Synthèses

SUSTAINABLE FOOD SYSTEMS FOR FOOD SECURITY

Need for combination of local and global approaches

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Chapter 12

Food security and natural resources: diversification strategies

Rémi Cardinael, Olivier Deheuvels, Louise Leroux, Julie Subervie, Akiko Suwa-Eisenmann, Cécile Bessou, Emmanuelle Bouquet, Thibault Catry, Regis Chikowo, Marc Corbeels, Gabriela Demarchi, Abdoul Aziz Diouf, Gatien Falconnier, Ndeye Fatou Faye, Jérémie Gignoux, Christèle Icard-Vernière, Camille Jahel, Pamela Katic, François Libois, Sabine Mercier, Claire Mouquet-Rivier, Talent Namatsheve, Andréa Renk, Ninon Sirdey, Isabelle Tritsch, Éric Verger

This chapter deals with two major issues rural households face in tropical areas: preserving natural resources and guaranteeing food security. Tackling these two challenges simultaneously may require developing profitable production systems that can both guarantee food security for farmers, while also ensuring sustainable management of natural resources. Doing so will require questioning the direct and indirect links between household food security and biodiversity at the farm and landscape levels. To what extent does the diversification of production systems influence household food security? And conversely, to what extent does the level of food security influence production system performances? Is it possible to reconcile environmental performance and food security, and could diversification be a viable solution? Are there mechanisms capable of supporting this dual objective? This chapter aims to answer these questions through five case studies centred on diversification strategies, including diversification of species in cultivated landscapes and diversification of agricultural activities: 1) agroforestry parklands in Senegal; 2) cocoa-based agroforestry systems in the Peruvian Amazon; 3) cereal-cowpea intercropping systems in Zimbabwe and sub-Saharan Africa; 4) perennial palm oil monoculture grown on land converted from diverse forest cover or previously cultivated land in Indonesia; and 5) extensive cattle production systems rapidly extending into the heart of the Brazilian Amazon rainforest. The findings presented here suggest technical solutions likely to resolve the trade-off between profitability and sustainability, while underlining the socio-economic obstacles to their implementation.

⏩ Diversifying farming systems to improve food security in Sahelian agroforestry parklands

A diversity of tree species and tree uses

In a context of increasing environmental and climatic concerns, agroforestry, defined as the integration and management of trees and woody shrubs with crops and livestock, has been acknowledged as an important contributor to food security and sustainable use of land and biodiversity in sub-Saharan Africa (Rosenstock et al., 2019). Agroforestry parklands are a specific case of agroforestry systems illustrative of Sahelian agricultural landscapes, where trees have been preserved or introduced for centuries by farmers in order to benefit from the numerous socio-ecosystem services they provide (Sinare and Gordon, 2015). In 2018, in the Niakhar and Nioro districts of Senegal's groundnut basin, we surveyed 412 households and conducted tree inventories for two types of dominant parklands in the region. We identified more than 60 different tree species, covering a large range of tree uses (Figure 12.1). The reported uses could either be categorised as providing ecosystem services (e.g., firewood, fodder, food) or regulating ecosystem services (soil fertility and shade). Households identified food provision (either direct or indirect, i.e., through greater crop yield) as the main use for the different tree species. The legume tree *Faidherbia albida* was the species with the most diversified uses, including soil fertility improvement and hence crop yield, leaves used as fodder for livestock, and firewood.

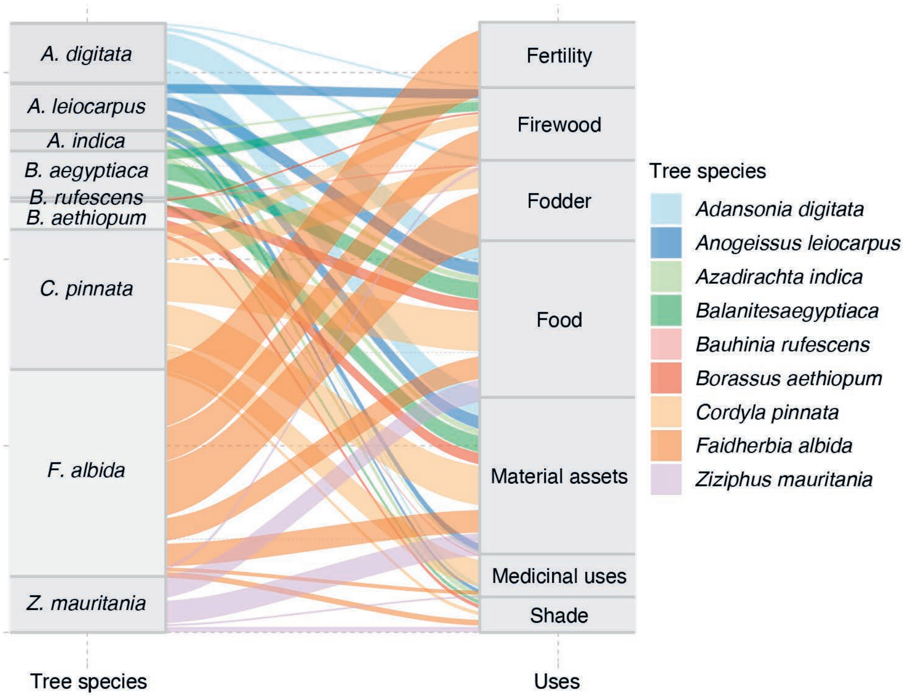

Figure 12.1. Sankey diagram linking the most important tree species (i.e., representing more than 3% of total trees) and the different tree uses (Source: Leroux et al., 2021).

