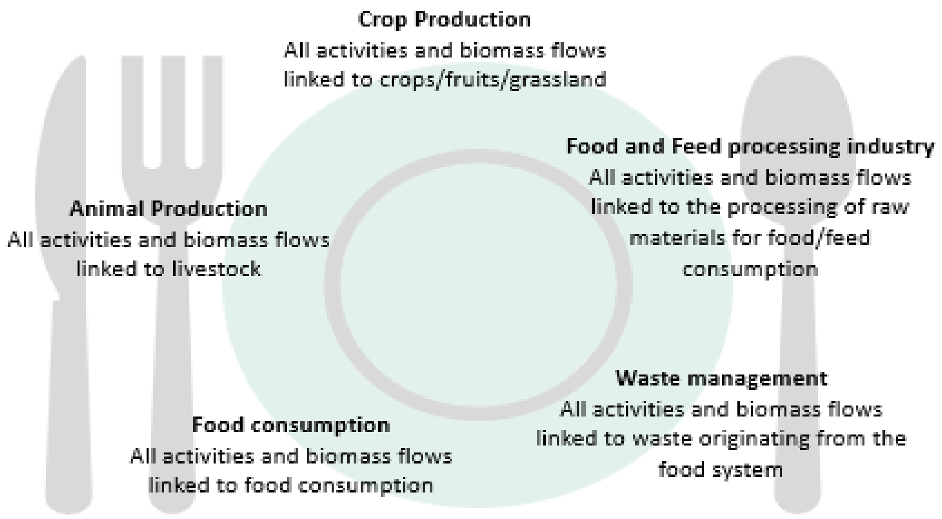


Figure 1: Food System definition

A large number of existing food systems, including those of tropical islands, tend to function linearly. For instance, because of limited land availability, farms and/or regions specialise in one product or in globalisation, they import large quantities of inputs (mineral fertilisers, soya, etc.) and food items.

Consequently, nutrient cycles are far from being closed and large quantities of nitrogen, phosphorus and phosphate are lost at local and global scale to the soil, water and the atmosphere, possibly polluting ecosystems and contributing to climate change. The world's food system is responsible for one third of total human-based greenhouse gas (GHG) emissions, including crop and livestock production, on-farm use of energy, land use and changing land use, transport of domestic food and food waste.

In addition to the crucial need for more sustainable food systems, especially to achieve sustainable development goals, food systems simultaneously face the challenge of feeding the growing human population (Springmann et al., 2018, Crippa et al., 2021; Tubiello et al., 2021).

Increasing the circularity of food systems

The circularity concept originated in industrial ecology and aims to minimise waste streams (Ellen MacArthur Foundation, 2021). In circular systems, the consumption of resources and the emission of pollutants to the environment are reduced by closing the materials and substances loop i.e., nutrients, water, soil. Applied to food systems, circularity implies practices which minimise the use of finite resources, promote the use of renewable resources and prevent losses of natural resources from the food system (figure 2). Losses can be reduced by facilitating recycling of by-products and wastes in a way that adds the highest possible value to the food system (de Boer & van Ittersum, 2018; van Zanten et al., 2019). For instance, in a circular food system, food production and consumption produces a variety of by-products, including crop residues, co-products from industrial food processing, food waste and human excreta. These by-products can be recycled into the food system to feed animals or fertilise crops, for example (de Boer & van Ittersum, 2018).

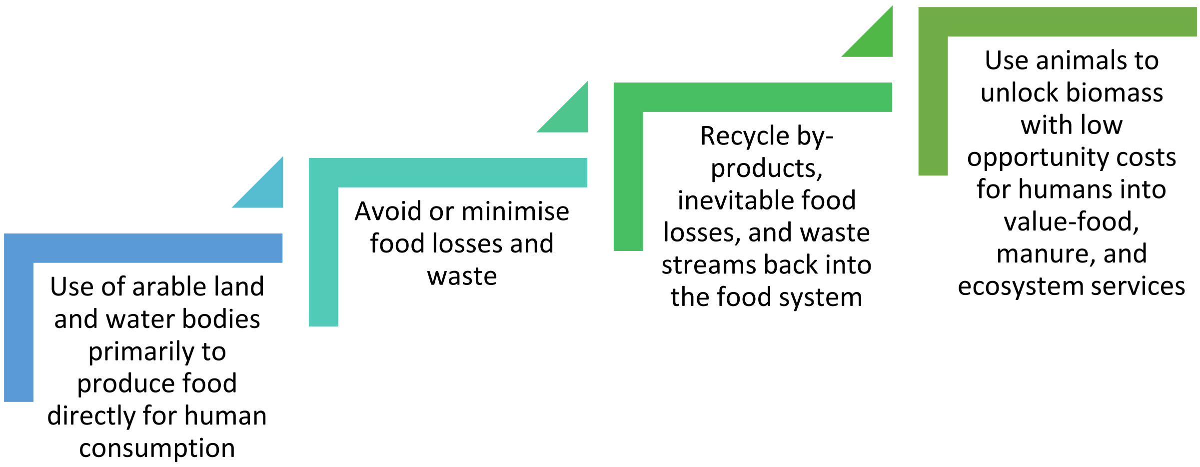


Figure 2: Four major principles of circular food systems

Potential role of livestock in food systems

Like food systems, livestock sectors are facing many challenges, including GHG emissions, land use, water and food-feed competition (Figure 3). On one hand, many recent studies suggest we should reduce our consumption of animal-source food to reduce the environmental impact of our food system. Indeed, animal sector is responsible for about 60% of all human-based greenhouse gas (GHG) emissions from the global food system and 14.5% of all human-induced GHG emissions (Gerber et al., 2013).

On the other hand, livestock systems are varied, ranging from smallholder mixed-crop–livestock systems to intensive livestock farming, and thus have a wide range of impacts and services. Livestock systems are a leading economic activity and provide livelihoods to the majority of island populations. In addition, livestock is multifunctional, and its objectives are not limited to food production. Livestock may play a financial role by providing extra income, or fulfill cultural and societal functions (religious sacrifices, status in the community, etc.) (Oosting et al., 2021; Oosting et al., 2014)

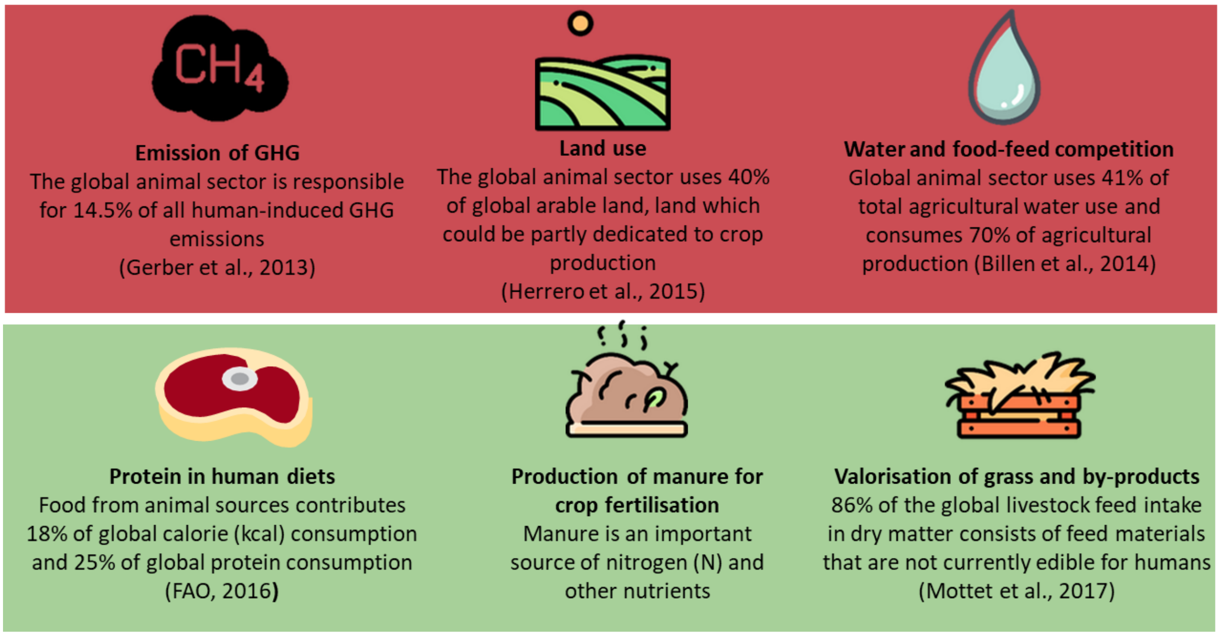


Figure 3: Impact of and services provided by the global livestock sector .

Moreover, according to Koppelmäki et al. (2021), most biomass and nutrient flows within food systems are related to livestock production, meaning livestock plays a key role in their circularity. The increasing demand for animal products (meat, fish, eggs, dairy products) in tropical regions is thus a major challenge, but also an opportunity.

Indeed, many countries include animal proteins in their national dietary recommendations i.e. country-specific dietary guidelines addressing public health and nutrition priorities and accessibility of foods (Oosting et al., 2021; FAO, 2018). Rearing livestock in a circular system can thus play a crucial role in feeding humanity (Herrero et al., 2015). Animals can convert non-human-edible biomass, as by-products considered as waste, into valuable food and manure (van Zanten et al., 2019)(Figure 4).

In this sense, better integration of livestock sector in the food system thanks to livestock-based circularity opportunities is of interest to both increase the services provided by livestock and to improve food system sustainability.

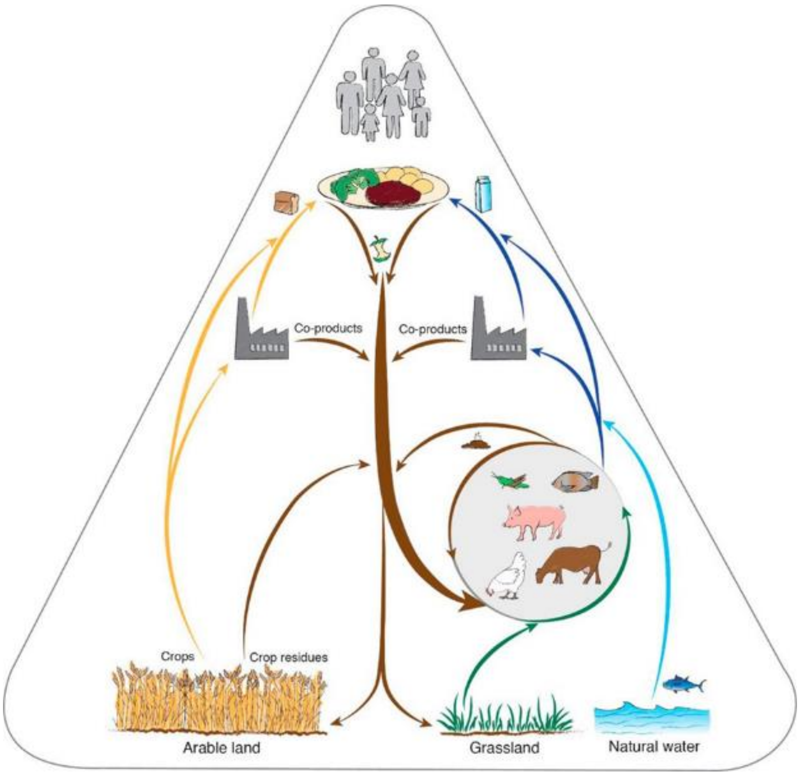
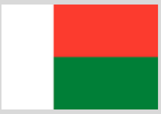


Figure 4: Inclusion of animals in circular food systems (van Zanten et al., 2019)

Need for methodological guidelines to improve circularity

With delimited boundaries, limited resource availability and carrying capacity, islands are appropriate regions to study circularity, meaning they could be leaders in sustainable and circular food systems. In addition, on an island, it is much easier to track biomass, nutrients and energy stocks and flows, produced, imported, exported or recycled. Any changes in the food system will be experienced faster and will be more pronounced, even more so if the island is small. Moreover, tropical islands face more intense climate change than other parts of the world.

