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# Circular Food Systems around the world: exploring concepts, ideas and opportunities

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This research was carried out by Wageningen Livestock Research and subsidised by the Dutch Ministry of Agriculture, Nature and Food Quality, within the framework of the Global Research Alliance on agricultural greenhouse gases (project number BO-44-00-003-749).

Wageningen Livestock Research

Wageningen, September 2023

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Bonilla Cedrez C., Andeweg K., Casu F.A.M, 2023. *Circular Food Systems around the world: exploring concepts, ideas and opportunities*; Wageningen Livestock Research, Public Report.

This report can be downloaded for free at <https://doi.org/10.18174/638397> or at [www.wur.nl/livestock-research](http://www.wur.nl/livestock-research) (under Wageningen Livestock Research publications).



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Public Wageningen Livestock Research Report

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- 2 What are the most appropriate treatment techniques that promote efficient utilisation of crop residues as fodder in smallholder farming systems?
- 3 What low-cost but durable alternative bio-digesters could be used by smallholder farmers?
- 4 To what extent can improved circularity contribute to reducing greenhouse gas emissions?
- 5 What methods are suited for GHG emissions assessment in such crop-livestock integrated systems?
- 6 What are the best capacity-building approaches for farmers in implementing innovations (e.g. fodder preservation and use, manure management, water harvesting, post-harvest handling) that promote circularity?
- 7 What are the best capacity-building approaches for local implementing partners on developing programs that encourage circularity, data collection, and assessment of greenhouse gas emissions from farming systems?
- 8 What is the role of policymakers and key value chain players in creating an enabling environment for promoting circularity in the food system?

## 2.2 Multiple on-going industrial symbiosis initiatives for a transition to a circular agri-food system on a tropical insular territory

*By Vivien Kleinpeter, Jonathan Vayssières, Pascal Degenne, Jean-Philippe Choisis, Tom Wassenaar, Danny Lo Seen, Mathieu Vigne*

### Introduction

Réunion is a French insular territory situated in the Indian Ocean. Like several tropical islands, Réunion has a high and growing human population (342 inhabitant /km<sup>2</sup>, +0.5% per year) that fuels two conflicting dynamics: an increasing need in food and a decreasing availability in agricultural land due to urban sprawl. Pushed by resource and land limitations, Réunion chose to both import human food and set up high-input agricultural production systems that rely on imports of mineral fertilisers and raw materials for animal feed. The food system relies mostly on the imports of about 430 000 tons fresh matter (tFM) of human food, including 70 000 tFM of drinks (French customs, 2019). The local agricultural area (41 940 ha) is mostly export-oriented: 54% is sugarcane, intended for the export of sugar, 29% is grassland (grazing and production of hay and wrapped hay), intended for the local livestock production systems and 13% is fruit and vegetable, mainly intended for the local market (Table 1). The local agricultural production itself relies heavily on imports: about 30 000 tFM of mineral fertiliser and 200 000 tFM of cereals and soybean meal to produce animal concentrate feeds (French customs, 2019). No mineral fertiliser production or extraction are performed in the territory, the use of local agricultural inputs only consists of the use of biomass. The local production covers the demand and consumption at 40 % for meat and 70% for fruits and vegetables (Table 2.2.1). Réunion being a European ultra-peripheral region, and a large part of the imports coming from continental Europe, long transportation distances are required (9 000 km by air, 14 000 km by sea).

This globalised agri-food system (AFS) has numerous negative externalities such as nutrient surpluses, resources depletion and greenhouse gas (GHG) emissions. A transition to a circular AFS can potentially increase the island autonomy, partially mitigate these negative externalities and foster local economy. Biomass-based circular economy (CE) is particularly relevant for tropical volcanic islands, like Réunion, endowed with rich soils and higher crop yields.

### Research question and methodology

We studied the opportunities associated with local biomasses used as agricultural inputs to increase circularity within the Réunion AFS and make the agricultural sector less dependent on imports. We also include in our study the local biomasses (by-products and wastes) potentially usable as agricultural inputs, although currently used by other sectors or eliminated (landfill or discharge to the sea). We put a focus on technical and logistical levers, e.g. those involving the technical and economical stakeholders holding the biomasses, as well as on material flows between local stakeholders at inter-firm level, i.e. on industrial symbiosis (Chertow, 2000) within the industrial metabolism (Ayres, 1989a, 1989b; Wassenaar, 2015).

The methodology used coupled a material flow analysis (MFA) (Kleinpeter et al., 2019) with a multi-stakeholder participatory approach (Vigne et al., 2021). The participatory approach consisted of an inventory of on-going industrial symbiosis initiatives, and for some of the latter a support for solving technical and logistical issues was provided using spatially-explicit modelling. The supported initiatives were chosen depending on the quantity of biomasses at stake, the potential benefits for farmers and the pertinence of the use of territory-level modelling.

## **Results of the MFA**

Results of the MFA show that 585 000 tons dry matter (tDM) of biomass used or usable as agricultural inputs are produced in Réunion (figure 1). Except for grassland productions, all biomass is by-products and waste. The agro-industry sector is predominant, representing 58% of the production, followed by the agricultural (29%), urban (12,5%) and forestry (0,5%) sectors. Of these 585 000 tDM produced, only 325 000 tDM are used in agriculture (83 %) or urban sectors (4%), or eliminated (13%) (figure 2.2.2). The rest, which corresponds to 44% of the local biomass production used or usable as agricultural inputs, is lost (i.e. 260 000 tDM). These losses correspond mostly to important atmospheric nitrogen and carbon emissions due to intermediary processes like biomass combustion, anaerobic digestion or composting. 88% of the emissions consist in the combustion of bagasse to produce electricity, from which the ashes are then used as fertiliser on agricultural soils. Intermediary processes include economic activities such as the business of recycling waste material into soil input and/or animal bedding.

The biomass is used by the agricultural sector as animal feed, animal bedding, fertiliser, amendment, soilless substrate, mulch and substrate to levelled land. Inter-firm biomass flows include the transfers between farms.

In Réunion the transfer of biomasses within the agricultural sector is usually not restricted to on-farm level. While production systems are highly specialised, large flows are observed between farms such as for instance cane straws for feeding and bedding herds or off-farm manure spreading.

This MFA leads us to identify three main levers to increase circularity at territorial level: i) A large part of eliminated materials could be used in agriculture, e.g. urban biowaste as fertiliser, food industry waste as animal feed; ii) Atmospheric emissions could be reduced to increase nutrient conservation and carbon sequestration; iii) The efficiency of agricultural processes at both plot and herd levels could be increased by better matching available inputs (fertilisers and feeds) with plant and animal needs.