The width of links is proportional to the number of times a tree species was cited for a specific use. Only the most represented tree species of both parklands are displayed (i.e., representing more than 3%).

Contribution of tree diversity to food availability

Different combinations of tree species and/or densities can lead to contrasting effects on crop productivity and hence food availability. Studies analysing tree diversity contribution to food availability are scarce and often consider only one species at a time. We monitored 70 farmers' fields for yield, crop management, soil type and soil nutrients during the 2018 cropping season. We constructed landscape diversity indicators using geospatial data. Millet was the main staple crop of the study area; as such, millet yield was used as a proxy for household food availability. Using machine learning (i.e., a gradient boosting machine), we investigated the contribution of landscape diversity, soil type and nutrients, and crop management in explaining millet variability in the two contrasted parklands. Among the highest contributing factors to millet yield variability, landscape diversity (i.e., tree species richness and tree density in field surroundings) accounted for 53% and 47% of the relative importance in Niakhar and Nioro, respectively. We also showed that a greater diversity in the parkland structure had a positive impact on millet yields, but only up to a certain level of diversity, above which no improvement in millet yields was observed. The way the different components of the parklands are mixed and managed strongly influence other ecosystem services (e.g., water regulation, pest incidence), with trade-offs and/or synergies occurring. Beyond the positive influence on millet yield at plot scale, correlation analyses showed that tree species diversity (assessed at household level, i.e., considering all of a household's fields) was significantly associated with greater millet production per capita ($r=0.38$). This suggests that optimising the management of tree density and species diversity may achieve greater household food availability and higher agricultural income.

Contribution of tree to food security and coping strategy

Using the Household Food Insecurity Access Scale (HFIAS) as an indicator, we analysed the outcomes of household socio-demographic surveys to investigate which factors were associated with food security, controlling for several socio-demographic variables. Half of the surveyed households experienced moderate or severe food insecurity. Econometric models for censored data, used to account for zero values of the dependent variable (e.g., tobit), showed that food security is positively associated with male-headed and wealthier households (more house assets and cows) and larger income from remittances (significant at 5%). Food security is also positively and strongly associated with higher food production, including millet production (significant at 1%). This tends to confirm the indirect contribution of landscape diversity to food security through improved food availability. Finally, food insecure households rely more on trees beyond their own plots, in community space or neighbours' plots, year round (significant at 1%). While diversifying access to trees does not allow most vulnerable households to be food secure, it might reduce the worst forms of food insecurity. In addition, for food insecure households, collecting from trees as a coping strategy during lean months was mentioned more often (significant at 1%). This coping strategy is used in the most severe situations, alongside selling productive or other assets and forced migration. These findings suggest that preserving parkland trees at both the farm and community scales, and allowing more vulnerable households to have access to them, would provide a safety net and increase these households' ability to cope with chronic and seasonal food insecurity.

⏩ Cocoa-based agroforestry in the Peruvian Amazon: does higher cultivated diversity provide better food security?

Agroforestry practices and plant diversity among indigenous cocoa producers

High levels of poverty, food insecurity, child mortality and morbidity persist amongst indigenous peoples in the Peruvian Amazon (Brierley et al., 2014). More than half of children under five in this region suffer from chronic undernutrition and anaemia, far above the national averages of 13% and 34%, respectively (Diaz et al., 2015). The health systems of diverse indigenous populations of the Peruvian Amazon are based on an integrated understanding of the world, where high native plant and animal biodiversity provides resources for nutrition and health and holds significant cultural value (Jones et al., 2018). Agroforestry practices relying on the association of crops or animals with trees to enhance ecosystem services are traditionally used by indigenous populations and support high levels of biodiversity.

We studied the Awajún indigenous communities living in the Amazonas department of northern Peru, where cocoa-based agroforestry systems (CAFS) are a source of both income and food. We found that these systems host more than 74 plant species intercropped with the cocoa trees. We hypothesised that a higher cultivated diversity in the CAFS is correlated with improved household food security and lower prevalence of malnutrition. We tested this hypothesis in two different Awajún communities located along the Marañon River, one a remote community accessible only by boat (Chipe), and the other accessible by road and river and connected to outside markets (Urakusa). We found a higher total diversity of plants cultivated in Urakusa's CAFS, with a higher number of forest-related species (Table 12.1). However, the cocoa tree population in Chipe (a mix of low-yielding native cultivars) is significantly more genetically diverse than in Urakusa (few high-yielding introduced varieties planted in larger plots). Finally, CAFS in Chipe host more Musaceae, forest and timber tree species but fewer roots, tubers, fruit and palm trees, which are all found in nearby forests, and fewer annual crops, which are cultivated on the river banks during the dry season.