In this guide, we propose a methodology with three levels of accuracy and investment, depending on the availability of data and resources which aims to identify livestock-based theoretical to operational circularity levers. Due to the particular context and characteristics of food systems in tropical islands, this methodology is largely constructed around island metabolism analysis, i.e. the analysis of biomass and nutrient flows with the aim of identifying hotspots where waste and losses are high, and where circularity can be constructed. The methodology is inspired by past and ongoing research in Reunion Island. Research results are presented to illustrate the three levels. In addition, we report on the first attempt to apply the methodology to Madagascar, another island in the Indian ocean with similar soil and climate conditions but which is much bigger, has a different food system, and a different socio-cultural and production context.



Madagascar

Area: 587,295 km².
Population: 28 million
Population density:
48 inhab/km²

Reunion Island

Area: 2,504 km²
Population: 859 959
Population density:
342 inhab/km²

Food system context

Madagascar

80% of the population works in agriculture:
Average farm size: 0.8 ha

Mainly **subsistence farming**
Main products: Rice, cassava and maize

Major challenge: **Food security**
(4th highest rate of chronic malnutrition in the world)

Reunion Island

5% of the population works in agriculture
Average farm size: 6.2 ha

High input systems (imported feed, food and fertilisers)
Main product: sugarcane

Major challenge: **Dependence on imported inputs** and GHG emissions

Livestock systems

Madagascar

Low structured sectors
- Beef cattle (zebu): Extensive system (rangeland)
- Dairy cattle (local + improved breeds): Highlands/Dairy triangle. Low milk productivity
  Local breed: **300 L/cow/year**
  Improved breed: **2 500 L/cow/year**
- Poultry/pigs: mainly backyard systems

Meat consumption: **12 kg/inhab/yr** (75% beef). Declining since 1960

Reunion Island

Highly structured sectors (cooperatives in most livestock sectors)

- Beef cattle (improved breeds): mainly extensive systems in the highlands
- Dairy cattle (improved breeds): mainly intensive. High milk productivity: **> 6 000 L/cow/year**
- Poultry/pigs: intensive and indoor

Meat consumption: **93 kg/inhab/yr** (+9% higher than in mainland France) (INSEE, 2017). Mainly poultry and pork and increasing.

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Figure 5: Food systems in Madagascar and Reunion Island

II. METHODOLOGY


Cortes Salgado P., CIRAD

Generalities

A three level methodology

The methodology offers 3 levels of accuracy and investment to cover the wide range of tropical island contexts.
The choice of the level depends on (Figure 6):

- Data availability: From macro data (i.e., imports, exports) to precise data on nutrient and biomass flows and stocks (i.e. internal flows between farming activities or between different economic sectors).
- Time, funds and human resources availability: Performing a precise inventory of data on biomass flows requires time, money, and human resources.
- The capacity to involve local stakeholders in the process: To propose relevant and operational scenarios with a major impact on the food system, local stakeholders, including technical and research institutes, cooperatives, farmers organisations, policy makers or representatives of civil society, need to be associated in this long and time-consuming process.

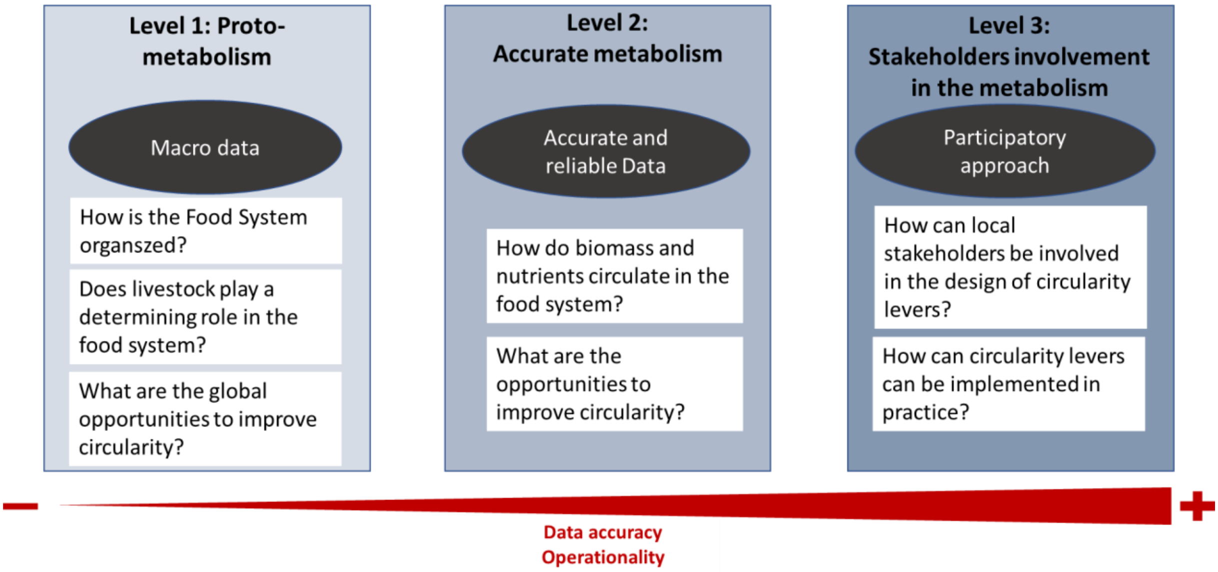

Figure 6: Research questions for the 3 levels

Note that all three levels have the same objective, i.e. identifying livestock-based levers to increase circularity in the FS.

Table 1: Particularities of the 3 levels

Data	Outputs	Advantages	Disadvantages
Level 1			
Macro data (FAO, customs, national agencies, etc.)	Proto-metabolism and livestock-based opportunities for circularity	• Rapid analysis • Low cost • Data available in open access	• Limited reliability of the dataset • Global opportunities • Top down approach

Level 2			
Accurate data via material flow analysis	Metabolism includes all nutrient and biomass flows and livestock-based scenarios	• Accurate analysis • Livestock based levers including disruptive scenarios	• Time consuming • Top down approach (theoretical levers)
Level 3			
Inventory of local stakeholders involved in the food system and in biomass production	List of actors involved in the food system and ongoing Initiatives	• Concrete and operational levers • Ownership by stakeholders (participatory approach)	• Time consuming • Difficult to go into disruptive scenarios

Complementarity and articulation of the three levels

The three levels can be applied independently or combined depending on the objectives and the means available (Table 1).

The methodology ensures complementarity between the three levels as each one produces different but complementary indicators (figure 7).

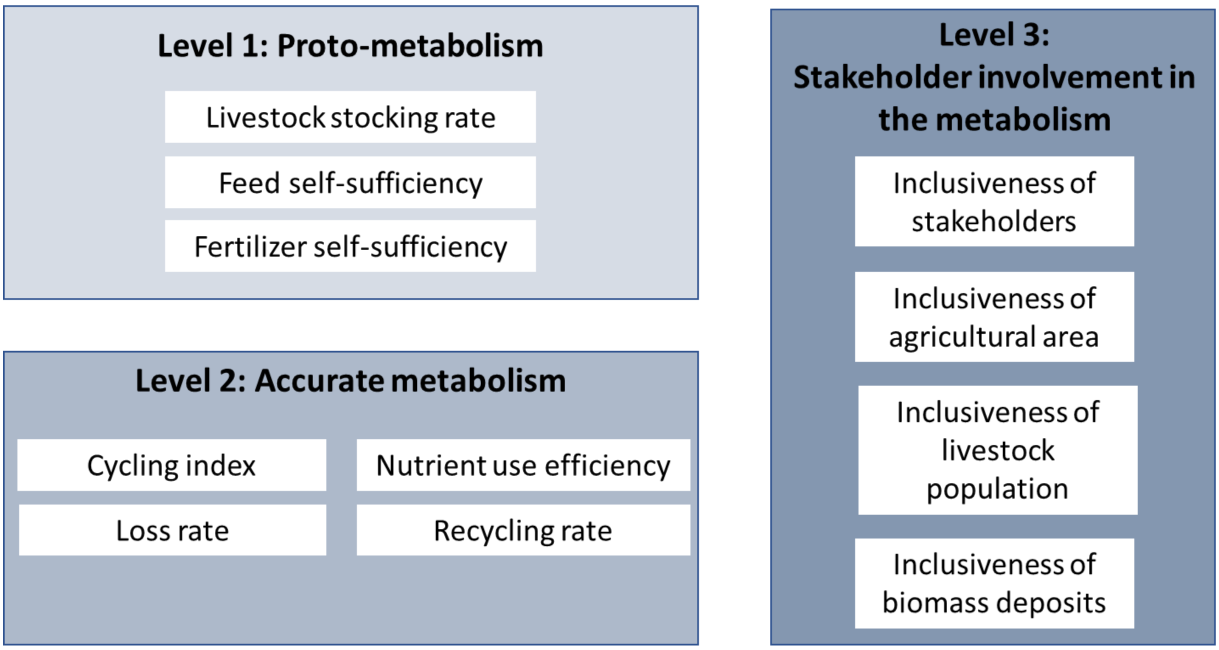

Figure 7: Indicators provided by the 3 levels of the proposed methodology

Figure 8 illustrates articulation between the three levels. The outputs of level 1 are global and theoretical levers based on macro data. The second level levers are realistic from a biological point of view but still theoretical from a socio-economic point of view. At level 2, the levers are identified based on accurate quantification of all stocks and flows within the food system, which may require a detailed stakeholder survey. Based on the metabolism and a selection criteria grid, the outputs of level 3 are realistic levers and scenarios, co-designed with local stakeholders. Local levers can be up-scaled to identify potential changes in the island metabolism.

At all levels, when possible, it is useful to run a simulation and undertake a multicriteria assessment of the impacts of the scenario concerned, particularly in terms of its carbon footprint (Figure 8).

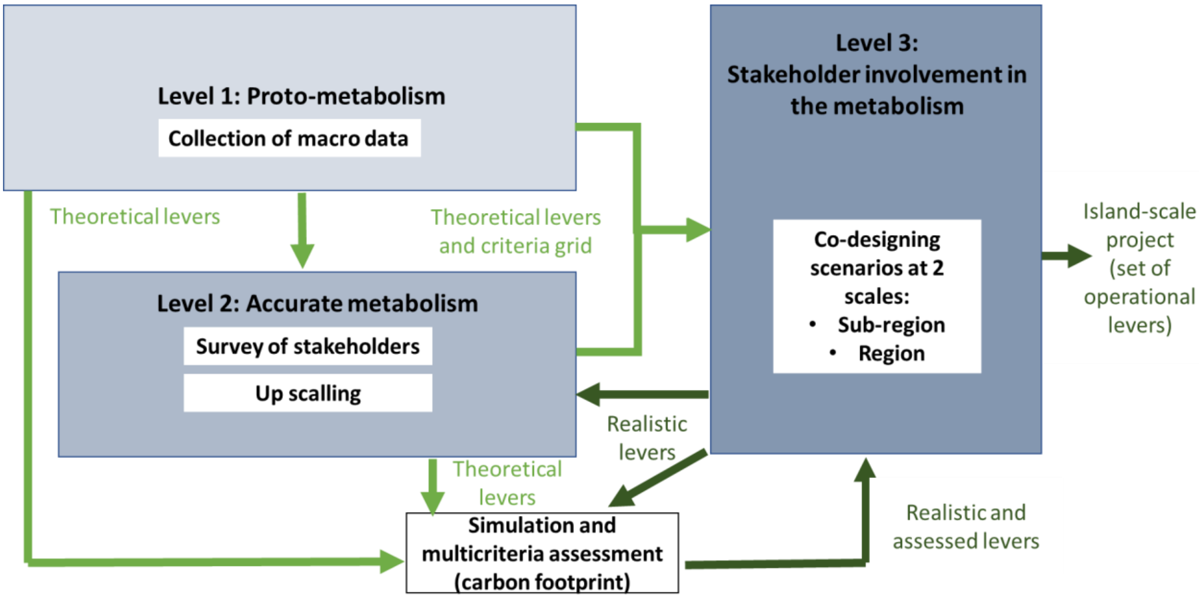

Figure 8: Articulation of the 3 levels of the proposed methodology

Level 1: Proto-metabolism

Goals

Level 1 has three goals:

- Obtaining an overview of the food system by characterising the island's proto-metabolism (Grillot et al., 2021), i.e. identifying the major components of the food system and the pool of biomass production.
- Discovering if livestock plays a determining role in circularity, i.e. checking if livestock production could have an impact on the food system by providing opportunities for circularity.
- Proposing opportunities to improve circularity within the food system, particularly by including livestock production.