## **Results of the participatory approach**

Results of the participatory approach show that the main stakeholders of the AFS in Réunion (farmers, cooperatives, industrials, energy producers, public and private waste management organisations and policy makers) are already involved in the transition to a CE. About twenty on-going industrial symbiosis initiatives were identified. All are expected to lead to a reduction in imports and an increase in the recycling of biomasses within Réunion. Four are in the design phase and were studied to co-build scenarios with the technical and economical stakeholders involved in order to choose the most realistic ones. Among the four, two were designed at the scale of the island and two on sub-territories. Three originated from difficulties in resource or waste management. The fourth originated from a changing legislation declaring mandatory the recycling of biowastes that are today deposited in landfills. They are thus mostly pushed by the need for solutions to technical and economic problems. The environmental benefits, such as climate change mitigation, are however also drivers in this transition, as funding institutions do take them into account when orienting funds to projects. In Réunion, reducing GHG emissions is especially relevant for the stakeholders, being themselves in a tropical area and thus particularly vulnerable to climate change (Mendelsohn et al., 2012).

## **Description of four industrial symbiosis initiatives**

The first initiative, led by the Réunion Pastoralism Association, is to implement collective fodder storage units (Lorré et al., 2020). Fodder is produced in Réunion within a large diversity of pedo-climatic zones and there is a spatial heterogeneity between production and consumption zones. The current problem is a fodder deficit during the dry season. More (imported) concentrates are then used and/or sometimes hay is imported during the driest years. However, grass is still available on grassland during the wet season but some are not cut due to the lack of anticipation and storage capacity. According to experts, a

part of the cane straw left today in the field could also well be extracted from the field without affecting yield. Spatially-explicit modelling showed that the surplus fodder could be collected and stored during the wet season, to make up for the fodder deficit during the dry season. The resulting import reduction of feed concentrates would be an economic benefit for the livestock farmers.

The second initiative, led by the Regional Chamber of Agriculture, is to spatially rearrange manure spreading plans (Jarry, 2019). Since about 2000, most livestock farmers (depending on the herd size) have had to set up a spatial manure spreading plan for each of their herds. Nitrogen and phosphorus thresholds per area spread are for example determined according to crop needs in order to avoid nutrient leaching. Spreading plans were set up over time by looking for plots that were not already in any spreading plan. New spreadable plots are needed when: i) new herds are being set up, ii) farmers are willing to increase their herd headcount and iii) plots of spreading plans are being taken by urbanisation. The current problem is the difficulty for those farmers to find agricultural areas to spread manure close enough to reduce travel costs. Nearby plots are indeed often already in a spreading plan. However: i) some spreading plans were first defined with a supply of nutrients under the threshold, ii) some plots are not spread with manure anymore, or less than defined originally (e.g. the herd headcount has been reduced) and iii) some nearby plots are today spread by remote livestock farmers when they themselves have spreadable plots close to their stabling. Spatially-explicit modelling showed that spreadable areas at short enough distances could be used by livestock farmers. It also shows that the spreading today is unbalanced as farmers sometimes avoid the remote plots and over-fertilise the nearby ones. The economic benefits for the farmers are the reduced transportation costs and the savings due to less imported mineral fertiliser.

The third initiative, led by ILEVA, a public structure in charge of the treatment of urban waste, consist in establishing co-composting platforms that mix urban green wastes with manure to produce an organic fertiliser (Darras, 2019). Today, the structure treats urban green waste on several platforms by making shredded green waste. This is then sold as amendment, mostly to farmers but also to private individuals for their garden and the municipality for its urban green space. The current problem is that the product is not attractive. To clear the stocks when the storage capacities are full, the platforms often need to give them away for free. They also sometimes ask farmers to spread on any lands even when agronomic needs are already satisfied. After cyclones especially, the storage capacities are quickly reached. With low or null prices, the product can also be used for land levelling instead of as amendment to feed the soil and the plants. Co-composting the shredded urban green wastes with manure brings added value and matches the needs of vegetable farms for organic fertiliser. It also matches the need of livestock farmers as no spreading plan is required when the manure used is composted and marketed. It also frees up spreadable plots for other farmers as non-composted manure is not allowed on vegetable plots during the vegetative phase (for sanitary reasons). Spatially-explicit modelling showed that the decision-making rules of the public structure, the livestock farmers and the vegetable farmers are compatible with the production of co-compost. Economic benefits for the livestock farmers are a cost and time saving due to less distance travelled when the co-composting platform are closer than their spreadable plots. Composting of manure also means less quantity transported. Economic benefits for vegetable farmers are the availability of local organic fertiliser instead of expensive imported ones.

The fourth initiative, led by the Regional Council of Réunion (in charge of the elaboration of the Regional Waste Prevention and Management Plan), is to set up a door-to-door separate collection of organic wastes from households, collective restaurants, retailers and food industries, and to transform the wastes into fertiliser to be used in agricultural fields (Hatik et al., 2020). Today most of them are collected mixed with other non-organic wastes and deposited in landfills. This does not include the organic wastes already collected separately such as urban green waste and paper. The most ambitious process considered for obtaining a product adapted for use as fertiliser is anaerobic digestion (also producing biogas). In particular, it anticipates the necessity to organise the collection and reuse of such organic waste which will become legally mandatory by 2025. Spatially-explicit modelling was used to show possible scenarios that involve composting, shredding and anaerobic digestion plants. Benefits for farmers are the increased availability of locally produced organic fertiliser.

### **Does recycling biomass mean increasing circularity?**

With these four initiatives, an increase in circularity is expected in terms of material flow. The initiatives plan to use more locally available un-used material and an increase in the material recycle rate (recycle

material/ total wastes) can be expected. However, other results could be found when looking at the nutrient flows due to new processes in the system that could globally lead to more nutrient losses. For example, an uncertainty is to be considered for the third initiative where the composting process is a source of nitrogen emissions to the atmosphere (Ba et al., 2020). Also, these four independently designed initiatives might in reality interfere and the expected recycling could in reality take place only partially. For example, the manure-green waste compost may compete in the same market segment as the digested food waste based fertiliser.

### **Does increasing circularity reduce GHG emissions?**

In order to evaluate the real potential benefits on climate change mitigation, a territorial carbon balance, including C storage and both direct and indirect emissions, e.g. using a "territorial life cycle analysis (LCA)" approach (Loiseau et al., 2018), is needed. For instance, all four on-going initiatives could decrease or increase GES emissions, depending of the emission segment.

On one hand, the reduction in imports of feed (initiative 1), fertiliser and amendment (initiatives 2, 3 and 4) means a reduction in indirect GHG emission due to their transport and fabrication. The reduction in local distance travelled (initiatives 2 and potentially 3) means less direct CO<sub>2</sub> emissions due to transport. The reduction in the spreading of fertilisers (initiative 2) means less direct N<sub>2</sub>O and NH<sub>3</sub> emissions (and then secondary N<sub>2</sub>O emission). The production of energy (initiative 4) means less indirect GHG emissions due to the production and imports of fossil fuel (Table 1) and less direct emissions due to combustion. The use of compost instead of minerals (initiatives 3 and 4) also means less post-application GHG emission (Walling and Vaneekhaute, 2020). The use of biowastes (initiative 4) means less GHG emission on landfill sites (Bogner et al., 2008). The use of more organic amendment (initiatives 3 and 4) means more carbon storage (Edouard Rambaut et al., 2021).