Food security and malnutrition in cocoa producers' families

Households in the Urakusa community display a slightly higher dietary diversity than those in the Chipe community (Table 12.1). Higher dietary diversity in Urakusa could be explained by higher plant diversity, but it is more likely the result of greater access to imported products due to road proximity. In this community, households consume a lower share of self-produced food (Table 12.1), indicating greater dependence on local markets supplied with imported food. Such dependence on imported products might explain the higher sense of household food insecurity measured by the HFIAS in the Urakusa community, compared with those in the Chipe community, which are used to relying on forest resources available year-round. Because imported products are potentially energy-dense and nutrient-poor, and include more processed and ultra-processed food, the dependence on imported products might explain overweight being more than twice as prevalent in women in the Urakusa community as in the Chipe community. While dietary diversity and food security differ between the two communities, both communities display a similar prevalence of stunting among children.

Table 12.1. Characteristics of the Urakusa and Chipe indigenous communities in the Peruvian Amazon. Source: Da Silva et al., 2018.

Community	**Urakusa**		**Chipe**	
Peruvian province	Bagua		Condorcanqui	
Connection with markets	Easy, by road and boat		Remote, by boat only	
Population	700 inhabitants		1,000 inhabitants	
Cocoa-based agroforestry systems (CAFS)				
Plot size	Medium-Large		Small	
Cocoa varieties	1–2 introduced varieties		Mix of native cultivars	
Cocoa yield	High		Low	
Cocoa tree density	Medium		High	
Associated plant diversity (species richness) at community level	59		42	
Forest-related species	40%		10%	
Timber and forest trees	11%		21%	
Musaceae (plantain and banana)	13%		29%	
Palm and fruit trees	41%		30%	
Root and tubers	14%		4%	
Annual crops	1.5%		0.5%	
Food security indicators	*May***	*November***	*May***	*November***
Household Food Diversity Index (HFDI*)	50%	18%	60%	17%
Prevalence of stunting*	37%	45%	38%	41%
Prevalence of overweight*	50%	53%	18%	28%
Prevalence of traditional dietary pattern*	36%	31%	52%	39%
Prevalence of food insecurity*	55%	61%	30%	18%

***HFDI**: this index was calculated based on 10 food groups with a high potential to contribute to the micronutrient adequacy of diets (the same as those used for the MDD-W) and that are consumed by a household in a week. The figures show the percentage of households that do not eat at least five of the ten possible food groups.

Stunting: Height-for-age for children younger than five, compared to a reference (z-score).

Overweight: BMI≥25 kg/m^2 for women.

Traditional dietary pattern: A household was defined as following a traditional dietary pattern when more than half of the food consumed within the household is self-produced.

Prevalence of food insecurity: Based on the Household Food Insecurity Access Scale (HFIAS), which is an experience-based measure of household food security over a one-month period.

****May** is the end of the rainy season and **November** is the end of the dry season.

Cropping diversification strategies and their effects on food security and malnutrition

We also provided evidence on the role played by CAFS in alleviating 1) the lack of traditional forest resources for indigenous communities living far from the forest, and 2) the lack of income and poor access to markets and processed products for remote communities living near the forest. Communities such as the Urakuza use their CAFS to continue cultivating traditionally domesticated plant species, particularly medicinal rather than edible plants, among introduced cocoa varieties. These strategies result in a substantially larger share of imported food in their diet. Unsteady sources of income for purchasing foods are supported by 1) access to off-farm jobs, and 2) more intensive management of the cocoa tree population inside the CAFS, brought about by development projects and built on a highly productive, foreign and homogenous genetic base. These strategies perpetuate vulnerability to food insecurity and child undernutrition, in addition to increasing the risk of overnutrition by relying on imports of processed and ultra-processed products.

Meanwhile, communities such as Chipe use their CAFS for producing cash crops such as cocoa, wood and plantain, and rely mostly on the forest for food and medicinal plants. Because they cannot afford to transport bulky harvests, they cultivate small plots where native cocoa trees are more densely planted in order to offset the low yield per tree due to the varieties with a better yield per hectare. While these communities are significantly less vulnerable to changes in external markets and income sources, they still face undernutrition issues characterised by low dietary diversity and child stunting. Our findings thus suggest that CAFS may very well be associated with various forms of malnutrition and food insecurity.

⏩ Cereal-cowpea intercropping in sub-Saharan Africa: implications for soil fertility and food security

Intercropping with legume crops to restore soil fertility

Contrary to popular belief, crop yields in many countries of sub-Saharan Africa (SSA) are more nutrient-limited than water-limited. Poor soil fertility and nutrient availability are the major biophysical limitations to crop production in SSA (Sánchez, 2002). Sandy acidic soils are widespread and regularly ‘non-responsive’ to mineral fertiliser application, meaning that crop yield increases are very limited following the addition of recommended amounts of mineral fertiliser. For these soils, it is highly recommended to simultaneously add organic amendments together with mineral fertiliser to increase fertiliser efficiency. However, the availability of biomass or organic amendments to improve soil fertility in SSA is often limited due to competition for other uses, such as livestock feed. Continuous nutrient mining without replenishment exacerbates the poor fertility of these soils. In such a context, using nitrogen-fixing plants in cropping systems can help restore soil fertility (Giller and Cadisch, 1995), while also offering opportunities for crop diversification.