System Definition

Proto-metabolism is the first step towards understanding the real metabolism and how the actors are organised (Grillot et al., 2021). Our system here is the island food system. At level 1, we include six sub-sectors: croplands, grasslands and rangelands, livestock, fisheries, households, and agroindustry. Flows entering and leaving the food system (imports and exports) and flows between the sub-sectors are included when data are available.

Data collection

Level 1 should be feasible for any island. Only general data are needed and they can be found in sources such as governmental websites, agricultural institutes or the FAO. The reliability of each source needs to be checked and noted.

Tools available to help characterise a metabolism (table 2):

Table 2: Example of tools available to build a representation of a metabolism

Data storage	• PostgreSQL (https://www.postgresql.org/): Open Source Relational Database • Microsoft Access (Microsoft Office) • Excel (Microsoft Office): Spreadsheet software program
Calculation (indicators, aggregation of flows, etc.)	• PostgreSQL • Microsoft Access
Metabolism representation	• STN2web (https://www.stan2web.net/): free software that helps perform Material Flow Analysis (MFA) • PowerPoint • E!Sankey: software to represent MFA in Sankey diagrams

Representing Macro Metabolism

A general representation can be achieved using the above-mentioned data. At this point, flows are only hypothesised. A graphical representation of the proto-metabolism can take different forms.

Whatever the form chosen, the representation should show the different sub-systems and the flows between them (figure 9).

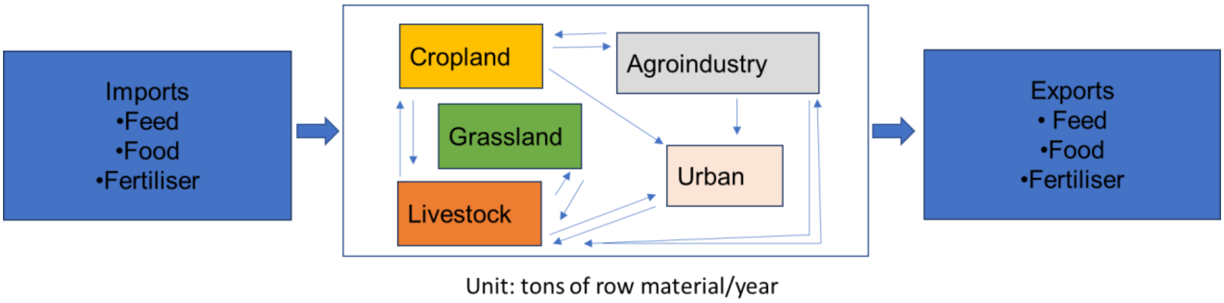

Figure 9: Example of a representation of a proto-metabolism

Indicators

For level 1, we propose 2 indicators to evaluate circularity and to create global livestock-based levers.

- Animal stocking rate

Stocking rate is the number of animals on a given amount of land and is best considered as a balancing act between feed supply and herd demand, and between manure supply and crop demand. At regional scale, this indicator shows if animal production is significant enough to contribute to food system circularity. For our calculation, we used the FAO tropical livestock unit (TLU) (Kassam et al., 1991).

- Feed and fertiliser self-sufficiency

Considering the difficulties involved in reintroducing animals in farms specialized in field crops, some authors suggest investigating the potential of integrating crops and livestock at regional level (Moraine et al., 2017). This integration can be evaluated by calculating feed and fertiliser self-sufficiency. A food system with high crop-livestock integration promotes the valorisation of by-products from food production and croplands into feed, and valorises the use of livestock manure as fertiliser (Bénagabou et al., 2017).

Animal Stocking Rate	Feed and Fertiliser Efficiency
$\frac{\boldsymbol{Livestock\ units}}{\boldsymbol{Land\ area\ (ha)}}$	$\frac{\textbf{Production (feed or fertiliser)}}{\boldsymbol{Total\ consumption\ (feed\ or\ fertiliser)}}$

Proposed levers based on these indicators

Based on these indicators, it is possible to propose general livestock-based opportunities for circularity. These are generally structural changes to the food system such as modifying the size of livestock, crop or grassland sub-sectors.

Level 2: Accurate metabolism

Goals

Level 2 has four goals:

- Conduct a complete inventory of biomass stocks and flows in the study region (material flow analysis)
- Convert biomass into nutrients and/or energy (substance flow analysis) and evaluate the island metabolism in terms of circularity
- Identify hotspots (losses)
- Make recommendations to improve circularity

System definition

Following level 1, our system at level 2 is still the food system but includes more sub-systems, i.e. the agricultural sector and all the economic sectors connected to the agricultural sector.

This system comprises:

- Agriculture (croplands, grasslands and rangelands, Livestock, Forest, Aquaculture)
- Households
- Industry (Food, Feed, Fertilisers, Energy production)
- Waste Management

Data collection

A material flow analysis (MFA) is performed, i.e. quantification of all stocks and flows of materials produced, already used or usable in agriculture in the study region. The biomass stocks and flows are then converted into energy and nutrients: Nitrogen, Phosphate, Potassium or Carbon (substance flow analysis). Biomass stock and flow quantification can be accomplished through interviews and surveys of local stakeholders.

The tools available to represent the metabolism are the same as those presented in level 1 (see table 2).

Representing Metabolism

Metabolism can be represented using one or several metrics e.g. Energy (MJ), Nitrogen (N), Phosphorus (P), Potassium (K) or Carbon (C). A wide range of representations is possible, even the definition of the system may vary. Figures 10 and 11 are two possible representations of nitrogen flows in France and Belgium respectively.

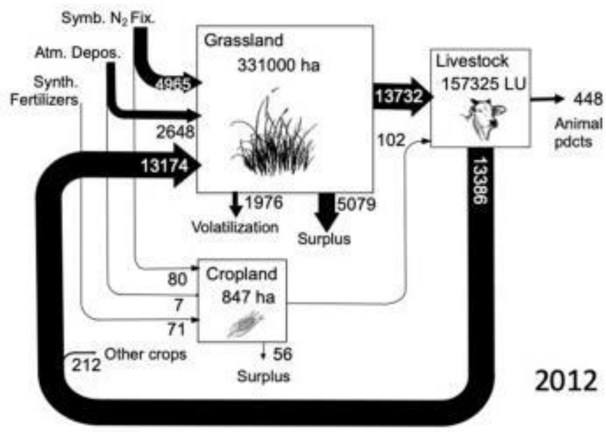

Figure 10: Flows of N in the agro-food system in France (le Noë et al., 2017)

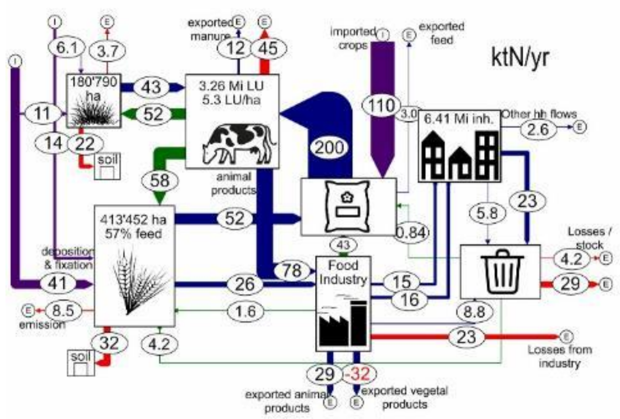

Figure 11: Flows of N in the agro-food system of Flanders (Papangelou & Mathijs, 2021)

Indicators

Four indicators are proposed for level 2. Data have been converted from tons of raw material into energy (MJ) or nutrients (N, K, P or C) and indicators are expressed as a %. Indicators can be calculated for the whole food system and/or for each sub-sector (e.g. focussed on the livestock sector). It is useful to calculate indicators for both the whole food system and for each sub-sector in order to locate inefficiency or losses and to propose specific levers for each sub-sector. The cycling index can be calculated only at the whole food system level (island scale) as it takes all system flows (including internal flows between sub-sectors) into account.

- **Nutrient use efficiency:** Ratio of nutrient outputs to inputs at the system (or sub-system) level. Generally, the more productive the system, the more efficient it is.
- **Recycling rate:** % of by-products and waste recycled in the system.
- **Loss rate:** Ratio of nutrient losses (gas emissions, runoff, etc.) to inputs.
- **Cycling index:** Ratio of internal flows to total system flows. The more autonomous the system and the more internal recycling flows it creates, the more circular it is.

Nutrient use efficiency

$$= \frac{Nutrient\ outputs}{Nutrient\ inputs}$$

Loss rate (%)

$$= \frac{Nutrient\ losses}{Nutrient\ inputs} \times 100$$

Recycling rate (%)

$$= \frac{Co-products\ and\ recycled\ waste}{Total\ co-products\ and\ waste} \times 100$$

Cycling index

$$= \frac{\text{Internal cycling flows}}{\text{Total system flows}}$$

Proposed levers based on the indicators

Based on the indicators calculated, it is possible to identify livestock-based opportunities for improving food system circularity.

Level 3: Stakeholder involvement in the metabolism

Goals

- Co-designing scenarios and levers with local stakeholders to improve circularity
- Up-scaling of specifically local levers to identify possible changes in regional metabolism

Inventory of local stakeholders

Level 3 starts with a broad consultation of all the stakeholders concerned with biomass in agriculture, including agronomists, farmers, technical staff, government representatives, local authorities in charge of agriculture. The participatory and multi-actor approach fosters synergies between stakeholders and the construction of collective projects leading to a consensus. It also gives local stakeholders ownership of the proposed scenarios.

Selection of case studies

A participatory selection of case studies was made using the criteria framework proposed by Vigne et al., (2021) which depends on:

- Importance (occurrence, quantity) of biomass deposits recorded in the level 2 inventory
- The number and type of actors involved, including those outside the agricultural sector
- Potential re-use of levers identified in other local contexts
- Potential contribution of solving the problem to improving the autonomy of the agricultural sector and of the region
- Capacity to call on the project's internal competencies, in particular in the agronomic sciences, to resolve these problems.

Treatment of the study cases

Modelling can be very useful to facilitate stakeholder appropriation of scenario construction. Spatial modelling is a good way to represent the impacts of different scenarios on biomass flows in a given region as well as to encourage the emergence of collectively shared solutions. Used as an intermediary object (Lardon, 2005), modelling greatly facilitates appropriation by all stakeholders of the problems brought to light during the different stages of the diagnosis. Modelling is particularly useful when the processes include not only technical and financial considerations but also informal social aspects. Simulation modelling tools provide better coverage of the needs of both producers and consumers, while accounting for logistical and regulatory constraints. The formalisation of circularity levers in the form of simulated scenarios using computer models facilitates the inclusion of diverse variables and the different points of view of the many stakeholders and helps each stakeholder to better understand his or her role in relation to the others in the complex system represented by the island (Vigne et al., 2021).