However, on the other hand, the potential increase of local distance travelled (initiatives 1 and 4) means more direct CO<sub>2</sub> emissions due to transport. The increase of the forage-to-concentrate ratio in the diet (initiative 1) could increase the CH<sub>4</sub> emission from enteric fermentation (Aguerre et al., 2011). The composting process (initiative 3) means more GHG emission during the pre-application (Ba et al., 2020).

### **Conclusion and perspectives**

In conclusion, the agricultural sector in Réunion already participates in the AFS circularity from a material point of view (i.e. the recycling of wastes and the reduction of imports). The trend of the carbon balance is more uncertain as the desired modifications of the system could, depending on the emission segment, either increase or decrease GHG emissions.

The research is now continuing on three fronts: i) A nutrient flow analysis and an ecological network analysis of the whole island economy will be performed to assess the efficiency and the integration of the different sectors, including agriculture; ii) An integrated spatially explicit simulation model of the island AFS is under-development, using the Ocelet modelling platform ([www.ocelet.fr](http://www.ocelet.fr)). The four initiatives in the design phase will be simulated. A multi-criteria analysis of the potential benefits will be performed, including both circularity indicators and the carbon balance of the modelled system. We found it necessary to use a spatially-explicit model. It allows to calculate distance travelled by materials using the road network in order to: a) implement in the decision making the distance between the suppliers and the receivers; b) quantify the local GHG emissions due to local transport; iii) The coexistence of the four initiatives over time will be simulated to consider potential interactions (positive or negative) between them. Indeed, the four initiatives were designed separately but some are willing to change the same material destination and/or are willing to create new products with the same use. The expected effects (technico-economic benefits, circularity and carbon balance) could thus be different for each initiative if other initiatives are put in place at the same time. Also, the sum of the expected effects of the individual initiatives considered separately could be different from the overall effect of simultaneously putting in place the initiatives due to possible interferences. So an integrated, multi-criteria, territory level, and simulation based assessment of the multiple on-going initiatives is needed.

Table 2.2.1. Main characteristics of Réunion island

variable		unit	value
population <sup>1</sup>		inhabitants	860 000
area		km <sup>2</sup>	2 500
population density		inhabitant /km <sup>2</sup>	342
land cover <sup>2</sup>	forest and natural area	%	71
	agricultural area		19
	artificialized area		10
agricultural area <sup>2</sup>		ha	41 940
agricultural area per crop <sup>2</sup>	sugar cane	ha (% among total)	22 700 (54)
	grassland		12 237 (29)
	fruits and vegetables		5 402 (13)
	other (fallow, non-food, cereal, oleaginous)		1 601 (4)
agricultural area per inhabitant <sup>2</sup>		m <sup>2</sup>	557
number of farms <sup>2</sup>		unit	6 800
number of farms with livestock <sup>3</sup>		unit	3 750
average area per farmer <sup>2</sup>		ha	6,2
livestock population <sup>2</sup>	bovine	heads	29 289
	porcine		68 977
	caprine		11 921
	ovine		3 454
	poultry		3 647 000
local food production <sup>2</sup>	vegetables	tons row matter (% intended for the local market)	52 800 (100)
	fruits		35 100 (90)
	meat (carcass equivalent)		32 475 (100)
	milk		18 437 (100)
food self-sufficiency <sup>2</sup>	meat	% of local demand and consumption	40
	fruits and vegetables		70
	cereals		0
electricity production <sup>4</sup>	imported coal / used oils	GWh (% of the total)	1 090 (36)
	imported fuel oil / diesel fuel		1 007 (33)
	hydraulic		418 (14)
	photovoltaic / wind power/ biogas		287 (9)
	local bagasse		240 (8)
	local bioethanol		7 (0)

Sources: INSEE 2020, DAAF La Réunion 2020, DAAF La Réunion 2010, Horizon Réunion 2019.

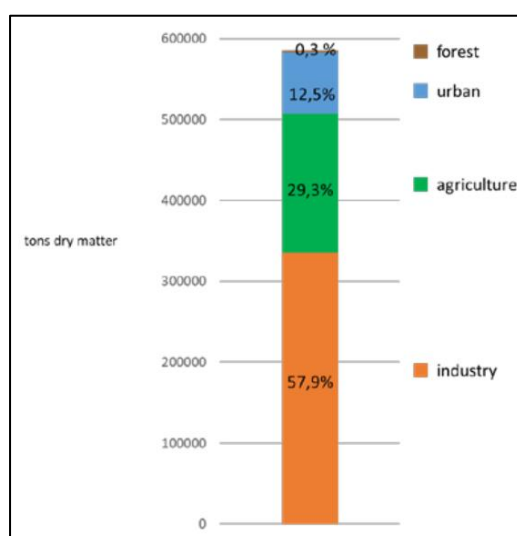


Figure 2.2.1: tons dry matter of local biomass used or usable as agricultural inputs produced in Réunion.



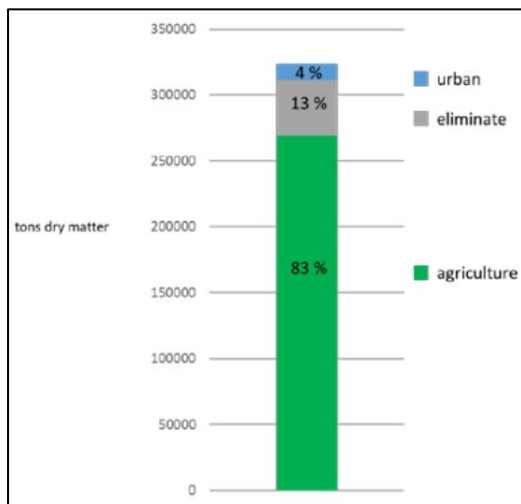


Figure 2.2.2: tons dry matter of local biomass used or usable as agricultural inputs in Réunion according to the destination: agriculture (soils, feed, animal bedding), urban (soils, feed) or eliminated (landfill or discharge to the sea)

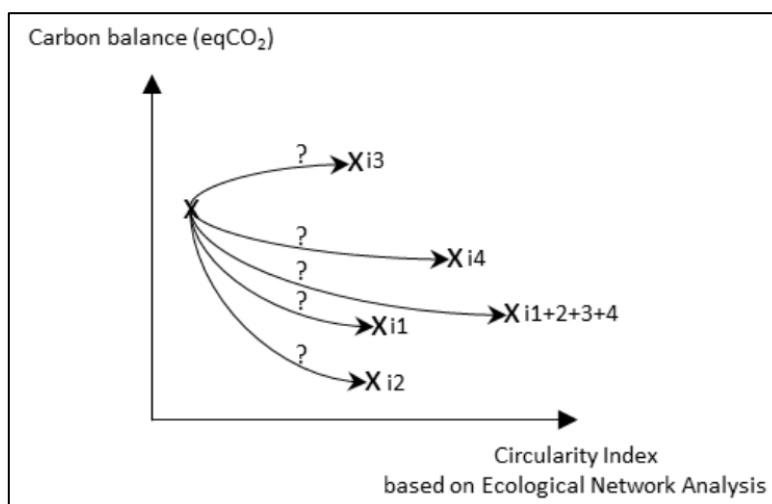


Figure 2.2.3: Hypothesis on consequences of the four industrial symbiosis initiatives individually ( $i1$  to  $i4$ ) and combined ( $i1+2+3+4$ ) on circularity and the Carbone balance of the modelised system among the AFS agri-food system.