Cowpea (*Vigna unguiculata* L. Walp) is one of the major grain legumes cultivated by smallholder farmers in SSA, either in rotation with staple crops or as an intercrop (Figure 12.2). It is a drought-tolerant crop, which performs better than other legumes under erratic rainfall. In sub-humid regions, cowpea is often intercropped with maize (*Zea mays* L.), whilst in semi-arid regions, it is intercropped with sorghum (*Sorghum bicolor* L. Moench) or pearl millet (*Pennisetum glaucum* L.R.Br). We systematically reviewed cereal-cowpea intercropping systems in SSA, and estimated that cowpea fixes 36 kg N ha^{-1} on average when intercropped with cereals (Namatsheve et al., 2020). The average annual nitrogen imbalance (or depletion) rate for cropland in SSA is estimated at 22 to 30 kg N ha^{-1} (Giller and Cadisch, 1995; Sánchez, 2002). If cowpea residue is left in the field, this could help counteract this imbalance. Nitrogen fixation could thus be boosted by selecting the right legume varieties, inoculating *Rhizobia* strains, liming, and adding phosphorus.

Intercropping with legume crops to increase land productivity

We found higher land productivity when cowpea was intercropped with maize, sorghum and pearl millet compared with sole crops, with average land equivalent ratios of 1.42, 1.26 and 1.30, respectively (Namatsheve et al., 2020). Yields of cereal crops are slightly but significantly reduced, but the total production of grain per hectare is higher when cereals and cowpea are intercropped rather than grown as sole crops. Maize is the main staple crop in several SSA countries, especially in eastern and southern Africa. Farmers therefore tend to favour maize production over other crops. As a result, many fields are under maize monoculture, with negative consequences in terms of soil nutrient depletion and pest management. Consequently, access to market and profitable prices for the legume crops are crucial to compensate for the lower maize yields and encourage a broader adoption of such cereal-legume intercropping systems.

Diversifying production with more nutritious crops

We carried out an on-farm field experiment of maize-cowpea intercropping systems (Figure 12.2) over two cropping seasons in Zimbabwe. We found no difference in maize and cowpea grain mineral contents in intercropping systems compared with sole crops (Namatsheve et al., 2021), contrary to several studies that showed that intercropping could improve iron and zinc nutrition of plants through rhizospheric processes (Zuo and Zhang, 2009). We therefore concluded that intercropping was either not an agronomic biofortification option in these nutrient-depleted soils, or that the design should be modified (cowpea planted in maize rows instead of between rows to maximise interactions). However, grain mineral contents (Fe, Zn, Mn, Cu, Ca, Mg, P, K) were, as generally observed, much higher in cowpea grains than in maize grains, for all nutrients considered. This has major implications, as iron and zinc deficiencies in humans are highly prevalent worldwide, and especially in Zimbabwe, with detrimental health consequences. For instance, in Zimbabwe, 27% of children under five suffer from stunting due to macro- and micronutrient deficiencies, and 29% of women of childbearing age are anaemic (UNICEF, 2019).

A shift in diet from maize-based meals to a more diversified diet including more pulses could thus contribute to solving this problem. In addition, cereal-legume systems could definitely play a role in supporting a shift towards more diversified diets (Bezner Kerr et al., 2019). However, the mineral content of grains can largely vary from one season to another since plant nutrition is affected by soil water availability and is therefore impacted by dry spells and erratic rainfall.

Figure 12.2. Maize-cowpea intercropping system in Zimbabwe. ©Rémi Cardinael.

⏩ Palm oil expansion and food security in Indonesia: heterogeneity and inequality effects

Food security could be achieved by diversifying income sources

Food security is not just about production; it also encompasses food availability at affordable prices and ensuring environmental sustainability. Accordingly, food security is related to diversification and market access, both in terms of income sources and crop choices. In developing countries where families include many adult members who earn their livelihoods through different activities, the income needed to purchase food can be procured in other ways than by producing staple crops, such as via cash crops, out-of-farm labour and remittances sent by migrants. Crop diversification might occur at the expense of the benefits associated with specialisation, such as economies of scale and high productivity in the 'best' activity. However, specialisation in one profitable crop often entails upfront payment for land preparation, seeds and inputs, which not all producers can afford. Specialisation also increases the dependence on one crop, which may fail or whose price might fluctuate widely. Lastly, specialisation in one crop through intensification can also have an environmental cost as the soil nutrients have no time to regenerate.

Oil palm expansion in Indonesia is an enlightening example of how market access matters for food security. Oil palm is a perennial crop that is used as a cooking oil, industrial input and biofuel. The crop is cultivated over 25 to 30 years, with an initial three-year period before the trees start producing. Good seedlings and annual fertiliser use can boost productivity. According to FAOSTAT data[21], nowhere has this crop's expansion been more striking than in Indonesia, where the cultivated land area has increased from 0.5 m hectares in 1980 to 12 m ha in 2017. Indonesia is now the world's top producer of palm oil, accounting for half of global production. This huge expansion has been identified by the Indonesian government as a major contributor to poverty reduction (Rival and Levang, 2013). However, part of the expansion of palm plantations has come at the expense of forests,[22] leading to losses in biodiversity and soil quality (Dislich et al., 2017) and the use of chemical inputs in intensified cropping systems has led to various environmental impacts (Bessou and Pardon, 2017). Looking at the impact of the expansion of palm oil plantations on rural households in Indonesia, we focused on two issues that are related to food security and crop diversification: general equilibrium effects that link the products and the factor markets, through changes on local prices and wages, and distributional effects between rich and poor.