Different tools can be used (table 3).

Table 3: Example of modelling tools used for level 3

Step	Tool
Participatory tools	• Companion Modelling (ComMod): a participatory gaming and simulation approach uses role-playing games and simulation models to tackle complex issues involved in renewable resources and environment management in collaboration with stakeholders (Collectif ComMod, 2005).
Spatial modelling	• R: free software environment for statistical computing and graphics • Ocelet (http://www.ocelet.org/): Modelling and simulation programming language dedicated to the simulation of landscape and environmental dynamics (CIRAD) • Gama (https://gama-platform.org/): Modelling and simulation development environment for building spatially explicit agent-based simulations. • MAELIA (http://maelia-platform.inra.fr/): Multi-agent platform for integrated assessment and modelling of agricultural regions and regional bioeconomy systems.

Indicators

Indicators are the inclusiveness of the scenarios in terms of:

- Agricultural area: Surface area and diversity of land use in the scenarios.
- Livestock population: Number and diversity of species in the scenarios.
- Stakeholders: Number and type of actors involved in the co-construction of the scenarios.
- Biomass deposit: Importance (occurrence, volumes and types) of the biomass concerned.

Proposed levers and new scenarios

After modelling different scenarios and calculating indicators, the best scenarios can be selected. Scenarios can be run at 2 scales, sub-region (local project) or island scale. Sub-regional scenarios and local levers can be then up-scaled to the island metabolism to identify possible changes.

Multi-criteria and integrated assessment

This assessment consists of jointly evaluating the local projects identified at the scale of the study region (figure 8). A multi-criteria (technical, environmental, economic, social) and integrated modelling approach enables analysis of the different interactions between these local projects, such as synergy, antagonism or the effects of competition on resources, regarding the issues, constraints and opportunities in the region concerned.

Multi-stakeholder consultation and the definition of a shared project

At a larger scale, a multi-stakeholder consultation should be held to define a shared regional project. The regional project should be based on a consensus (i.e. agreed on by the largest possible number of different actors). Local solutions do not necessarily have to be extrapolated at higher scales, but it is important to assess how the different local circularity levers would participate in the whole island project if they are all incorporated.

III. APPLICATION TO CASE STUDIES


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Madagascar

For the case study in Madagascar, only level 1 was performed due to limited data availability. Addressing level 2 will require more time and means to collect precise data.

Level 1

Based on macro data (trademap, FAOStat, InStat, etc.), a proto-metabolism was characterised to get an overview of the Malagasy food system (figure 12).

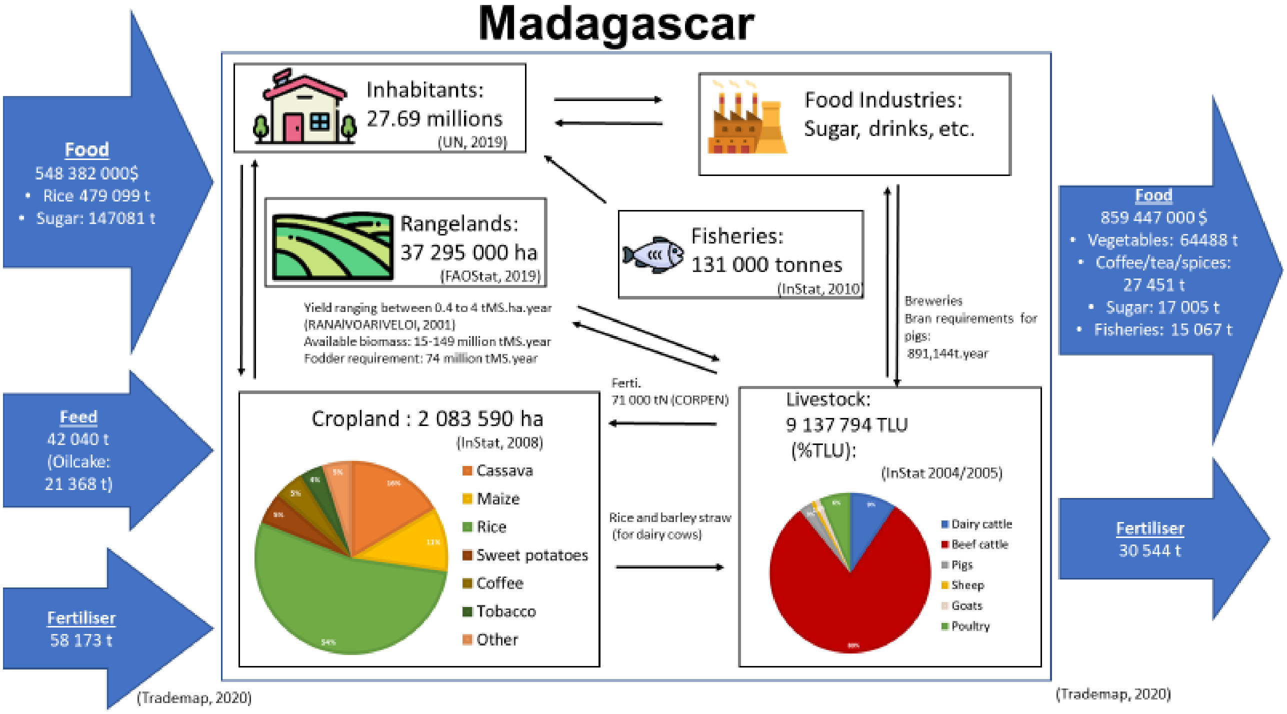


Figure 12: Proto-metabolism of Madagascar

The country has few imports. Rice is the main import as a base for human diets. Few inputs are used for crop production. The main crop grown is rice, and all crops are mainly grown for self-consumption and for sale at the local market. In the livestock sector, beef is the main product and beef cattle are mainly grass-fed. A market for dairy products is developing. Rangelands have a big potential as they represent a large area but yields are low and vary considerably depending on the region and the season. Food industries are not well developed. Exports are low in terms of quantity but high in economic value (i.e., high value products such as vanilla).

Using the proposed methodology, and based on the metabolism, the following indicators were calculated (table 4).

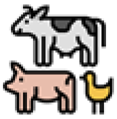
Table 4: Indicators provided by the level 1 in Madagascar

	Madagascar
Food import /inhabitant (kg/inhabitant/year)	Dairy products: **0.5** Meat: **0.003** Rice: **17**
Imports of fertiliser per ha of arable land	58 173 000/ (2 083 590 + 37 295 000) = **1.5 kg/ha/yr**

Stocking Rate (TLU / ha)	9 137 794 / (2 083 590 + 37 295 000) = **0.23 TLU/ha** Very variable: up to 2 TLU/ha in the dairy triangle (in the highlands)
Imports of animal feed / TLU	42 040 000 / 9 137 794 = **5 kg/TLU/yr**

Note we were unable to calculate animal feed and fertiliser self-sufficiency due to limited data availability. This would require in-depth characterisation of agricultural production systems in Madagascar.

However, thanks to the proto-metabolism and calculated indicators, some levers are proposed below:



1. **Main lever: Increase the animal stocking rate**. Currently production and demand are low. More livestock would mean more organic matter and more co-products to valorise and more opportunities for circularity based on livestock.

2. Intensify livestock production systems
Current milk and meat productivity are low. Better alimentation with more forage inputs per animal would increase productivity and produce more manure to be used to increase crop production.

3. Maintain and improve grazing systems by introducing legumes, crop rotation, etc. Rangelands are now characterised by low productivity and are under valorised due to the low stocking rate (under grazing).

Reunion Island

In Reunion Island, Level 1 and 2 were performed in full. Based on the results of past and current studies, Level 3 was partially addressed.

Level 1

Proto-metabolism of the Reunion Island food system revealed high imports (Figure 13).

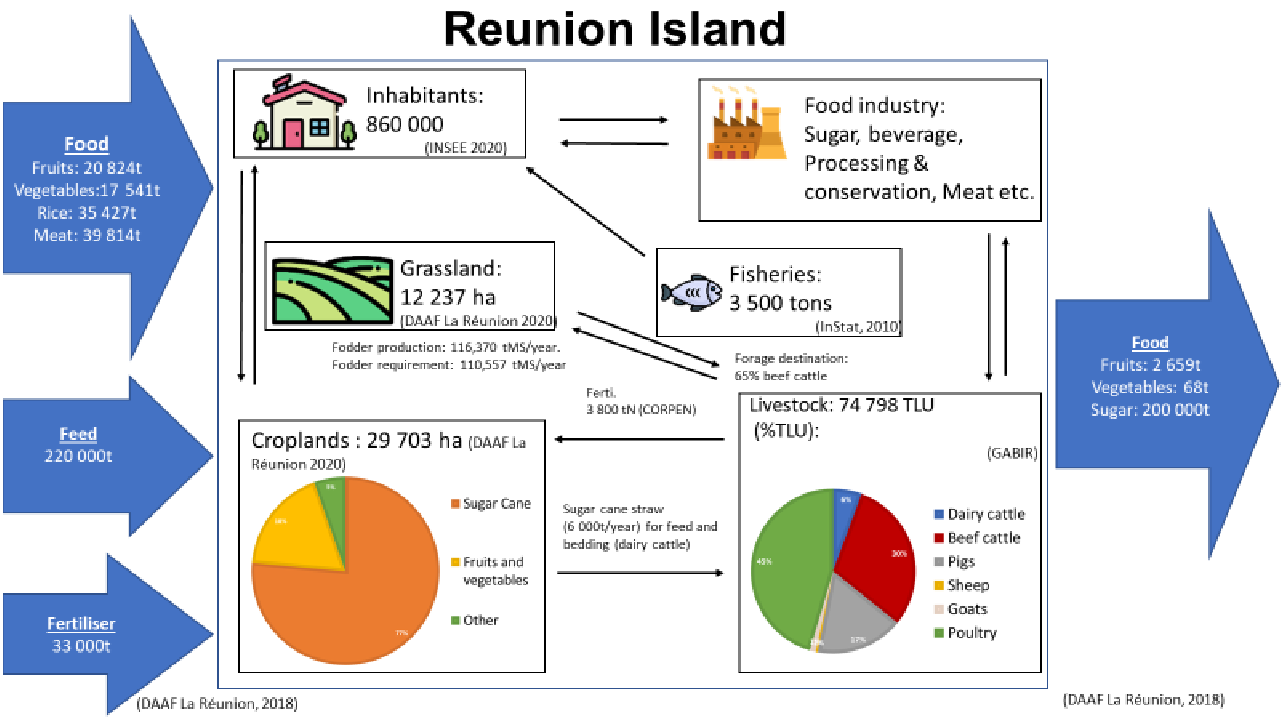


Figure 13: Protometabolism of Reunion Island

Imports of all food, feed and fertilisers are all high. Concerning crop production, 75% of arable land is used to grow sugar cane for export as sugar. Other crops are mainly grown for local consumption. Local livestock production (poultry, beef cattle and pigs) for local consumption is well developed. Despite the amount of land used to produce fodder, which could cover fodder requirements, use of imported feed is high.

Calculated indicators for level 1 are listed in table 5 below.

Table 5: Indicators provided by level 1 in Reunion island

	Reunion island
Food imports /inhabitant (kg/inhabitant/year)	Dairy products: **19** Meat: **46** Rice: **41**
Imports of fertiliser per ha of arable land	33 000 000 / (29 703 + 12 237) = **787 kg/ha/yr**
Stocking Rate(TLU / ha)	33 000 000 / (29 703 + 12 237) = **787 kg/ha/yr**
Imports of feed / TLU	220 000 000 / 74 798 = **2 941 kg/TLU/yr**

Based on the proto-metabolism and corresponding indicators, proposed levers for level 1 are:

1. Increase crop-livestock integration at the island scale to reduce imports of inputs. Better valorisation of manure as fertiliser and of crop by-products as animal feed.

