Tradeoffs and synergies between food security and forest cover in Brazilian drylands

Felipe Melo[1], Lucas Alencar[1], Cristina Baldauf[2], and Adriana Pellegrini Manhães[3]

[1]Universidade Federal de Pernambuco Centro de Biociencias
[2]Universidade Federal Rural do Semi-Arido
[3]Universidade Federal do Rio de Janeiro

November 10, 2022

Abstract

Global food demand is expected to increase in the next decades pushing agricultural expansion and deforestation. However, food production in agricultural lands is just one dimension of food security, to which forest goods and services also contribute. In this paper, we aimed to explore the relationship between forest cover and food security. We hypothesised that food security is improved by both human-made and green infrastructure combined. To test this relationship, we explore the relationships between forest cover and a multidimensional index of food security that included both socioeconomic and natural variables taken from Brazilian official databases for 1,141 municipalities of the Brazilian Caatinga (a seasonally tropical dry forest). The index was formed by 12 principal components axes (12 PCs) and we found that financial poverty (PC 1) and economic inequality (PC 2) were the main determinants of food insecurity in Caatinga. We found that lowest food security values were found in two contrasting contexts: one is represented by poor and unequal municipalities with high forest cover while the other refers to poor and less unequal municipalities but with little forest cover. Municipalities with intermediate levels of forest cover had slightly higher food security, a consistent pattern across time (2006 and 2017). Win-win scenarios where both forest cover and food security increased with time were almost as common as lose-lose situations (25% and 22% respectively). This suggests a sort of balance between forests and human-made land uses and reinforces that natural capital contributes to food security. Zero-hunger is a main issue for sustainable development goals and our results adds to the notion that both sustainable use of forests and socioeconomic improvements must coexist rather than being treated as antagonistic policies.

Introduction

One of the major global challenges for the next decades is to increase food security while preserving natural habitats (Godfray *et al.*, 2010; Latawiec *et al.*, 2015). Historically, food production comes via the expansion of agriculture over pristine natural habitats (Alexander*et al.*, 2015), placing industrial food systems among the main drivers of land-use change (Foley *et al.*, 2011; IPBES, 2019). More food production, however, does not guarantee access and conversion of natural habitats into agricultural fields has limited impact on food security due to access limitations (FAO, 2020). On the other hand, natural habitats can play a major role on food security for rural people as sources of plants, fisheries, wild meat and insects, for example (Baudron*et al.*, 2019). Access to forests can alleviate poverty by allowing many kinds of traditional management practices such as slash-and-burn agriculture, extensive pastoralism and diverse types of extractivism (Jagger*et al.*, 2022). Understanding the relationships between food security and forests is crucial to achieve biodiversity-friendly schemes of food production such as: sustainable intensification of agricultural production (Pretty & Bharucha, 2014) and crop yield improvement (Schütz *et al.*, 2018) that must reduce demand for new lands and therefore, halt deforestation (Lambin*et al.*, 2018). Fighting climate change while the population grows demands conciliating food security and protection of forests (Melo *et al.*, 2021). For this, we need a paradigm shift that places food security in all its dimensions, including not only the access to the products of agricultural fields but the access to forest goods and services.

According to the Food and Agriculture Organisation of the United Nations (FAO, 2013), there are four main dimensions of food security. First, *availability* , refers to the amount of food available in the system, considering, among others, food production and population size (Burchi & De Muro, 2016). Then, *utilisation refers* to how people cook, process and store the food available in the system, but this dimension is also related to water and sanitation issues, both affecting food utilisation and health (Ericksen, 2008; FAO, 2020). A third aspect, *stability,* deals with the capacity of the system to guarantee food supply in the face of several types of disturbances, such as climate, market or political instabilities (Kah, 2017; Tendall *et al.*, 2015). Finally, *access* is the capacity of people to access the food produced in the system, either buying it or being capable of producing it themselves (FAO, 2013; Klassen & Murphy, 2020). The last is thought to be the main cause of food insecurity because the amount of food needed to meet current basic world population demands is actually produced (Barrett, 2010). Economic poverty precludes access to the food market while utilisation of natural resources can alleviate food insecurity of rural poor (Miller & Hajjar, 2020). Therefore, addressing food insecurity in a broad way demands understanding the nature of the relationship between extent of natural habitats and the several dimensions of food security.

Although the scientific literature highlights the tradeoff between the establishment of new crop fields and the increasing deforestation (Meyfroidt, 2018), forest can help to improve food security (Miller *et al.*, 2020; Rasmussen *et al.*, 2020). Agroforestry systems, for example, can contribute to improve availability, access and stability of food systems at regional scales (Rosenstock *et al.*, 2019). In many poor regions of tropical countries, forests are used as grazing fields for extensive pastoralism practices while helping to maintain forest cover (Alencar *et al.*, 2022; Baudron *et al.*, 2019). Despite this important linkages between forests and food security have been recently recognised (Bahar *et al.*, 2020), the forest-food nexus needs to be better explored (Melo *et al.*, 2021). Important knowledge gaps on the role of natural habitats for poverty alleviation and food security still persist and limit the quantification of forests to food security. Because a diverse set of natural and socioeconomic drivers can affect food security, we need to test and re-create ways of measuring the determinants of access to food.