## 2.3 Achieving carbon neutral and resilient Mediterranean agro-food systems through the circular management of organic resources

By Ngonidzashe Chirinda, Mohamed Louay Metougui, Amine Ezzariai, Mohamed Hafidi, Naoufal Mahdar, Youssef Berriaj, Alberto Sanz Cobeña, Shamie Zingore, Hichem Ben Salem, Hazelle Tomlin, Richard Eckard

### Description of the Mediterranean food system

A food system includes all the elements and activities linked to production, processing, distribution, preparation, and food consumption (HLPE, 2014). The traditional Mediterranean food systems in Southern Europe and North Africa are based on local agricultural products and emphasise the connections between biodiversity, local food production, culture and sustainability. Nevertheless, despite the traditional Mediterranean food systems having deep socio-cultural roots, increased globalisation and dramatic changes in regional food production systems and supply chains increasingly disrupt it with dire consequences on local production and more impoverished rural communities (González de Molina *et al.*, 2020). On the other hand, recurrent droughts, resource depletion, increased health consciousness and

rising inequalities necessitate a return to less intensive (in terms of resource use) and locally-based production systems. Moreover, the traditional Mediterranean diet is presently gaining increased attention due to its health benefits and the Mediterranean culture and traditions (Saulle and La Torre, 2010; Springmann *et al.*, 2018). From an environmental perspective, Saez-Almendros *et al.* (2013) estimated that a return to a traditional Mediterranean diet would result in a >70% decrease in the agro-food system-based greenhouse gas (GHG). Despite local variations, the traditional Mediterranean diet is frugal and plant-based, with daily consumption of vegetables, fruits, legumes, nuts, whole grains, and unsaturated fats' food such as olive oil; a low (weekly) consumption of eggs and dairy products (mainly cheese); moderate but variable consumption of fish (depending on the local distance from the sea), and a low level of meat consumption (Trichopoulou *et al.*, 2014). Most of the Mediterranean fruits and vegetables were traditionally consumed fresh and, in some cases, preserved by natural preservation means. However, since the last quarter of the 20<sup>th</sup> century, fruits and vegetables have been subjected to highly mechanised processing to produce juices, sauces, and other products.

### **Problem statement**

In the previous decades, the agricultural industry has become the main driver for urbanisation, economic development, and fast growth. In the Mediterranean region, the human population went from 281 million in 1970 to 472 million in 2010. It is currently estimated that from the ~500 million persons living in the region, more than 60% are living in the burgeoning cities. Currently, urban population growth is based on a linear food system supplying the necessary calories, albeit with enormous costs to human health and the environment. Population growth and higher incomes increase the flow of food from rural to urban areas. However, poor synchrony between food supply and demand and agro-processing creates massive amounts of organic waste in unconsumed or spoiled food or unused agro-processing by-products. For example, in Spain, France and Italy, more than 7.6 million, 9 million and 8.8 million tonnes of food are wasted each year (Charalampopoulou *et al.*, 2014; Capone *et al.*, 2016). In North African countries, an estimated 32% of the food is wasted, mostly in urban centers, with significant amounts of food wasted during social events and festivities (FAO, 2014). In the Mediterranean region, food waste is disposed of on dumpsites or landfill, where they present several challenges, including high landfill maintenance costs and greenhouse gas emissions of 4.4 Gt CO<sub>2</sub>-eq per annum (Capone *et al.*, 2020) and health risks. However, since only a small fraction of the produced waste is currently valorised, there are considerable opportunities to valorise waste and increase circularity leading to sustainable use of nutrients, energy and matter. The Mediterranean area is also vulnerable to climate change due to recurrent and extended drought periods, water resource depletion, emerging plant and animal diseases and biodiversity loss.

### **Opportunities to increase circularity in the Mediterranean food system**

The Mediterranean Circular Food Systems (Med-CiFoS) network will focus on increasing the visibility of organic waste production, the related management options and promoting environmental biorefinery and circular management of the agro-food component of Municipal Solid Waste (MSW). The network's goal is to explore opportunities for decreasing the amount of organic material deposited at dumpsites and landfills and increase the share of recycled by investing in the valorisation of organic waste. Reducing losses of carbon and nutrients in MSW and increasing their cycling in food systems is one of the critical imperative investments for building a sustainable food system at multiple levels and creating positive economic, social and environmental benefits. A possible way forward is to accelerate and scale circular economy strategies. The first step towards achieving this goal will be to map organic waste sources, drivers and attitudes responsible for organic waste generation in at least eight cities in Mediterranean countries. A combination of desktop studies, surveys and stakeholder workshops will be used. The resultant in-depth understanding of local production-consumption-waste management patterns will facilitate the exploration of benefits of circular management on local food security and determine carbon (C), nitrogen (N) and phosphorus (P) flows from agricultural lands to cities and potential flows from the selected cities to local farms. Focusing on local systems will enable us to identify the potential of various types of organic waste to produce bioenergy, livestock feeds and biofertilisers and also unlock opportunities for sustainable growth. A detailed assessment of components (crop, livestock, household) and overall system-level C, N and P balances at various spatial scales will be conducted to assess the critical intervention points that offer the highest prospects for reducing losses and enhancing the cycling of C and nutrients. Furthermore, the potential for recycling MSW to reduce the leakage of nutrients in the local food systems will be addressed using four key steps (i) estimating the quantity of

MSW of potential agronomic value; (ii) determining the nutrient value for replacing external nutrient sources; (iii) assessment of potential undesirable quality traits for crop nutrition and animal feed, including biochemical (e.g. secondary compounds, fungi, mycotoxins) and heavy metal contaminants and (iv) developing guidelines for integrated agricultural management practices that prioritise the use of local recycled waste products and optimised supplementary use of external resources. Organic waste treatment options will depend on the local context, the type of available organic waste and the local demand for different waste treatment by-products in the different regions.