2. Diversify land use and introduce crop rotation to improve feed and food self-sufficiency.

Level 2

Levers proposed in level 1 are global and theoretical. To propose more specific levers, a level 2 analysis and the accurate characterisation of the island metabolism was needed. To this end, data from surveys of local stakeholders and from literature were used to obtain a more accurate picture of the metabolism of the food system in Reunion Island. All stocks and flows of materials related to biomass were quantified and converted into nitrogen (N) (Alvanitakis, 2021).

In the metabolism below (figure 14), flows are classified in different types and each colour represents a different type of flow (e.g. red arrows represent N emissions to the atmosphere, and soil and water).

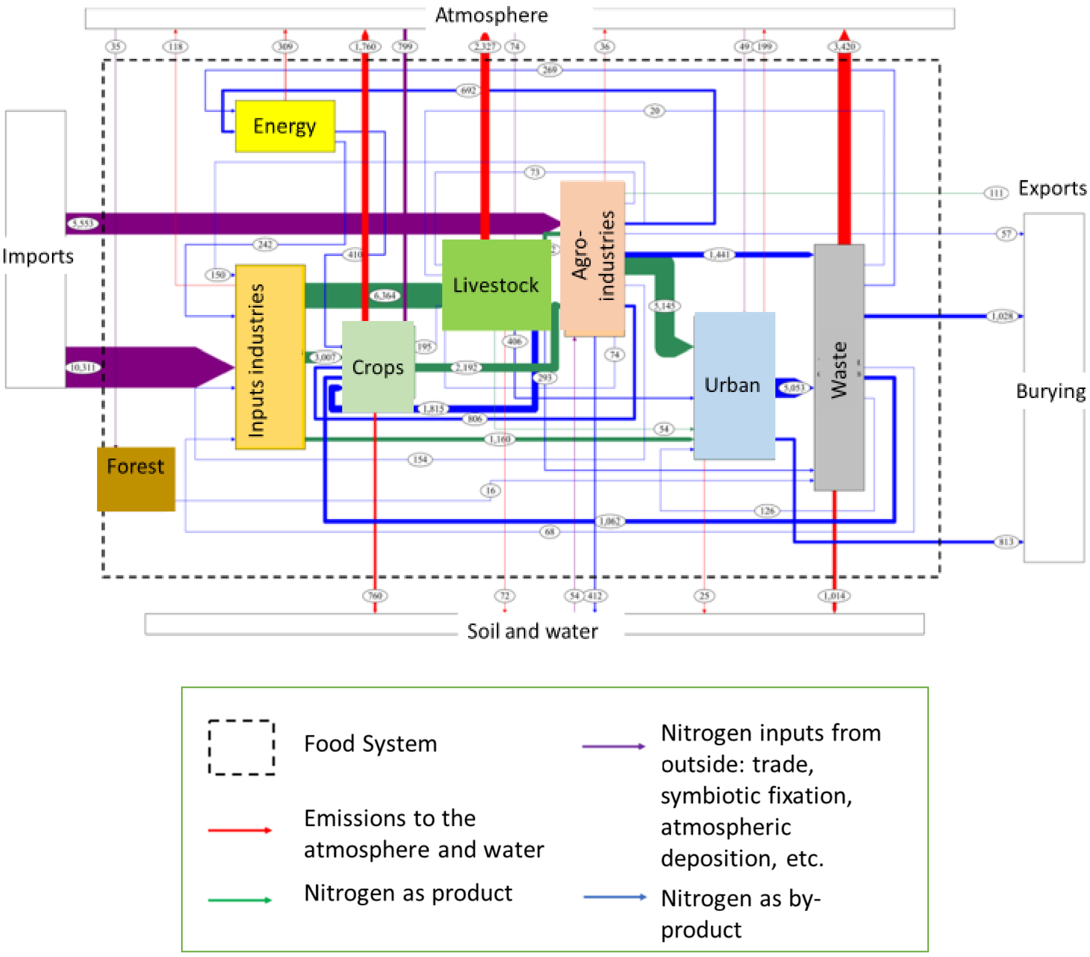


Figure 14: Accurate metabolism of the food system in Reunion Island (in tons of nitrogen) (Alvanitakis, 2021)

Based on the metabolism, some numbers can be highlighted. Reunion Island imports 16 000 tons of nitrogen per year, mainly in feed and fertilisers. The island exports only 100 tN/year in the form of fresh fruits and sugar cane (sugar is poor in nitrogen). We can thus affirm that Reunion Island is a nitrogen sink as a large quantity of nitrogen enters the system and only a small quantity leaves it. Symbiotic fixation and atmospheric deposition are limited, representing only 1 000 tN/year while 10 000 tN are lost every year to the air, soil and water, and 2 000 tN/year are not recycled (landfill and burning). Using these numbers, indicators can be calculated.

- Indicators

Table 6: Indicators provided by level 2 in Reunion Island

	Livestock	Crops	Waste management	**Island food system**
Nitrogen use efficiency	0.81	0.37	0.21	**0.07**
Loss rate	19%	26%	67%	**60%**
Recycling rate	100%	100%	59%	**87%**
Cycling index	-	-	-	**0.52**

Nitrogen use efficiency is very low (<0.1) as the system imports a lot of nitrogen in food, feed and fertilisers) and the main export is sugar which is poor in nitrogen. Losses are mainly gaseous, with a total of 10 000 tN/year, more than half the losses are to the atmosphere. Symbiotic fixation is very low and under used. The recycling rate is high for crops and livestock as by-products are all reused and recycled. The waste management sector is the one with the highest losses and is the least efficient.

Based on the previous indicators, theorical levers can be proposed. Two categories of livestock-based levers are proposed to improve circularity in the metabolism:

Increase recycling

1. Use household and industrial biowaste as animal feed. Currently 1 000 tN/year are buried in landfills and lost whereas they could be used as feed.

2. Use shredded green waste as animal bedding. Currently green waste is also buried and represents a loss of 400 tN/year. The current slurry system could be replaced by a solid manure system.

3. Valorise sludge from wastewater treatment plants as fertiliser for forage crops. Currently sludge is dumped in the sea or buried and represents a loss of 1 000 tN/year.

Increase process efficiency

1. Balance inputs and needs in space and over time for both livestock and crops, including grasslands). This represents 3 800 tN/year (represented by the N stock variation in the crop box)

2. Reduce losses related to manure management (1 400 tN/year). Not all losses can be prevented, but 20% to 30% of the emissions in stables and during storage could be prevented by using specific manure management techniques.

3. Increase symbiotic nitrogen fixation via legume forage crops (2 000 tN/year) that would also increase protein in animal diets.

These levers could save up to 10 000 tN/year. Compared to level 1, they appear more realistic and contextualized, as they are based on more precise figures. However, these levers are still general. Indeed, although they are biologically realistic, their technical and socio-economic implementation requires further evaluation. For instance, considering the spatial structure of the landscape, soil-climate conditions, and farming systems diversity in Reunion Island, it is important to assess if the different levers can be implemented throughout the Island or not.

Level 3

To identify realistic levers, local stakeholders thus participated in the design of scenarios and in proposing practical levers to be developed in level 3.

First, the proto-metabolism developed in level 1 was used to identify livestock-based circularity levers with stakeholders. Second, a participatory selection was made of some circularity levers, according to an ad-hoc criteria framework considering:

- The representativeness of different types of biomass and the diversity of stakeholders involved in the metabolism;
- The quantity of biomass deposits;
- Potential scaling-up of the identified solutions to the whole island.

Note that the livestock sectors could improve food system circularity through three types of interactions (figure 15):

- Interactions between livestock systems within the livestock sector,
- Interactions within the agricultural sector, thanks to crop-livestock integration, either at farm level or between specialised farms at regional level,
- Interactions between the livestock sector and non-agricultural sectors, for instance agro-industrial sectors.

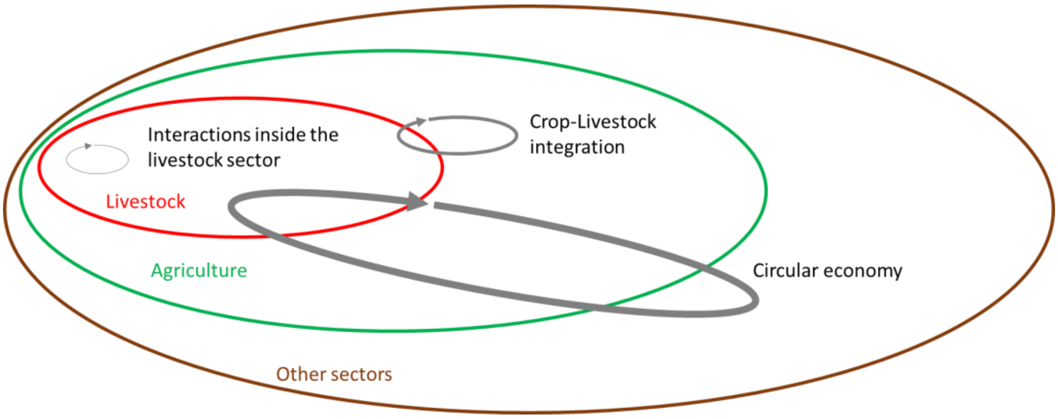


Figure 15: Type of interactions with the livestock sector whiting the food system used to characterise circularity levers

After reaching agreement, 5 circularity levers were selected with local stakeholders and implemented at the island scale or sub-regional scale (Figure 16).

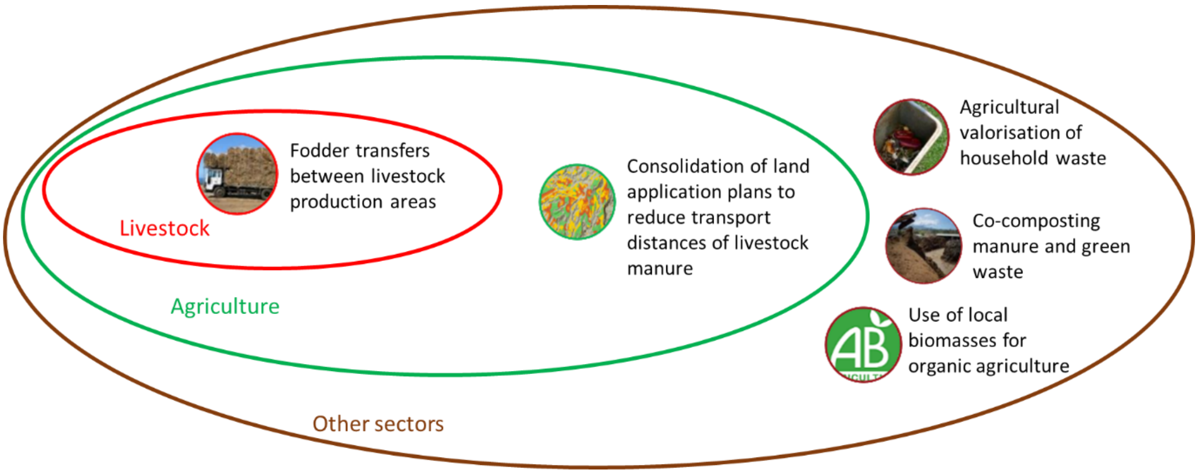


Figure 16: Type of circularity levers depending on interactions with the livestock sector whiting the food system

Among the levers considered, only two are illustrated in this report: (i) the consolidation of land application plans to reduce the distance livestock manure has to be transported in St Joseph municipality and (ii) co-composting manure and green waste in the southwestern part of Reunion Island. Both levers address the constraints for spreading manure produced by livestock farming systems identified by the livestock farmers themselves, which is a major limiting factor to the further development of livestock activities on Reunion Island.