Looking at all households living in a given community, and not only food crop producers

Households working in the palm oil sector were not the only ones who benefitted from oil palm expansion. Through general equilibrium effects on local wages and prices, the expansion of oil palm has also affected other households in the area. Industrial plantations require infrastructures, such as roads, which improve market access for other produce as well. Thus, we compared all households in areas where palm oil plantations were introduced between 1995 and 2005 with similar areas that were suitable for palm oil production but still without plantations in 2005. The extended time span made it possible to compare the same districts over time and control for unobservable differences between districts (such as political or historical backgrounds) potentially associated with entry into the palm oil sector.

21. FAOSTAT database can be reached here: https://www.fao.org/faostat/

22. Between 1990 and 2008, 17% of deforestation was directly linked to palm plantations in Indonesia (Cuypers et al., 2013).

Distributional effects matter for food security

While the general public often associates palm oil with industrial plantations, in fact, smallholders hold a significant share of total plantations (about 40 percent of total area in 2015). Moreover, because many industrial concessions are now certified by the Roundtable on Sustainable Palm Oil (RSPO), most of the land acquired through expansion in recent years is now in the hands of smallholders. Yet, palm oil smallholders are hard to identify because of their diversity. Historically, oil palm development in Indonesia has been based on joint ventures between plantation firms and local communities. Villagers allocate land to a firm (forming so-called *nucleus plantations*); in exchange, the firm creates family plantations (the *plasma*), which depend on the main firm for credit, seedlings, inputs and technical assistance, and which then deliver their produce to the firm's mill (since it must be processed within two days after harvest). In addition, other smallholders are *independent*: they are newcomers, or former *plasma* households who have repaid their debt to the firm and may or may not be still dependent, to a varying degree, on the firm's mill for processing. Smallholders' plantations are thus very heterogeneous in terms of status, size, and economic and environmental efficiency.

Oil palm expansion led by these heterogeneous independent smallholders is likely to increase inequality. With constraints on access to technical knowledge, capital and secure land titles, not all independent smallholders can afford economically and environmentally efficient good practices nor smooth out the risk of international price fluctuations. We matched maps of industrial plantations (Austin et al., 2017) in various years with nationwide household budget surveys which reported the location of each household. We compared food consumption in villages where oil palm plantations were created within a 10-km radius between 1996 and 2005 with villages not affected by oil palm expansion. We assessed the impact of proximity to oil palm plantations on local distribution of consumption. We looked at the share of household consumption that was purchased as an indicator of market access. We found that households relied more on markets for their food when they lived in a plantation area, and that this change benefitted the poor households in these areas more than the rich households.

⏩ Switching to more diversified and sustainable production systems in Brazil: effectiveness and permanence of REDD+ programmes

REDD+ initiatives to reduce deforestation in the Amazon

Certain cropping systems such as soya bean production or extensive livestock farming, as practised in the Brazilian Amazon, have negative consequences for the environment, including increased fertiliser and pesticide runoff, overuse of freshwater resources, greenhouse gas emissions, and biodiversity loss, that are too substantial for these systems to be maintained. As a result, there has been a proliferation of subnational initiatives financed by the United Nation's REDD+

programme (Reducing Emissions from Deforestation and Forest Degradation) for many years in the Brazilian Amazon (Sills et al., 2014). Most of these REDD+ initiatives are hybrids of the integrated conservation and development project (ICDP) approach and new forest conservation approaches, such as payments for environmental services. They take the form of conservation programmes in which participants are encouraged to eliminate their reliance on deforestation activities altogether by switching towards more diversified and sustainable agricultural production systems (more intensive farming and greater crop diversity typically). These programmes aim to resolve the trade-off between preserving forest resources and guaranteeing food security for small landowners (Duchelle et al., 2017).

The Sustainable Settlements in the Amazon project, a Brazilian REDD+ flagship project that aimed to curb deforestation, offered technical assistance and conditional payments[23] to 350 households for maintaining forest cover on at least half of their land between 2013 and 2017. The participants in the project lived in 13 settlements located in the municipalities of Anapu, Pacajá, and Senador José Porfírio, near the BR-230 Trans-Amazonian Highway, an area with high past and present levels of deforestation. The project sought to provide technical assistance to these smallholders, help them comply with the law, and engage in a no-fire agricultural transition. These actions were aimed at facilitating a transition towards more diversified and sustainable agricultural practices and helping smallholders to intensify livestock farming and diversify crop production. Simonet et al. (2019) define the Sustainable Settlements project as a multi-component REDD+ project mixing incentives, disincentives and enabling measures.[24] We assessed the applicability of publicly available remote-sensing datasets to evaluate the impact of the Sustainable Settlements programme in the Brazilian Amazon (Demarchi et al., 2020).

Effectiveness of REDD+ programmes

First, we reconstructed forest loss for the period between 2008 and 2018 of 21,492 farms in the Trans-Amazonian region, using data derived from two land-cover change datasets: Global Forest Change (GFC) and Amazon Deforestation Monitoring Project (PRODES). Second, we evaluated the consistency between the two data sources. Lastly, we estimated the long-term impact of the Sustainable Settlements programme using microeconometric techniques that draw from pre-treatment outcomes of non-participants to construct counterfactual patterns of participants in the programme. Although the deforestation estimates at the farm level vary considerably from one dataset to another, we found that an average of about 2 hectares of forest were saved on each of the 348 participating farms during the first years of the programme, regardless the data source used (Figure 12.3).