### **Effects of improved circularity on mitigating greenhouse gas emissions.**

Disposal of organic waste in landfills is an essential source of GHG emissions in the Mediterranean region. For example, a study conducted in Italy suggested that 14.3 million tonnes of CO<sub>2</sub> equivalent were related to food waste in 2012 (WWF-Italy 2013). The IPCC (2019) gives the regional defaults of municipal solid waste that originates from food as 36% and 50% in the Southern Europe and North Africa region, correspondingly. The fraction of municipal solid waste disposed of in open dumpsites is 79% in North Africa (IPCC, 2019). According to the IPCC (2019), almost none of the MSW generated in Southern Europe is disposed of in open dumpsites. On the other hand, 17% and 76% of MSW generated in North Africa and Southern Europe are correspondingly disposed of in landfills (IPCC, 2019). However, since those data are based on limited studies, they are associated with high uncertainties. These uncertainties influence the estimations of current emissions and an accurate assessment of the mitigation potentials of circular management of organic waste. Nonetheless, based on current understanding of GHG science, avoiding disposal of organic waste on open dumps and landfills results in the avoidance of GHG emissions, and the circular management of organic resources reduces fertiliser requirements and, consequently, GHG emissions associated with fertiliser production, which vary based on the production technology, feedstock and energy sources. For example, emission factors for urea production (1.3 to 5.5 kg CO<sub>2</sub>-eq./ kg of N) are lower than those for ammonium nitrate production (3.5 to 10.3 kg CO<sub>2</sub>-eq./kg of N) due to higher N<sub>2</sub>O emissions from nitric acid production during the production of ammonium nitrate (Brentrup *et al.*, 2004; Walling and Vaneeckhaute, 2020).

Though studies are limited, a French report (ADEME, 2012) showed that GHG emissions from the composting of MSW vary widely (0-106 kg CO<sub>2</sub>-eq./tonne of waste) based on the feedstock and the various parameters influencing microbial processes. In a recent study on food waste emissions, Jeong *et al.* (2019) reported CH<sub>4</sub> and N<sub>2</sub>O emission factors of 0.17–0.19 g-CH<sub>4</sub> kg-waste<sup>-1</sup> and 0.10–0.13 g-N<sub>2</sub>O kg-waste<sup>-1</sup> for the composting process. In the same study (Jeong *et al.*, 2019), for anaerobic digestion, emission factors for CH<sub>4</sub> and N<sub>2</sub>O were reported to be 1.03 g-CH<sub>4</sub> kg-waste<sup>-1</sup> and 0.53 g-N<sub>2</sub>O kg-waste<sup>-1</sup>, respectively. The by-products of controlled aerobic or anaerobic treatments are also valuable soil amendments that increase C storage and provide nutrients to supplement crop growth. Other waste treatment processes that support circular food systems, such as feeding waste to insects and feeding insects to livestock, are expected to have lower GHG emissions than conventional livestock production systems (Oonincx *et al.*, 2010).

Increasing circularity would reduce waste transportation to landfills typically done using heavy vehicles, representing a source of GHG emissions. Also, within landfill sites, additional GHG emissions result from waste movement and the use of bulldozers and compactors to manage waste heaps. At dumpsites, the open burning of organic waste results in different greenhouse gas emissions, including CO<sub>2</sub>, N<sub>2</sub>O and CH<sub>4</sub>. The appropriate use of food wastes in livestock feeding could also contribute to the decrease of GHG emissions. The emission reductions could be achieved through balanced diets containing food wastes, mixing with tannin or saponin-containing feed sources or additives. Therefore, unambiguously, innovative recycling of organic waste resources will support low-carbon development.

### **Other socio-economic-environmental benefits of circular food systems**

Circular food systems can lead to waste minimisation, increased economic benefits, reduced price volatility, increased revenue streams and employment growth (Ghisellini *et al.*, 2016). Production models that replace the concept of "end of life" with circular food systems based on the reduction, alternative reuse, recycling, and recovery of materials contribute to improved livelihoods, economic growth, human health and the environment (Kirchherr *et al.*, 2018). For example, new sources of income and jobs can be created when building the processing infrastructure, improving waste collection systems, waste processing, by-product packaging, and marketing, among other activities in the organic waste value chain. In the case of tomatoes, which are an essential component of the Mediterranean diet, those that

do not meet food quality standards may be used as animal feed and feedstock for vermicomposting and other aerobic and anaerobic treatment processes (Fritsch *et al.*, 2017). This implies the creation of more value and economic activity around what is currently considered waste.

At dumpsites and landfills, organic waste creates conditions conducive to the survival and growth of microbial pathogens and may also be a food source for enteric pathogen carriers such as rodents, insects, birds and large wild mammals (Mavropoulos, 2015). In addition, biodegradable waste represents a source of odors that increase the risk of illness (i.e., nausea, headaches, drowsiness, fatigue, and respiratory problems) for communities living near landfills or dumpsites (Steinheider, 1999). Therefore, reducing the amount of organic waste will mitigate the adverse health effects on communities living near dumpsites or landfill. Circular food systems also improve mutually rewarding linkages between rural and urban communities by fostering socially innovative, efficient and sustainable food systems that increase food security, create new by-products and jobs, reduce input costs, and create new and versatile markets for both high and low-quality farm produce.

### **Key knowledge or experimentation questions**

Nitrogen (N) is both essential for food production but also the element most inefficiently recycled in agricultural systems, with >60% of the N in grazing systems and >30% N in cropping systems not recycling back into plant growth (Whitehead 1995). This N can be lost through nitrate leaching, organic matter leaching, denitrification and ammonia volatilisation, the latter two processes contributing to direct and indirect N<sub>2</sub>O emissions, respectively. These losses have been exacerbated through cheap industrial sources of N, like urea fertiliser, which also comes with a relatively high embedded carbon footprint from manufacturing. Therefore, research aimed at improving the circularity of N in agriculture has both productivity and greenhouse gas benefits, with whole-system N balances being a handy indicator of the overall efficiency of circularity. The research to be conducted through Med-CiFoS will inform strategies to reduce reliance on highly labile inputs of N through improved recycling of organic waste streams. The research will also focus on comparing nutrient balances along more linear supply chains with local food systems and exploring these systems' options for improving circularity. Based on scientific experiments aimed at identifying suitable options and key elements to treat and/or valorise various types of organic waste to obtain biofertilisers, bioenergy and livestock feed (e.g. ensiling, pelleting, solid-state fermentation, introducing mixed animal diets). Aligning with the concept of feed-food safety, Med-CiFoS will also invest in checking the nutritive value and the availability of secondary compounds and toxins like mycotoxins in food wastes that will be distributed to animals. The potential transfer of these undesirable compounds to animal products will also be assessed, and better integration of food waste in livestock feeding will be recommended. Thus, Med-CiFoS will align with the concept of feed-food safety and show how food waste could be an alternative feed source to alleviate livestock feeding costs and reduce the water footprint of livestock-based systems and animal products. This intercontinental, multi- and inter-disciplinary and multi-sectoral network will generate information and evidence on the valorisation of organic waste and support the development of circular food systems in the Mediterranean region.