Different drivers are responsible for such constraints. For instance, in the south-western part of Reunion Island, the constraints are mainly due to the industrialisation and specialisation of livestock farming systems, particularly poultry and pig farms that produce liquid manure (figure 18), but also due to the spatial organisation of agricultural activities and specialisation in certain parts of the island. Sugar cane is mainly grown in the lowlands while livestock are raised and grasslands are located in the highlands (Figure 17).

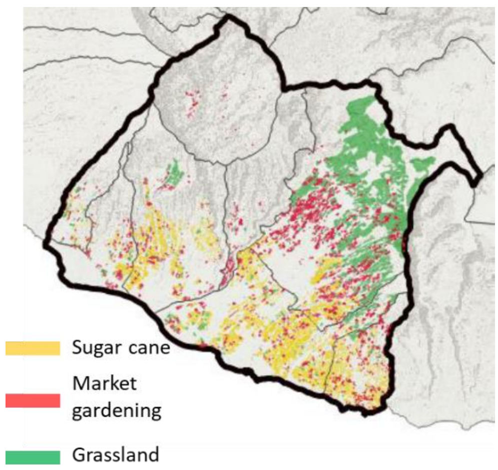


Figure 17: Land use

Figure 18: Pig farming in St Joseph

Added to these two factors, the specific topography of St Joseph municipality, (figure 19) means livestock farmers have to travel long distances to spread manure, which is both time-consuming and expensive. As a consequence, a significant proportion of the land in the region receives little or no organic fertiliser (Figure 20), despite the positive balance, at communal area scale, between organic N produced by livestock and crop N needs.

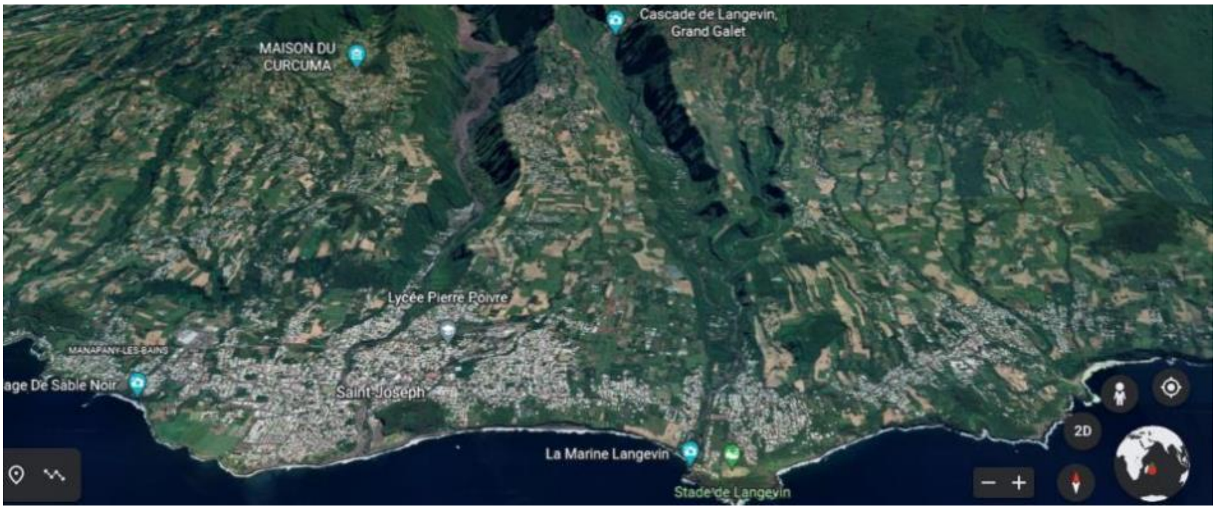


Figure 19: Topography of St Joseph municipality

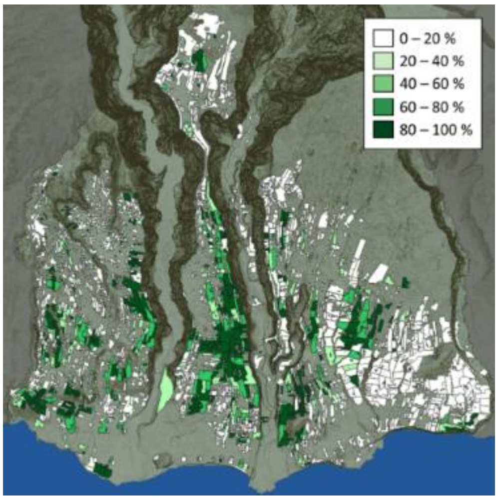


Figure 20: N coverage rate by organic fertilisation (in %) of cultivated plots in the study region (Jarry, 2019)

Figure 21: Green waste

In the two areas, co-composting manure with green waste emerged as a possible solution during the different consultations (direct interviews, focus groups, etc.). Indeed, due to tropical conditions, green waste production in Reunion Island is high (Figure 21). According to the figures provided by the metabolism in level 2, green waste production is eight times higher than in mainland France. In the south-western part of Reunion Island, co-composting manure and green waste would make it possible to produce an easily transportable and valuable organic fertiliser that could be sold to market gardeners. In St Joseph municipality, this would also reduce the risk of over-manuring on the plots located close to the farms by increasing the spreadable surface (Jarry, 2019).

As a green waste platform treatment already exists in south-western Reunion Island (Figure 21), discussions of such a solution were undertaken. Four scenarios for co-composting were first identified using a participatory approach with focus groups involving local stakeholders (farmers, green waste treatment operators, local policy makers, etc.):

- Individual co-composting platforms on livestock farms,
- Individual co-composting platforms on market gardening farms,
- Small collective platforms disseminated across the territory,
- A single large platform managed by a private operator.

Among these options, two were selected by the focus groups. Individual co-composting on livestock farms or on market gardening farms require more detailed investigation in the future. Such choices were motivated by the possible reduction in the cost of transport (calculated using spatial simulation models) and because, based on previous experiences on Reunion Island, collective management was identified as a potential source of conflict.

Following the proposed methodology, continuing level 3 would first involve up-scaling this specific local lever to island scale to identify other potential areas of interest, while also accounting for local problems. Then, based on the diversity of other problems and proposed solutions, but also other options for biomass valorisation (e.g. energy production), simulations should be run to explore potential conflicts, synergies or trade-offs between the proposed levers and to fully assess their consequences for the carbon footprint of the food system as a whole. These studies are currently underway in Reunion Island (Kleinpeter et al., 2021).

IV. DISCUSSION

Articulation of the methodology

We assume that the 3 levels are complementary (Figure 22) thanks to the approach used and the indicators proposed. For instance, by providing a first overview of the flows that comprise the metabolism, level 1 would make it possible to select major flows of interest to be more deeply investigated in level 2. In addition, like in level 1, contacting and/or interviewing local stakeholders during the level 2 stage made it possible to inform them and to try and get them involved in stage 3. Another example of complementarity is that levels 1 and 2 offer a conceptual model of flows that can be used to identify levers with stakeholders in level 3. What is more, the nutrient metabolism produced by level 3 can be re-used to upscale the levers identified in level 3 for the simulation and multicriteria assessment of scenarios.

In this sense, we assume that, in optimal conditions, each level should be performed in order to propose a complete and realistic "regional project", which would be based on a set of operational livestock levers co-designed and validated in a participatory approach with all the stakeholders involved in the food system and which have been assessed in terms of their socio-eco and environmental impacts on the territory (Angeon & Lardon, 2008; Lardon & Piveteau, 2005).

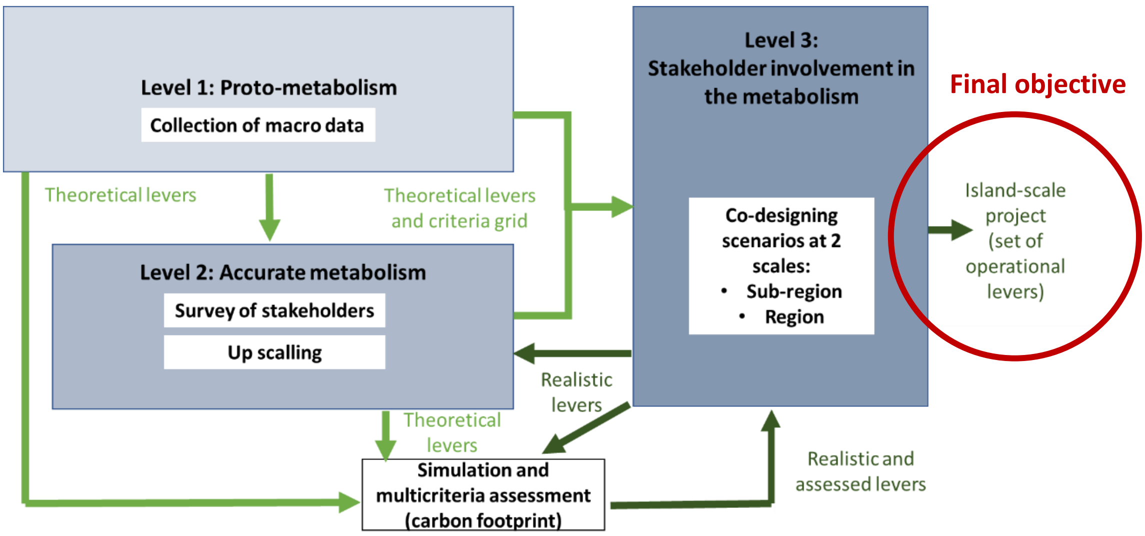


Figure 22: Articulation of the methodology

Application of the methodology depending on the diversity of food systems in tropical islands

Due to financial constraints and time limits, the methodology was only partially applied to Reunion Island and Madagascar. The application to Madagascar only took place at level 1. Although few data were available, we can assume that if we had had more time, we could have tried to apply level 2, at least in some parts of the island where the description of the farming systems is more complete (in the Central Highlands for instance) (Duba, 2010; Kasprzyk et al., 2008). Concerning Reunion Island, about 10 years have passed since CIRAD began working on this case study. Level 2 and the beginning of level 3 have been successfully applied. In the different case studies chosen, levers were identified and some have already been or will be applied. To conclude level 3 and to propose a complete project for the whole island based on improved use of biomass, including in the livestock sector, what is still missing is up-scaling of identified levers to the island scale. This up-scaling should involve simulations and a multicriteria assessment to identify potential changes in the island's metabolism. This step is actually underway in Reunion Island, where two PhD student are examining levers at the scale of the whole island to improve circularity and self-sufficiency in the food system and to reduce its carbon footprint.

However, looking beyond Reunion Island and Madagascar, tropical islands have very diverse food systems, ranging from systems that are completely dependent on imports to food systems that are close to achieving self-sufficiency. Therefore, before promoting the transferability of the methodology proposed here, it will need to be applied to other tropical islands with different food and livestock systems to check its transferability. In particular, dealing with islands with no or only a limited livestock sector would be of interest to check if the methodology is capable of imagining (new) livestock systems closely connected to the other economic sectors that can actively contribute to the circularity of the island's food system.

To explore the diversity of tropical island food systems, different possible case studies around the world were identified in the different webinars (Figure 23).