23. Conditional payments or payments for environmental services are financial incentives offered to farmers or landowners in exchange for managing their land to provide some sort of ecological service.

24. Despite the proliferation of REDD+ initiatives in recent years, their effectiveness has rarely been rigorously evaluated (Jayachandran et al., 2017; Simonet et al., 2019; Roopsind et al., 2019). This is partly due to the low availability of data required for this type of analysis. Over the past 20 years, however, availability of remote-sensing data for detecting changes in land cover worldwide has evolved dramatically, offering new opportunities for the evaluation of forest conservation programmes.

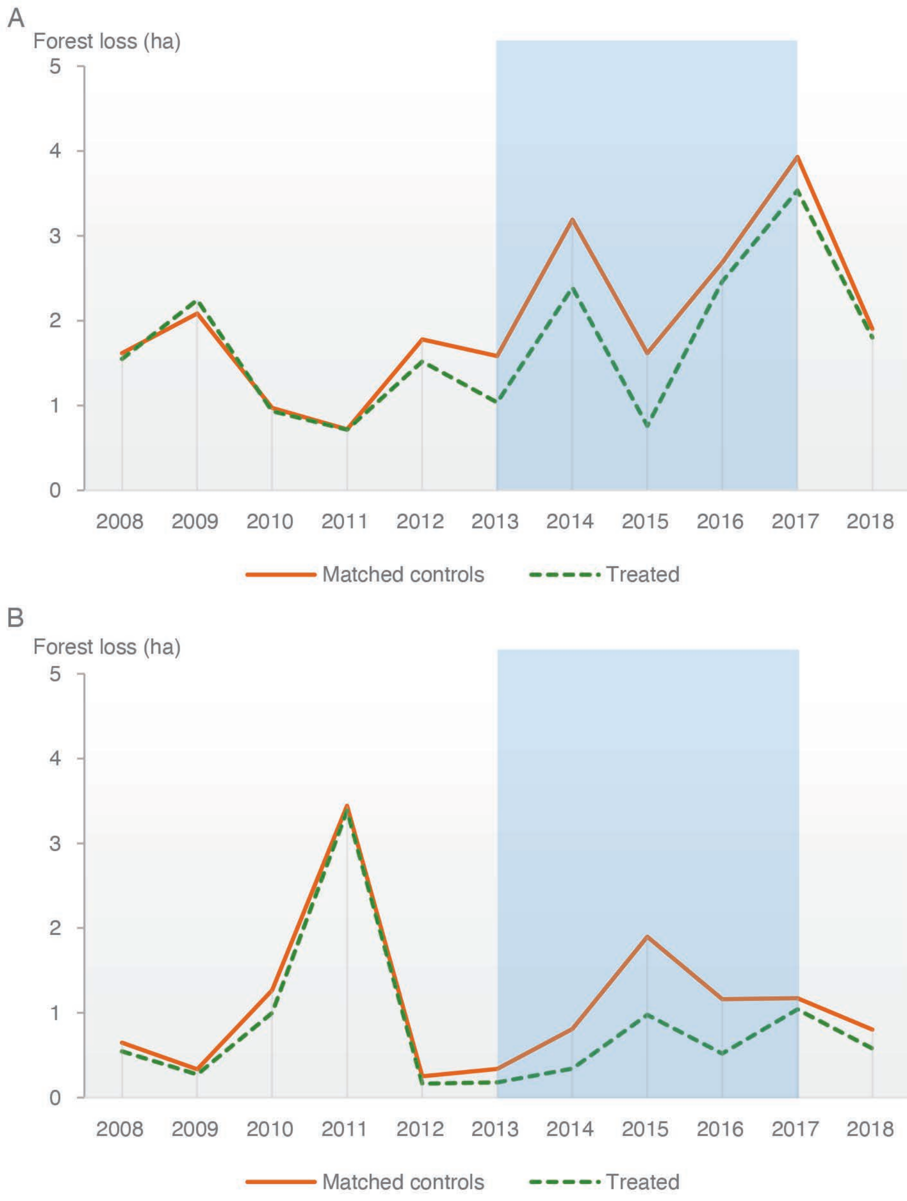

Figure 12.3. Impact of the Sustained Settlements in the Amazon programme on deforestation using GFC (A) and PRODES (B) datasets. The gap between the two curves indicates the impact of the Sustained Settlements programme (Source: Demarchi et al., 2020).

According to the GFC dataset, the participant group deviated significantly from the trajectory of the control group from 2013 to 2015. The same phenomenon was demonstrated with the PRODES data (with a one-year lag). Under the hypotheses made when constructing the control groups, this clear break in the deforestation trend among participants can be attributed to the Sustainable Settlements programme.

Permanence of REDD+ programmes' effectiveness

We also showed that the participants returned to a business-as-usual pattern at the end of the programme. It is interesting to point out that the environmental gain generated during the four years of the programme was not cancelled out by any catch-up behaviour. We failed to detect a significant impact of the programme for the years 2016, 2017 and 2018 using the GFC data or for the years 2017 and 2018 using the PRODES data. The participant group, whose trajectory had diverged from that of the control group, went back to the same behaviour after three years, which indicates that the impact became insignificant as the programme ended (Figure 12.3).