## **2.4 Challenges, opportunities, and research needs to improve circularity in the Peruvian food system**

*By Alejandro Parodi, Ian Vázquez-Rowe, Kurt Ziegler-Rodriguez, Gustavo Larrea-Gallegos, Ekatherina Vázquez*

### **Main**

Peru is the third largest and the fourth most populated country in South America. Its varied geography (i.e., coastline, highlands, and tropical rainforests) has shaped the cultural diversity of Peruvians since ancient times and has led to the use and domestication of a broad variety of crop and animal species. Food and agrobiodiversity are important elements of Peruvian identity and cuisine, allowing Lima to be currently recognised as the gastronomic capital of Latin America. Peru has also been an important player in global food trade. During the 19th century, Peru was the major exporter of *guano*, a highly demanded agricultural fertiliser. Since the mid-20th it has been the main supplier of fish meal and, nowadays, has become the leading exporter of a wide range of fresh agricultural products such as green asparagus, blueberry and avocado. A large-scale and

export-oriented agricultural sector has flourished in recent decades, but still a great contrast exists with smallholder farmers, who occupy most of Peru's agricultural land, safeguard the agrobiodiversity that Peruvians feel proud of, but are in most cases poor and food insecure. The aim of this short communication is to describe the current trends and challenges in the Peruvian food system and to identify opportunities and research needs to foster the transition towards more circular food systems.

## **1. Trends and challenges in the Peruvian food system**

### **1.1 Fisheries**

In the Pacific Ocean, both industrial and small-scale Peruvian fisheries coexist in an upwelling area which sustains one of the world's largest fisheries (FAO, 2020). Most of the fish biomass caught consists of anchoveta (*Engraulis ringens*), a low-trophic level fish species, which is fished by industrial vessels, and reduced to fishmeal and oil in different processing factories along the Peruvian coast. Most fishmeal is exported as feed (Figure 1), with China being the importer of nearly 90% of Peruvian fishmeal exports (PRODUCE, 2018). Small-scale fisheries are responsible for 10% of the reported landings, but unlike industrial fisheries, most of the catches are destined for direct human consumption in the national market (Figure 2.4.1). Even though small-scale fisheries play a key role for food security and employment in the fisheries supply chain (Christensen et al., 2014), the increasing fishing effort of small vessels is unsustainable and uneconomic for most artisanal fishermen (De la Puente et al., 2020). With the aim to increase the inclusion of fish in Peruvian diets and improve the income of small-scale fisheries, the Peruvian government has been promoting the consumption of anchoveta and other fish species for direct human consumption since 2011 via the program "A comer pescado" (i.e., let's eat fish!) (PRODUCE, 2019). Nonetheless, the existence of perverse legal incentives and informal networks that encourage the use of anchoveta landings for fishmeal reduction are blocking the mainstream use of this vast resource as human food (Majluf et al., 2017).

### **1.2 On-land agriculture**

#### **1.2.1 The Coastal region**

Coastal agriculture, being close to seaports and the main urban settlements, has been characterised by being export-oriented and highly capital-intensive (Banco Mundial, 2017). The Peruvian coast is located in a warm and mainly hyper-arid region where agriculture is practiced in the valleys that cut through otherwise desert areas and in irrigated areas in which water is obtained from aquifers and recently constructed trans river basin diversion infrastructure. This region only represents 23% of Peru's agricultural land (Figure 2.4.2a & 2.4.2b), but contributes to nearly half of Peru's agricultural GDP (Banco Mundial 2017). The region produces crops for different markets, including high-value export-oriented crops (e.g., asparagus, table-grapes, mango, artichokes), industrial crops (e.g., sugar cane) and crops destined for food and feed purposes (e.g., maize, rice, sweet potato). Although highly productive, Peruvian coastal agriculture depends on an intensive use of external inputs (Bartl et al., 2012). The high application rates of (mostly imported) inorganic fertilisers have been identified as one of the main contributors to greenhouse gas (GHG) emissions of food products produced in the region (Vázquez-Rowe et al., 2016; Morales et al., 2018). This high-input agriculture occurs near to Peru's most populated urban settlements. In big cities such as Lima-Callao, where one third of the Peruvian population lives, huge amounts of food loss and waste are sent to landfills or dumped (i.e., see section 1.3) and nutrients contained in human excreta are not reutilised in the food system (Vázquez-Rowe et al., 2021).

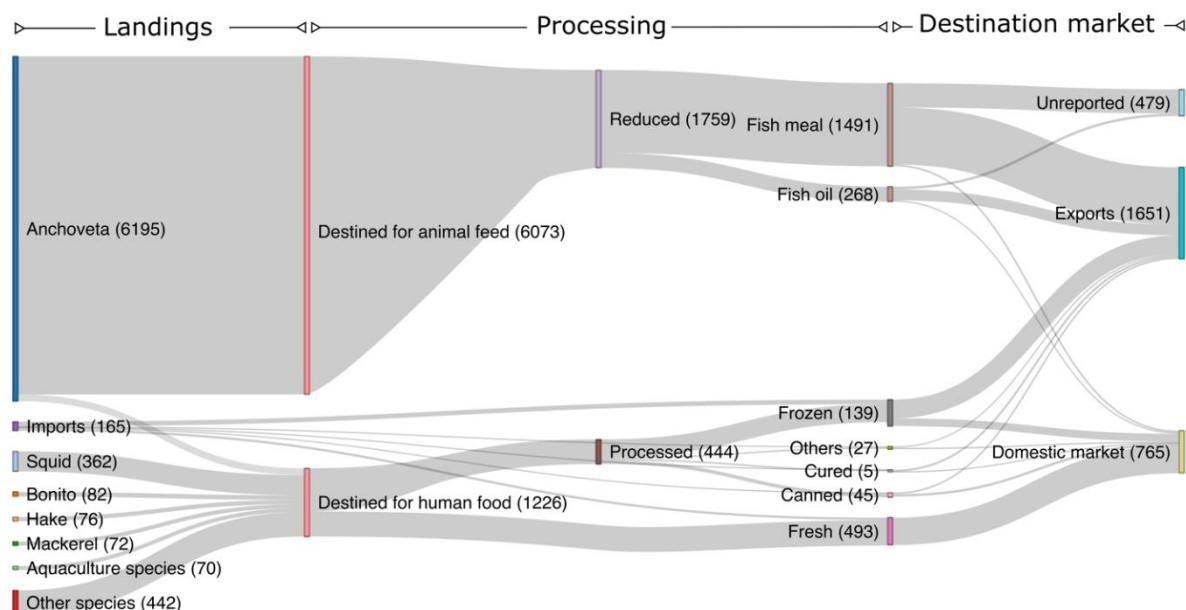
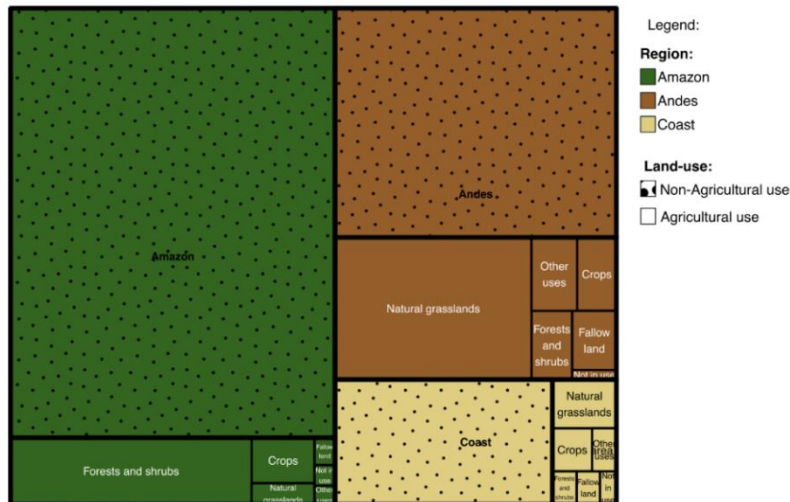