Human-made or “grey” infrastructure is surely required to improve food security (Devereux, 2016). For example, roads help to guarantee access to markets and water dams to irrigation schemes (de Fraiture & Wichelns, 2010; Khan *et al.*, 2009). The same is true for the “green” infrastructure (*sensu*Silva and Barbosa 2017) if we consider natural habitats as complementary sources of food items. However, current development models usually replace “green” by “grey” infrastructure and threaten landscapes of crossing a tipping point that compromises the ability of natural habitats to provide the services and goods that may improve food security (Swift & Hannon, 2010). Little grey infrastructure is a signal of underdevelopment that might reduce food availability due to limited access to food markets (Khan *et al.*, 2009). On the other hand, little remaining natural habitats may represent a lack of complementary source of food for people, thus also reducing food security (Vysochyna *et al.*, 2020). If it is true, it is reasonable to expect that a combination of better social indicators and enough natural habitats must provide better food security. At least theoretically, this is in accordance with the concept of “optimal landscapes” that both preserves natural habitats and produce food in a landscape structure that allows the high levels of food production, ecosystem services and biodiversity conservation (Arroyo-Rodriguez*et al.*, 2020).

The Brazilian seasonally dry tropical forest, also known as Caatinga, constitutes an opportunity for assessing the trade-offs and synergies between food security and forests. This region is characterised by high levels of social vulnerability (Hummell *et al.*, 2016) and low food security when compared to the other regions of Brazil (Gubert*et al.*, 2017). Around 60% of its forest cover is preserved, though severely degraded and fragmented (Antongiovanni*et al.*, 2018). People in this region depend largely on small-scale agriculture and extensive pastoralism that are periodically affected by seasonal droughts, thus reducing food availability (Melo, 2017). Natural resources are therefore an important asset for the 28 million people living in this dry forest and are likely to provide both goods and services that contribute to food security. The objective of this work is to understand the nature of the relationship between food security and forests at the regional scale. For this we focused on: 1) identifying the main socioeconomic indicators of food insecurity in the Caatinga through a multidimensional index of food security and; 2) understanding the spatial configuration of food insecurity and deforestation. Our results offer important evidence on the contribution of forests to food security that should be useful to regional landscape management and challenge the notion that current models of development based on land-use change can alleviate poverty and food insecurity.

Materials and Methods

The Caatinga socioecological system

The Caatinga dry forest has high inter-and intra-annual rainfall variation, changing up to 1000% from one year to another in the same place (Andrade*et al.*, 2017). The rainfall amount goes from 400 to 1500 mm per year across the biome, being considered the wettest seasonally dry forest in the world (Andrade *et al.*, 2017). The vegetation is dominated by small-leaved, thorny trees and several species of succulents (Queiroz *et al.*, 2017). Water for irrigation comes mostly from rivers and wells, but as almost all rivers are intermittent, the largest share of the agriculture is rain-fed or relies on rainfall accumulated in the wetter valleys (Sampaio*et al.*, 2017). Water for consumption comes from diverse sources (e.g. wells, cisterns, water trucks), but they are not necessarily of adequate quality, which can impact local food security (Sena *et al.*, 2018). The Caatinga has very diverse soil conditions, but most of the areas present low fertility which reduces the agricultural aptitude (Sampaio *et al.*, 2017). Combined, those environmental characteristics contribute to the low productivity of the agricultural system and to poor socioeconomic conditions of most farmers (Tabarelli *et al.*, 2017).

The set of municipalities comprising the Caatinga have the lowest levels of human development in Brazil (Silva *et al.*, 2017). Most of the municipalities are considered rural (IBGE, 2017), where most farmers produce maize and beans associated with small-scale animal production for their subsistence (Sampaio *et al.*, 2017). Goat production is the main strategy that poor rural farmers use worldwide in arid and semiarid regions (Caatinga included) especially during long droughts because of their tolerance to such climatic conditions and their ability to feed on natural vegetation (Devendra, 1999). Bovine production is mostly developed in a pasture with exotic grasses; however, only capitalised farmers normally engage in cattle production (Sampaio *et al.*, 2017). Furthermore, the Caatinga is the most densely populated dry forest in the world with millions of people living in rural communities highly dependent on forest products (Albuquerque *et al.*, 2017). Although the Caatinga still has intermediate levels of forest vegetation cover, the forest fragments are not evenly distributed across the biome (Antongiovanni*et al.*, 2018) and have high levels of chronic anthropogenic disturbance linked to the historical use of native vegetation by local people (Antongiovanni*et al.*, 2020).