These results suggest that the gains achieved by the programme until 2018 represent a three-year delay in the deforestation that would have otherwise occurred without the programme. This means that we are in the scenario where the programme participants agreed to modify their behaviour for the duration of the programme, only to return to a business-as-usual pattern after the programme ended. This suggests that the intervention was not sufficient to trigger lasting change in farmers' behaviours. Additionally, we did not detect a higher rate of deforestation in the participating group than in the control group after the end of the programme, meaning that participants did not catch up on their postponed deforestation. Thus, the environmental gain generated during the three first years of the programme was not subsequently cancelled out, and it persisted at least until 2018 (when the analysis ended). This study describes a situation in which the effort to preserve biodiversity is not sustained when a programme ends, since it conflicts with the objective of food security for populations that fail to adopt diversified agricultural systems and remain stuck in agricultural systems based on the destruction of the forest resource.

Overall, the results of these different projects implemented in different regions of the world suggest that diversification strategies, whether for production systems or sources of income, can play a key role in the dual objective of preserving natural resources and guaranteeing food security. Indeed, it has been shown that the diversification of agroforestry-based production systems is likely to increase crop yields and reduce the vulnerability of households by improving their food security. It has also been shown that forgoing crop diversity and opting instead for monoculture can increase inequalities in access to the consumer goods market and thus threaten the food security of the most vulnerable households. Finally, we have shown that while mechanisms such as payments for environmental services may resolve the trade-off between natural resources and food security in tropical areas, their long-term effectiveness remains to be demonstrated.

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⏩ References

Austin, K., Mosnier, A., Pirker, J., McCallum, I., Fritz, S., & Kasibhatla, P. (2017). Shifting patterns of oil palm driven deforestation in Indonesia and implications for zero-deforestation commitments *Land Use Policy*, *69*, 41–48. https://doi.org/10.1016/j.landusepol.2017.08.036

Bessou, C., & Pardon, L. (2017). Environmental impacts of palm oil products: What can we learn from LCA? *Indonesian Journal of Life Cycle Assessment and Sustainability*, *1*(1), 1–7. https://doi.org/10.52394/ijolcas.v1i1.2

Bezner Kerr, R., Kangmennaang, J., Dakishoni, L., Nyantakyi-Frimpong, H., Lupafya, E., Shumba, L., Msachi, R., Boateng, G.O., Snapp, S.S., Chitaya, A., Maona, E., Gondwe, T., Nkhonjera, P., & Luginaah, I. (2019). Participatory agroecological research on climate change adaptation improves smallholder farmer household food security and dietary diversity in Malawi. *Agriculture, Ecosystems, & Environment*, *279*, 109–121. https://doi.org/10.1016/j.agee.2019.04.004

Brierley, C. K., Suarez, N., Arora, G., & Graham, D. (2014). Healthcare access and health beliefs of the indigenous peoples in remote Amazonian Peru. *The American Journal of Tropical Medicine and Hygiene*, *90*(1), 180–183. https://doi.org/10.4269/ajtmh.13-0547

Cuypers D., Lust A. , Geerken T., Gorissen L., Peters G., Karstensen, J., Prieler, S., Fisher, G., Hizsnyik, E., & Van Velthuizen, H. (2013). The impact of EU consumption on deforestation: comprehensive analysis of the impact of EU consumption on deforestation. Final report. Publications Office, Luxembourg. http://ec.europa.eu/environment/forests/pdf/1.%20Report%20analysis%20of%20impact.pdf

Da Silva, J., Deheuvels, O., & Mercier, S. (2018). Survey on agroforestry practices and Food security indicators. Diversycao project. GloFoodS 2017–2019.

Demarchi, G., Subervie, J., Catry, T., & Tritsch, I. (2020). Using publicly available remote sensing products to evaluate REDD+ projects in Brazil. CEE-M Working Paper Series https://hal.inrae.fr/hal-02898225

Díaz, A., Arana, A., Vargas-Machuca, R., & Antiporta, D. (2015). Health and nutrition of indigenous and nonindigenous children in the Peruvian Amazon. *Pan American Journal of Public Health*, *38*(1), 49–56. https://pubmed.ncbi.nlm.nih.gov/26506321/

Dislich, C., Keyel, A., Salecker, J., Kisel, Y., Meyer, K., Auliya, M., Barnes, A., Corre, M., Darras, K., Faust, H., Hess, B., Klasen, S., Knohl, A., Kreft, H., Meijide, A., Nurdiansyah, F., Otten, F., Pe'er, G., Steinebach, S., Tarigan, S., Tölle, M., Tscharntke, T., & Wiegand, K. (2017). A review of the ecosystem functions in oil palm plantations, using forests as a reference system. *Biological Reviews*, *92*, 1539–1569. https://doi.org/10.1111/brv.12295

Duchelle, A., de Sassi, C., Jagger, P., Cromberg, M., Larson, A., Sunderlin, W., Atmadja, S., Resosudarmo, I. A. P., & Pratama, C .D. (2017). Balancing Carrots and Sticks in REDD+: Implications for Social Safeguards. *Ecology and Society*, 22(3), 2. https://doi.org/10.5751/ES-09334-220302