In addition to Madagascar and Reunion Island in the Indian Ocean, these are:

- In the Caribbean: Aruba (Box 1), Cuba (Box 2) and Guadeloupe (Box 3)
- In the Pacific Ocean: Wallis and Futuna (Box 4) and New Caledonia (Box 5)

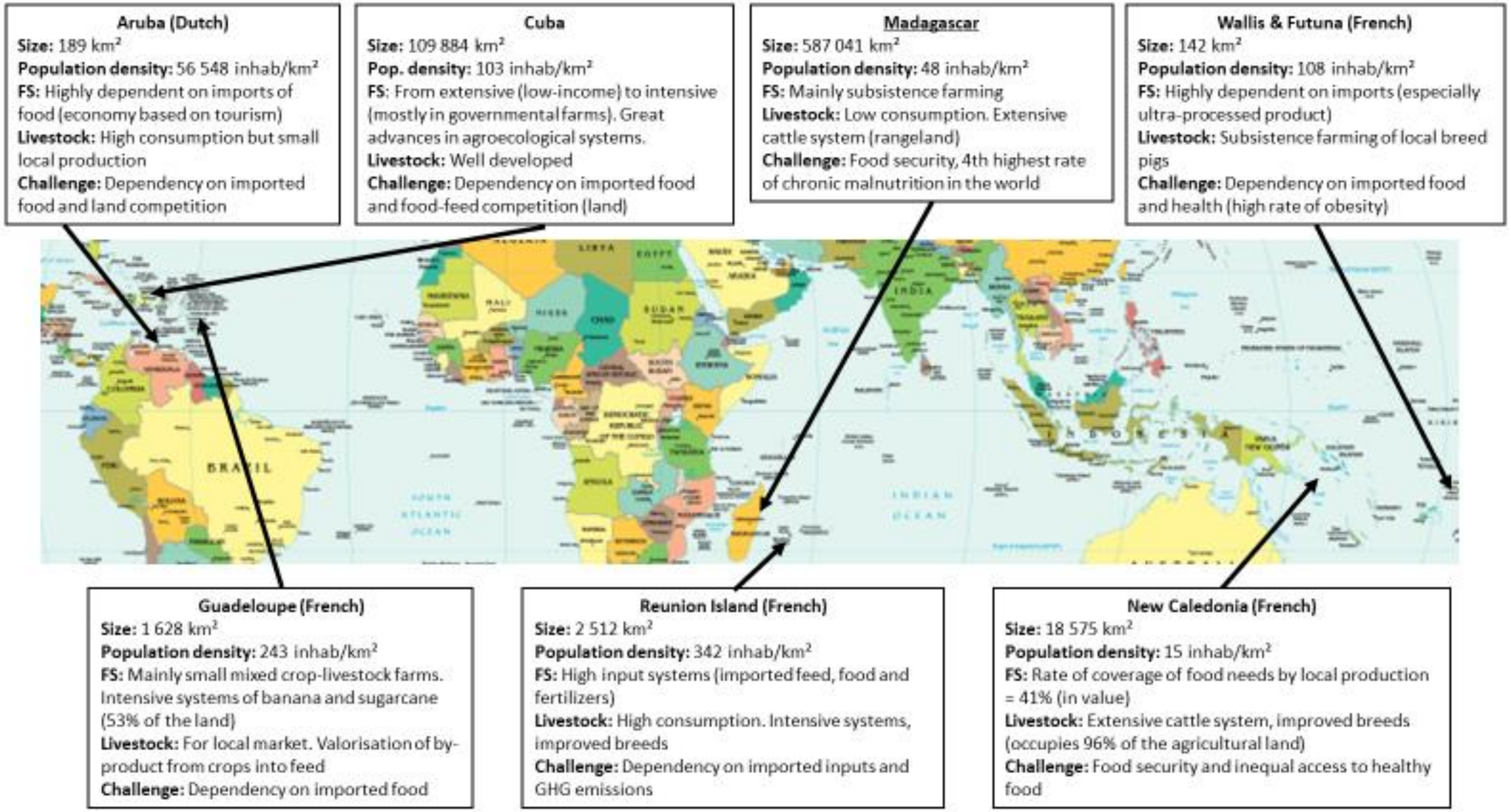


Figure 23: Tropical islands and food systems in the Atlantic, Pacific and Indian Oceans

Box 1: Aruba

Aruba (Atlantic Ocean)

Amber S. van Veghel[1,2]
[1]*SISSTEM, University of Aruba*
[2]*Sustainability in the Agri-Food chain Group, BIOSYST department, KU Leuven*

Figure 24*: One way to reduce the carbon footprint of Aruba's food system is to import foods with the least possible environmental impact.*

Food System

Aruba is an island located in the Dutch Caribbean with a population of ~110.000 citizens on just 180 km^2. Aruba has a strong focus on tourism, and tourists also need to eat. However, agricultural land is scarce and there is competition for land from other sectors. Our team in Aruba conducts research on topics such as food security, increasing local food production and consumption, and indoor vertical farming.

Role of livestock

Animal based products play an important role in the food culture of Arubans as well as of tourists. Chicken is the most widely consumed livestock product in Aruba, followed by beef. A small portion of animal products are produced locally: goats and sheep (21% local), beef (0.0%), pork (2%), chicken (0.5%), eggs (27%), and fish (18%). Local production of chicken, eggs and fish may be underestimated.

Problems linked to the food system

Preliminary research showed that although beef contributes only 3 weight% to the import of food and beverages, it accounts for 26% of greenhouse gas emissions (GHGs) of imported food and beverages. However, high variability in GHGs has been measured for beef. (Poore & Nemecek, 2018) showed that GHGs can range from 10 – 432 kg CO_2eq per kg of beef. This variability decreases when calculated at national level.

Livestock based levers to improve circularity

Assessing and consequently reducing GHGs of food imports is one way for import dependent islands to progress towards a more environmental-friendly food system. My PhD focuses on using life cycle analysis (LCA) to determine the environmental impact of different food imports, such as meat, so that consumers and those involved in the food system can make a more informed decision on more sustainable procurement.

Box 2: Cuba

Cuba (Atlantic Ocean)

Eliel González-García[1] and Carlos A. Mazorra Calero[2]

[1]SELMET, INRAE, CIRAD, Montpellier SupAgro, Univ. Montpellier, [2]Ciego de Ávila University (UNICA), Cuba

Figure 25: Mixed, crop-livestock integrated farming system in Cuba

Food System

Of the total country area (10 988 000 ha), 10 380 000 ha is land, 6 401 000 ha is crop and livestock farming land and 3 242 000 ha is forest (FAOSTAT, 2019). A wide range of agriculture and livestock farming systems (LFS) coexist, ranging from extensive (low-income) to intensive (highly dependent on external inputs, mostly in state owned farms). The human diet is based on rice, beans, pork and chicken, roots and tubers, vegetables and local desserts based on fruits (e.g. coconut, guava, mango). The main national agricultural productions are sugarcane, tobacco, coffee, rice, beans, roots and tubers (cassava, sweet potato, taro), and tropical fruits such as citrus, plantain and banana, mango, papaya, *mamey sapote*, pineapple, avocado, guava, and coconut. The main exports include cigars, raw sugar, nickel products, rum and zinc. Despite major advances in agroecological systems, food self-sufficiency has not yet been achieved. Food imports currently include cereals, milk powder, oil crops, meat, pulses, fish and seafood, offal, starchy roots, animal fats, eggs, vegetables, sugar and sweeteners and vegetable oils.

Role of livestock

Cuba has several livestock production sectors, based on dairy ruminants (cattle -including buffalo- and goats), and meat production based on ruminants (cattle, sheep, goats) or non-ruminants (chickens, geese, ducks, turkeys, plus pigs and rabbits). Several LFS coexist, often based on the type of land ownership, whether State, cooperative or small private producers. Mixed crop-livestock, highly diverse farming systems are very often found in small- and medium-size farms (mostly privately owned or cooperatives).

Problems linked to the food system

As a tropical island, Cuba is highly dependent on grains and cereals for human consumption. Food-feed competition is therefore frequent at the intersection between the objectives of food sovereignty and those of farm self-sufficiency in grains and concentrates for animal feed systems (mainly monogastric). To alleviate this situation, locally autonomous animal feeding systems have been developed from alternative sources (at the farm or island level), based on fodder and concentrates with acceptable nutritional value (e.g. roots and tubers, fruit pulp).

Livestock based levers to improve circularity

Animal production is a key factor in promoting the circularity of agricultural systems, in both rural and peri-urban regions (e.g. through agroecology, urban agriculture, permaculture). Beyond the crucial need to provide protein nutrition for the general population and farming families, animals contribute to (**i)** preparing the land for cropping (i.e. pairs of bovines used for animal traction); (**ii)** recycling straw, agro-industrial by-products and crop residues, sources not used by monogastric; (**iii)** organic fertilisation with manure and slurry; (**iv)** guaranteeing the biodiversity of agroecosystems; (**v)** acting as an economic buffer for families in rural areas in times of crisis; (**vi)** guaranteeing the transmission of local, rural traditions (i.e. "knowledge circularity").

Box 3: Guadeloupe

Guadeloupe (Atlantic Ocean)

Jean-Luc Gourdine[1], Audrey Fanchone[1]
[1]INRAE UR ASSET

Figure 26: Use of creole pork to valorise unmarketable crop products in Guadeloupe

Food System

Guadeloupian agriculture is mainly based on small mixed crop-livestock systems on farms of an average size of 4.1 ha; 53% of Guadeloupe's agricultural land is used to grow sugarcane and banana, two highly subsidised export crops. Pasture and fallow currently account for close to half the arable land on the island. Food crops (vegetables, tubers, and plantain), ruminants (mainly cattle, goats, and sheep) and small livestock (poultry, pigs, and rabbits), which are less subsidised and destined for the local market, are often produced along with one or both of the two major export crops.

Role of livestock

Feeding animals with crop residues mainly concerns pig production. Crop residues mainly concern sugarcane, banana, tubers, arboriculture, market garden crops and non-marketable fruits. To a lesser extent, crop residues are used as complementary cattle feed but much less frequently. Organic fertilisation, which is based on the use of livestock manure, is only used for market garden crops and tubers.

Problems linked to the food system

In Guadeloupe, integrated crop-livestock systems are still rooted in the landscape, mainly in traditional form on smallholder farms where they provide households with both food and income. However, high variability exists among systems that contrasts family farms with a high level of crop-livestock integration with intensive productivity-oriented farms. In family farms, available family labor and trust in employees may hold back the development of whole-farm crop-livestock integration and increase in the number of livestock units, whereas, in more intensive farms, management of the nutritional value of crop by-products would do so.

Livestock based levers to improve circularity

Several animal-based levers could be applied to improve circularity in such systems. Among them, genetic levers are well documented by INRAE Guadeloupe. This approach promotes the use of local breeds (creole pigs) rather than genetically improved pigs because of their lower nutritional requirements which makes them well suited to valorise the crop by-products (often of low nutritional value) available in such systems.

Box 4: Wallis & Futuna

Wallis & Futuna (Pacific Ocean)

Marine Esnouf[1], Clément Gandet[2]

[1]Direction des services de l'agriculture, de la forêt et de la pêche (DSA)

[2]Pacific Community (SPC)

Figure 27: *Crop-pig park rotation in subsistence farming systems based on local pig breeds*

Food System

Most of the inhabitants still produce root crops for customary purposes. However, these products are less and less valued for self-consumption by families and young people are not attracted to agriculture. The food system is highly dependent on imports, especially ultra-processed products. The obesity rate is alarming, including among children.

Role of livestock

With more than 22,000 pigs for 12,000 inhabitants, subsistence farming of local breed pigs is omnipresent. It is mainly practiced for customary events. The size of the farms rarely exceeds ten mother sows. Few farms are professionalised and knowledge of feeding, watering, reproduction management that lead to good productivity is rare.

Problems linked to the food system

Traditionally pigs were scavengers and fed on shellfish, supplemented by coconut and cassava. The stocking of pigs for health and safety reasons (1980s) and higher standard of living gradually led to a change in management: use of cheap imported pellets instead of shellfish, lack of protein in the rations led to very fat pigs, and to the concentrated infiltration of slurry in small areas of land by the sea.