Figure 2.4.1. Biomass flows (thousands of metric tons) of the Peruvian fisheries and aquaculture sectors in 2018. Data were obtained from 2.

### 1.2.2 The Andean region

Andean agriculture is dominated by mixed crop-livestock smallholder farming in small agricultural units commonly smaller than 2.5 ha (MINAGRI, 2019). In 2012, nearly one third of the agricultural land in the Andes was destined for self-consumption (see Figure 2B). Nonetheless, Andean small-scale agriculture plays a key role for the provisioning of vegetables, fruits and animal products for Peruvian cities. Andean farmers use and maintain a vast crop genetic diversity (Torres-Guevera et al., 2017), produce foods with low use of external inputs (Bartl et al., 2011), and manage highland resources to obtain food and materials (Verzija & Quispe, 2013), but many of them live below the poverty line (Eguren & Pintado, 2015). In addition, the slow onset effects of climate change pose an extra challenge, threatening their livelihoods and future food supply (Perez et al., 2010). To reduce poverty incidence in the region, the Peruvian government has been trying to involve small-scale farmers in the production of high economic-value crops for international and national markets (i.e., *Sierra y selva exportadora* program). High transaction costs, poor infrastructure for connectivity to markets, limited water reservoirs for irrigation, and high post-harvest losses are some of the main challenges to success on this aim (Banco Mundial, 2017; Díaz-Valderrama et al., 2020; Bedoya-Perales & Dal' Magro, 2021; Escobar & Caverro, 2012). The inclusion of small-scale Andean farmers in an export-oriented economy has potential to improve livelihoods, especially when participatory approaches are used to involve farmers in the supply of crops to added-value food chains (Devaux et al., 2021). However, if their inclusion is not implemented properly, it can cause significant changes in land use patterns, farming practices, and diets (Bedoya-Perales et al., 2018a; Bedoya-Perales et al., 2018b).

A)



B)

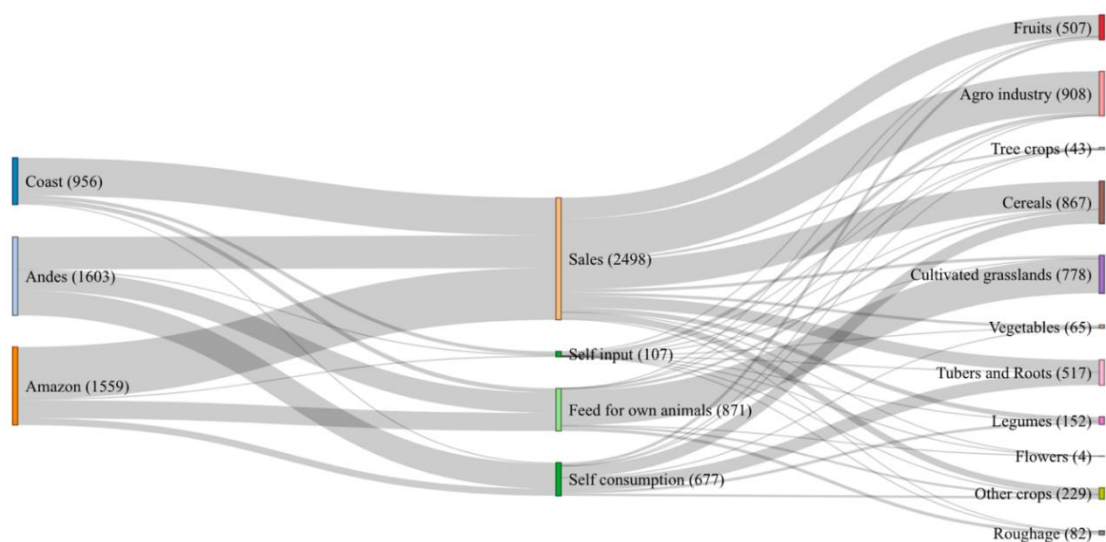


Figure 2.4.2. A). Land-use patterns in Peru by area (i.e., rectangle size), region (i.e., colour), and agricultural or non-agricultural use (i.e., background pattern). Most of the area under non-agricultural use corresponds to natural ecosystems (i.e., deserts, mountains and forests). The land use of the "crop" area of each region is shown in panel B. 2.4.2B). Use of the agricultural cropland per region, destination and type of food. All flows are based on cropland area (i.e., thousands of hectares). Data for both figures correspond to 2012 and were obtained from INEI (2012).

### 1.2.3 The Amazon region

The Amazon concentrates the highest biological diversity. Although population density is low, it is Peru's largest geographical region (Figure 2A). Despite its remoteness, most Amazonian cropland is used to produce food crops for the market rather than for local subsistence (Figure 2B). Local indigenous people have practiced for millennia a complex and long-term system of slash burn agriculture known to have influenced today's Amazonian tree communities (Levis et al., 2017; Roosevelt, 2013). However, they are commonly and sometimes unfairly blamed to be the main drivers for deforestation in the Peruvian Amazon (Ravikumar et al., 2016). Recent assessments have shown that in the past 20 years, the main deforestation drivers in the Peruvian Amazon were associated with medium and large-scale monocultures of cacao and palm, cattle ranching and illegal gold mining (Finer & Novoa, 2015; Finer & García, 2017). Recently, the Peruvian government promoted the implementation of agroforestry-based systems (Law N° 29763) as a way improve to improve the livelihoods of small-scale farmers, stimulate land restoration and halt deforestation to meet Peru's carbon reduction targets (Robiglio & Reyes, 2016). Coffee and cacao agroforestry systems have the potential to improve the livelihoods of Peruvian farmers (Pokorny et al., 2021) and ensure the provisioning of forest ecosystem services (Jezeer et al., 2019; De Leijster et

al., 2021). However, without the adoption of good agroecological practices, land tenure measures and the consideration of farmers' interest and capabilities, deforestation due to land-use expansion is a permanent threat (Pokorný et al., 2021; Hotz & Guarín, 2014; Boeckx et al., 2020).