Giller, K. E., & Cadisch, G. (1995). Future benefits from biological nitrogen fixation: An ecological approach to agriculture. *Plant and Soil*, *174*, 255–277. https://doi.org/10.1007/BF00032251

Jayachandran, S., Laat, J. D., Lambin, E. F., Stanton, C. Y., Audy, R., & Thomas, N. E. (2017). Cash for carbon: A randomized trial of payments for ecosystem services to reduce deforestation. *Science*, *357*, 267–273. https://doi.org/10.1126/science.aan0568

Jones, A. D., Creed-Kanashiro, H., Zimmerer, K. S., de Haan, S., Carrasco, M., Meza, K., Cruz-Garcia, G. S., Tello, M., Plasencia Amaya, F., Margot Marin, R., & Ganoza, L. (2018). Farm-level agricultural biodiversity in the Peruvian Andes is associated with greater odds of women achieving a minimally diverse and micronutrient adequate Diet. *The Journal of Nutrition*, *148*, 1625–1637. https://doi.org/10.1093/jn/nxy166

Leroux, L., Jahel, C., Faye, N. F., Sirdey, N., Falconnier, G. N., Diouf, A. A., & Bouquet, E. (2021), SERENA Project.

Namatsheve, T., Cardinael, R., Corbeels, M., & Chikowo, R. (2020). Productivity and biological N_2-fixation in cereal-cowpea intercropping systems in sub-Saharan Africa. A review. *Agronomy for Sustainable Development*, 40, 1–12. https://doi.org/10.1007/s13593-020-00629-0

Namatsheve, T., Chikowo, R., Corbeels, M., Mouquet-Rivier, C., Icard-Vernière, C., & Cardinael, R. (2021). Maize-cowpea intercropping as an ecological intensification option for low input systems in sub-humid Zimbabwe: Productivity, biological N_2-fixation and grain mineral content. *Field Crops Research*, *263*, 108052. https://doi.org/10.1016/j.fcr.2020.108052

Rosenstock, T. S., Dawson, I. K., Aynekulu, E., Chomba, S., Degrande, A., Fornace, K., Jamnadass, R., Kimaro, A., Kindt, R., Lamanna, C., Malesu, M., Mausch, K., McMullin, S., Murage, P., Namoi, N., Njenga, M., Nyoka, I., Paez Valencia, A. M., Sola, P., Shepherd, K., & Steward, P. (2019). A planetary health perspective on agroforestry in Sub-Saharan Africa. *One Earth*, *1*(3), 330–344. https://doi.org/10.1016/j.oneear.2019.10.017

Rival, A., & Levang, P. (2013). *La Palme des controverses : palmier à huile et enjeux de développement*. Éditions Quae, Versailles.

Roopsind, A., Sohngen, B., & Brandt, J. (2019). Evidence that a national REDD+ program reduces tree cover loss and carbon emissions in a high forest cover, low deforestation country. *Proceedings of the National Academy of Sciences*, *116*, 24492–24499. https://doi.org/10.1073/pnas.1904027116

Sánchez, P. A. (2002). Soil fertility and hunger in Africa. *Science*, *295*(5562), 2019–2020. https://doi.org/10.1126/science.1065256

Sills, E. O., Atmadja, S. S., de Sassi, C., Duchelle, A. E., Kweka, D. L., Resosudarmo, I. A. P., & Sunderlin, W. D. (Eds.) (2014). REDD+ on the ground: A case book of subnational initiatives across the globe, Bogor, Indonesia: CIFOR. https://doi.org/10.17528/cifor/005202

Simonet, G., Subervie, J., Ezzine-de-Blas, D., Cromberg, M., & Duchelle, A. (2019). Effectiveness of a REDD+ project in reducing deforestation in the Brazilian Amazon. *American Journal of Agricultural Economics*, *101*(1), 211–229. https://doi.org/10.1093/ajae/aay028

Sinare, H., Gordon, & L. J. (2015). Ecosystem services from woody vegetation on agricultural lands in Sudano-Sahelian West Africa. *Agriculture, Ecosystems & Environment*, *200*, 186–199. https://doi.org/10.1016/j.agee.2014.11.009

UNICEF (2019). The state of the world's children 2019. Children, food and nutrition: Growing well in a changing world. UNICEF, New York. https://www.unicef.org/reports/state-of-worlds-children-2019

Zalles, V., Hansen, M. C., Potapov, P. V., Stehman, S. V., Tyukavina, A., Pickens, A., Song, X. P., Adusei, B., Okpa, C., Aguilar, R., John, N., & Chavez, S. (2019). Near doubling of Brazil's intensive row crop area since 2000. *Proceedings of the National Academy of Sciences of the United States of America*, *116*(2), 428–435. https://doi.org/10.1073/pnas.1810301115

Zuo, Y., & Zhang, F. (2009). Iron and zinc biofortification strategies in dicot plants by intercropping with gramineous species: A review. *In* Lichtfouse, E., Navarrete, M., Debaeke, P., Véronique, S., & Alberola, C. (Eds.). *Sustainable Agriculture*. Springer, Dordrecht, pp. 571-582. https://doi.org/10.1007/978-90-481-2666-8_35