Livestock based levers to improve circularity

The DSA and PROTEGE project implemented by Pacific Community (SPC), tries to limit the negative impacts of livestock farming by setting up rotating parks in areas that are less sensitive to water contamination. That means moving animals quite often to limit infiltration, and then cultivating the land to take advantage of the fertilisation provided by the pigs. In order to limit the risk of soil contamination, trials on the use of purifying plants are carried out in the traditional system of succession of Taro, yam, fallow land after the passage of the pigs.

Box 5 : New Caledonia

New Caledonia (Pacific Ocean)

Clément Gandet[1]

[1]*Pacific Community (SPC)- PROTEGE project*

Figure 28: Extensive cattle system in New Caledonia

Food System

New Caledonia faces major challenges in terms of food security, with increasing impacts on health and very high inequalities in access to healthy, good quality food. The low population density and extensive agricultural activities limits their environmental impacts. The rate of coverage of food needs by local production is 41% in value, including self-consumption, which accounts for 30% of the diet of low-income populations.

Role of livestock

Beef cattle farming is a historical sector in New Caledonia and represents a major challenge for the island economy. Indeed, it occupies 96% of agricultural land and covers more than 60% of the demand. The herd is mainly grass-fed, with an average of almost 2 ha per animal. Originally, cattle production was based on pure European breeds (Limousin, Montbeliarde) that were progressively tropicalised (i.e. crossed with Brahman) to acquire greater resistance to ticks (*Rhipicephalus mcroplus*).

Problems linked to the food system

Livestock farmers are seeking to improve their livestock systems through better management of the fodder resource, but also by strengthening intra-breed genetic selection or by cross-breeding, particularly to cope with recurrent and increasingly severe droughts. In the past, bad practices associated with the cutting of trees in the pastures led to severe degradation of the soil in pastures.

Livestock based levers to improve circularity

As part of the PROTEGE project, pasture management (quality and quantity of grass grazed and stored, animal weighing) is monitored in a network of farmers. In addition, measurements are carried out to assess the ecosystem services provided by this type of farming by monitoring the effects of the different farming practices on biodiversity (crop auxiliaries, plant cover, soil micro-organisms, soil meso/macrofauna) and soil organic matter, including carbon storage.

Future perspectives to complete the metabolism? methodology

In addition to its possible application to other contexts, we suggest the proposed methodology could be used to design a "regional project" based on an increase in circularity thanks to livestock-based levers. With this end in view, coupling the methodology with existing approaches could be useful.

Concerning the identification of levers, it would be interesting to couple our proposed methodology with foresight approach (FAO, 2018b; le Mouël & Forslund, 2017). For instance, in Reunion Island, Billen (2022) combined a study of the island metabolism, similar to our level 1, with a foresight analysis to identify theoretical changes. This study included for instance, changes in the human diet, with less animal products, as part of a food autonomy strategy. Despite the risk of the inapplicability of the proposed levers, such foresights facilitate the design of disruptive scenarios that require powerful decisions and have major policy implications. In addition, foresight analysis makes it possible to investigate paradigm changes that cannot be identified at a smaller scale.

Concerning the environmental assessment of scenarios, many approaches are available to assess environmental impacts at regional scale (Loiseau et al., 2012). Among them, it would useful to combine the metabolism approach with a life cycle assessment (LCA) of the food system. LCA is a method that assesses the environmental impacts of a system throughout its life cycle by accounting for and evaluating resource consumption and emissions from the cradle (production of the inputs) to the products' end-of-life (collection/sorting, reuse, recycling, waste disposal). LCA combined with the metabolism approach would enable the complete assessment of a regional project, and would provide larger environmental indicators than nutrient or energy balances, such as eutrophication, biodiversity loss and both direct and indirect contributions to climate change.

To give an example, the carbon footprint of the agricultural sector in Reunion Island was assessed (Poulet, 2021) and the results showed an emission of 13,2 tCO2eq per hectare of agricultural land and 0.65 tCO2eq per inhabitant. "Off-island" emissions, including indirect emissions during the production and transport of imported agricultural inputs like feed concentrate and mineral fertilisers represented 42% of the total emissions, whereas only 58% of the emissions occurred on the island itself (Figure 29).

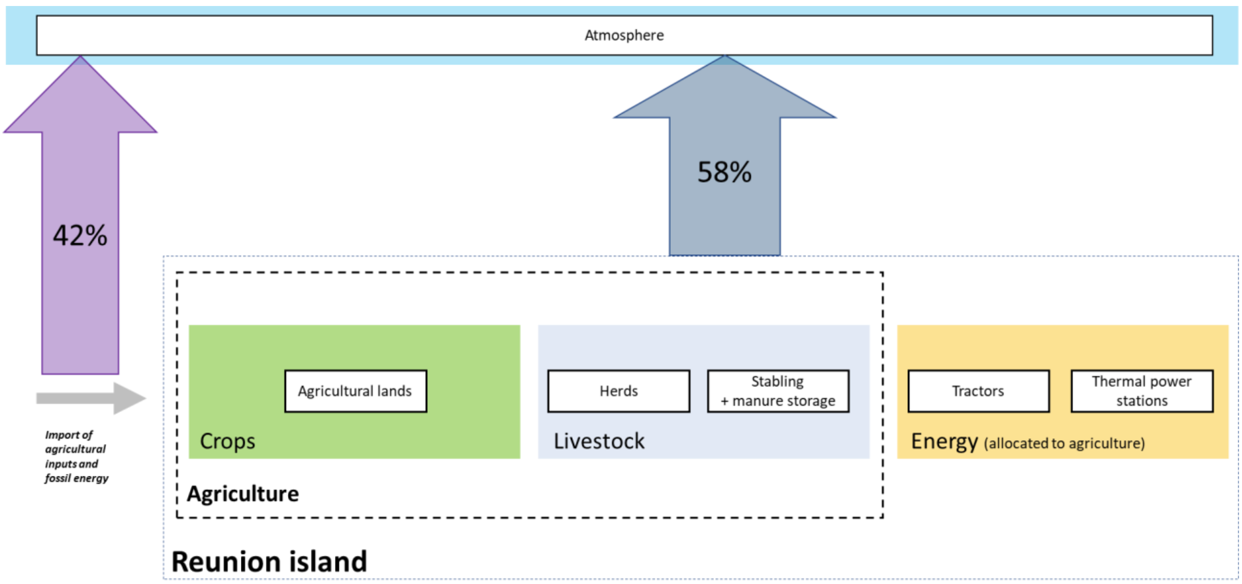


Figure 29: Agricultural carbon footprint in Reunion Island (Kleinpeter, 2022, adapted from Poulet, 2021)

Among emissions, the livestock sector is responsible for 74% of agricultural GHG emissions from Reunion Island (including methane from enteric fermentation and nitrous oxide from manure management). These results suggest that livestock-based levers in Reunion Island could reduce GHG emissions at both livestock sector and food system levels. In addition, the detailed nutrient metabolism characterised in level 2 should facilitate the full assessment of the contribution of the different components of the food system to its carbon footprint (including the livestock, crops, agro-industry, and energy sectors). It would also facilitate a significant LCA of the different circularity levers individually and combined to determine if livestock based circularity can really contribute to climate change mitigation.

V. CONCLUSION

Today tropical islands are on the frontline of climate change and face many challenges to improve their food security. Circular food systems are required to increase island self-sufficiency and to limit the environmental impacts of their food systems. Livestock have a crucial role to play in circular food systems by valorising co-products, waste and rangeland resources and converting them into valuable food and organic fertilisers.

In this context, this report provides local stakeholders, including technical staff, teachers or researchers, with a methodological framework to identify, promote and implement livestock-based levers to increase food system circularity in tropical islands.

The report is based on expertise acquired in research undertaken in both Reunion Island and Madagascar. It highlights the usefulness of energy and nutrient metabolism approaches, from proto to detailed metabolisms, to identify livestock-based circularity levers. This approach makes it possible to account for livestock interactions with other economic sectors like crops, agro-industry, waste management and the energy sectors. Our two case studies also underline the importance of involving a wide range of stakeholders in the design of circular food systems (from farmers to policy makers, and including private companies, local and regional authorities) to propose a shared and realistic regional project.

Applying the proposed framework to other territories would be useful to evaluate its transferability, i.e. its ability to account for the diversity of livestock systems and soil-climate and socio-economic contexts encountered in tropical islands around the world. The different webinars organised around the methodological framework enabled us to build a first small community of research and development organisations involved in different insular contexts (Appendixes 1 to 3). The webinars led to a proposal to include 5 potential additional case studies in the Atlantic and Pacific Oceans (Boxes 1 to 5). In the future, this community could be enlarged through the GRA Circular Food Systems Network (https://www.wur.nl/en/research-results/research-institutes/livestock-research/show-wlr/circular-food-systems-network.htm) and other networks, for example, the Metabolism of Islands network (https://metabolismofislands.org/).

APPENDIX

Appendix 1: Webinar 1 - Methodological discussion (February 23rd, 2022)

Given name / Family name	Institute / Organisation
Philippe **Lescoat**	AgroParisTech
Sophie **Madelrieux**	INRAE
Gilles **Billen**	Sorbonne Université
Myriam **Grillot**	INRAE
Bernard **Bonnet**	Association Oasis Réunion
Sabrina **Dermine-Brullot**	Université de Technologie de Troyes (UTT)
Nicolas **Bijon**	CIRAD
Thomas **Puech**	INRAE
Sandrine **Allain**	INRAE
Souhil **Harchaoui**	INRAE
Audrey **Tanguy**	Mines Saint-Etienne
Jean-Romain Bautista **Angeli**	INRAE
Jean-Philippe **Steyer**	INRAE
Amélie **Gonçalves**	INRAE
Marie **Rosse**	INRAE
Aristide **Athanassiadis**	Ecole Polytechnique Fédérale de Lausanne (EPFL)
Zoé **Legeai**	INRAE
Jean-Philippe **Choisis**	INRAE
Julie **Fleuet**	Université de Technologie de Troyes (UTT)
Killian **Chary**	Wageningen University (WUR)
Nouraya **Akkal-Corfini**	INRAE
René **Poccard**	CIRAD
Amandine **Galibert**	INRAE
Thomas **Starck**	Polytechnique
Eliel **Gonzalez**	INRAE

Appendix 2: Webinar 2- Applicability in other tropical Islands – Atlantic Ocean (March 7th, 2022)

Given name / Family name	Institute / Organisation	Case study
Audrey **Fanchone**	INRAE	Guadeloupe
Amber **Van Veghel**	University of Aruba	Aruba and Curaçao
Simron J. **Singh**	Waterloo University, Canada	Metabolism of island & Island Industrial Ecology
Shula **Rahman**	Waterloo University Canada	Barbados, Dominica, Grenada and Jamaica
Florian **Halter**	University of Augsburg	-
John **Telesford**	-	Grenada
Adolfo **Avarez Aranguiz**	Wageningen University (WUR)	-
Flavia **Casu**	Wageningen University (WUR)	-

Appendix 3: Webinar 3 - Applicability in other tropical Island – Pacific Ocean (March 8th, 2022)

Given name Family name	Institute / Organisation	Case study
Pablo **Corral-Broto**	Reunion University	Reunion Island
Clement **Gandet**	SPS – The Pacific Community	New Caledonia, French Polynesia, partnership with Fiji and Vanuatu
Vincent **Galibert**	Chambre d'agriculture NC	New Caledonia
Sripad **Sosale**	SPS – The Pacific Community	Pacific
Elenoa **Salele**	SPS – The Pacific Community	Fiji - Pacific
Joanne	Ministry for Primary Industries (MPI) & GRA	New Zealand
Benjamin **Micoulaud**	Ministry for Primary Industries	New Zealand

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