### 1.3 Solid waste management

Peru has a rudimentary waste management sector, mostly dominated by illegal open dumping. However, landfilling of all types of waste, including household organic waste and even agricultural residues, is recently overtaking open dumpsters as the main final disposition route throughout the country. Even though landfilling has the potential to alleviate some of the environmental and social impacts associated to open dumpsters (Ziegler-Rodriguez et al., 2019), most Peruvian landfills lack gas or energy recovery systems, which can lead to overall increases in GHG emissions. High levels of food waste and loss (FLW) that can reach 45% of the total food produced (Díaz-Valderrama et al., 2020; Bedoya-Perales & Dal' Magro, 2021), population growth, expected increases in organic waste share due to improvements in the average Peruvian diet (Larrea-Gallegos & Vázquez-Rowe, 2020) are all critical issues to be taken into consideration to establish a transition towards robust waste management systems. Recent Peruvian waste management evaluation studies have focused on mitigating GHGs via energy-recovery in landfilled systems. Nevertheless, even though this transition is thought to be gradual, it might be inefficient as it acts in detriment of the waste management hierarchy, where residue valorisation should be maximised (Margallo et al., 2019). Thus, it remains vital to quantify the GHG mitigation potential of existing and prospective circular practices that target the use of organic waste before it reaches the landfill. Examples of existing circular practices include the informal (but unsafe from a public health perspective) (Rosario & Miñano, 2014) and formal (Sinba 2021) use of food waste as pig feed. The recovery of food loss in the agro-export sector to develop value added products (e.g., pharmaceuticals, biomaterial) is a pending issue that will require further investment.

## 2. Problem statement

The Peruvian food system is highly heterogeneous and faces different challenges. Even though anchoveta is a highly abundant edible fish which could ensure a high-quality human nutrition in a country where malnutrition persists, nearly all biomass is reduced to fishmeal and exported to China to be used as livestock and fish feed in a clear case of food-feed competition. On land, the high-input and linear-oriented agricultural systems of the Coastal region have high yields, are profitable, but are carbon-intensive due to their high reliance on mineral fertilisers. This occurs in a context where there are limited incentives and intentions to adopt fertilisation practices based on the use of recovered nutrients from crop residues, urban waste streams or nutrients recovered from human excreta. In addition, due to the lack of investments to produce fourth range, value added products that can be exported through marine freight, some food products produced in the Coastal region are airfreighted abroad on a fresh basis, skyrocketing GHG emissions. In the Andean region, most smallholder farmers safeguard a high agrobiodiversity, use circular practices embedded in multifunctional crop-livestock systems, and obtain animal-based food and materials from natural grasslands, but many of them live below the poverty line. Andean farmers are being motivated to join an export-oriented economy but without proper implementation this could lead to negative outcomes for their traditional livelihoods. In the Amazon, the government has proposed the adoption of agroforestry-based systems to halt deforestation and improve farmer's livelihoods. However, farmers operating under agroforestry systems use good agricultural practices and, in some cases, envision land-use expansion as a more likely alternative to improve their livelihoods, compared to increasing the productivity of current plantations. Lastly, the Peruvian waste management system is transitioning from the use of open dumpsters to landfill systems. While this is a positive move, most of the implemented landfills lack gas recovery systems and no further technological improvements have been considered (e.g., anaerobic digestion or incineration). This could lead to overall increases in GHG emissions, especially considering the upcoming trends in dietary changes. So far, most of the attention on mitigating GHG emissions from FLW has been on formalising the waste sector and using gas and energy recovery systems, while alternative waste valorisation strategies have had limited representation in the technical and political agendas.

## 3. Opportunities to improve the circularity of the Peruvian food system

Peru's Ministry of the Environment (MINAM, using its acronym in Spanish) launched a new initiative in late 2019, named *Plataforma Perú Circular*, which aims to build agreements between



the private and the public actors, especially in food-related sectors such as fisheries and agriculture. In parallel, other national ministries related to the primary sector (e.g., production, agriculture) have recently initiated conversations with stakeholders to establish a roadmap on circularity. Additionally, the recent creation of environmental management schemes, such as the nationally determined contributions (NDCs), include a set of mitigation actions for organic waste treatment, agriculture and forestry. The abovementioned initiatives show that there is a desire from public actors to incentivise circularity in the Peruvian food system. However, it is crucial that all these initiatives come together into an integrated national circular vision that tackles key challenges that the country is facing (see section 2), including food insecurity. Such vision should not only involve governmental and private actors, but also include farmers, academia and civil society. Recent successful examples have shown the importance that market participatory approaches can have on the livelihoods of smallholder farmers when local and added-value food chains are created. Such chains disrupt the existing model established since colonial times based on the production and export of raw products and focus on the commercialisation of added-value food products for new markets (e.g., not only export raw potatoes or cacao seeds, but also export potato chips and chocolate!). Recently, an increasing number of local start-ups are becoming new actors in the food system by aiming to process locally added-value products for local and international niche markets. This scenario creates an opportunity to foster the utilisation of by-products in the circular economy, increase the competitiveness of the Peruvian food sector, foster innovation and recognise the value of traditional circular practices performed by smallholder farmers.

#### **4. Research actions needed**

To improve and foster the circularity of the Peruvian food system, we propose the following research actions:

- Evaluate at a food system level the effect that the inclusion of anchoveta for human consumption would have on dietary GHG emissions. Such assessment should not only focus on the impacts that this measure will have at the Peruvian level but should also consider consequences in the existing supply chains (i.e., rebound and ripple effects) that currently depend on imported Peruvian anchoveta fishmeal and oil.
- Quantify the environmental mitigation potential (i.e., GHGs, nitrogen and phosphorus eutrophication, water use) of the use of crop residues and urban-waste streams recovered from nearby cities (i.e., compost, nutrients extracted from human excreta) to reduce the high dependence on mineral fertilisers in the Peruvian coastal agriculture. Considering that circularity does not guarantee reductions in environmental impacts (Schaubroeck, 2020), such assessments are key to foster a transition from linear to circular agricultural practices in the region and to keep the sector competitive by meeting future environmental demands of international markets (i.e., US, EU).
- Assess on a quantitative and qualitative basis the current use of on-farm traditional circular strategies used by Peruvian farmers and their contribution to the national food supply. A national benchmark is crucial to recognise the dimension that these practices have for national food security, to value them, and to implement participatory approaches to optimise them via the implementation of local added-value supply chains.
- Evaluate the current yield gap of crops produced under agroforestry-based systems in the Peruvian Amazon and estimate how much it could be reduced by treating and reusing postharvest waste and improving the use of fertilisers and nutrient recycling.
- Quantify the mitigation potential of existing and potential alternative waste valorisation strategies (i.e., composting, animal feed, production of insects) that target the recovery of nutrients from waste streams to be reused in the food system and compare their performance with energy-focused waste management strategies.