Food security index and forest cover change

We developed an index of food security for the Caatinga using the four dimensions described in FAO (2013) to select the variables to represent each dimension. All variables were collected from the Brazilian official sources (e.g. IBGE, Ministry of Health) using 1,141 municipalities of the Caatinga as sample units (Figure 1). We selected 38 variables that are summarised in Table 1. The respective premise and sources of each variable are in Supplementary Table 1.

Table 1. Variables used to build a food security index for the Caatinga municipalities and the respective measure and brief definition.

Type of variable	Measure	Definition
Access	Income	Average per capita income of households in each municipality
	Half minimum wage	Percentage of the population of the municipality with an income belo
	A quarter of minimum wage	Percentage of the population of the municipality with an income belo
	Unemployment rate	Percentage of the number of people in the municipality over 16 who a

Type of variable	Measure	Definition
	Low Mass Body Index	Percentage of the number of people in the municipality with body ma
	Height deficit by age	Percentage of the number of children below height expected for their
	Weight deficit by age	Percentage of the number of children below expected weight for their
	Illiteracy rate	Percentage of the population aged 25 and over who is illiterate
	High school	Percentage of the population aged 25 or over who has completed hig
	Graduation level	Percentage of the population aged 25 or over who has completed hig
	Poorest fifth	Average per capita income of the poorest fifth in the municipality
	Extreme poverty	Percentage of the population of municipalities in extreme poverty
	Poverty	Percentage of the population living in poverty
	Income of the richest	Percentage of total municipal income appropriated by 20% of the pop
	Gini index	Gini index of income
	Under-five mortality	Probability of dying between birth and the exact age of 5, per 1000 c
Availability	Agriculture workers	Percentage of the population aged 18 or overworking in the agricultu
	Rural population	Percentage of municipality inhabitants in rural areas
	Urban population	Percentage of municipality inhabitants in urban areas
	Pesticides	percentage of establishments using pesticides in the production
	Irrigation	percentage of establishments with any type of irrigation
	Corn production	Municipal average corn production
	Bean production	Municipal average beans production
	Bovine production	Municipal livestock production of cattle
	Caprine production	municipal goat production
	Woman headed establishments	Percentage of establishments headed by women
Stability	Dependency ratio	The proportion of the population under 15 and over 65 related to the
	Associated producers	Percentage of producers associated with cooperatives and/or class en
	Protected springs	Percentage of establishments with springs protected by forest
	Springs not protected	Percentage of establishments with springs not protected by forest
	Protected rivers	Percentage of establishments with rivers protected by forest
	Rivers not protected	Percentage of establishments with rivers not protected by forest
	Financing (Rural credit)	percentage of the total number of establishments with rural credit
Utilisation	High Body Mass Index	Percentage people in the municipality with obesity
	Sewage	Percentage of people in households with an inadequate water supply
	Organic Agriculture	Percentage of establishments with organic production
	Wells	Percentage of households with wells
	Cisterns	Percentage of households with cisterns

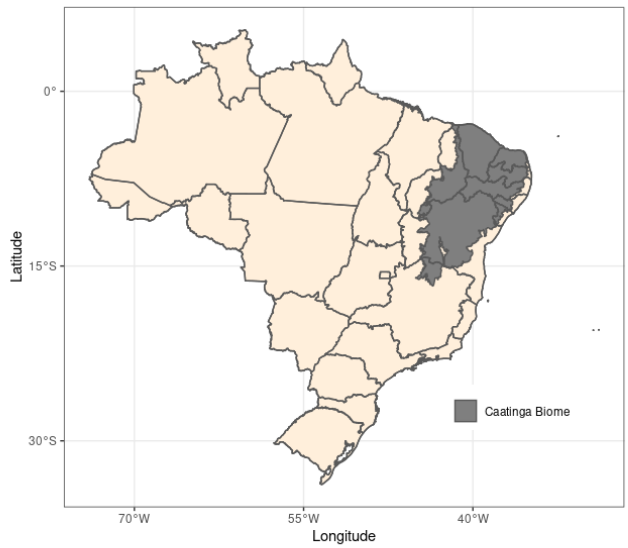

Figure 1. Map of Brazil identifying the Caatinga biome from where the data of 1141 municipalities were used to understand the relationship between forest and food security.

We built a multidimensional food security index for two time-points (2006 and 2017) to understand how it changed over time and how it is related to forest cover change. We built one index using a Principal Component Analysis for each year to reduce a large number of variables into a few dimensions following a method proposed by Hummel *et al*(2016). We selected only the PCs with an eigenvalue greater than 1 (Cutter *et al.*, 2003) and then we changed the cardinality of each PC depending on whether the variables that compose the PC contribute positively or negatively to food security (Supplementary Table 2). The final food security index for each year was calculated as the sum of the individual scores of each PC for each municipality based on Hummel *et al*(2016). We estimated the food security change in the municipalities by calculating the difference between the final index score between 2006 and 2017.

We gathered the data of native vegetation cover from the MapBiomas project (MapBiomas, 2020). We considered all categories of forest (forest, savanna, mangrove and forest plantations) and non-forested native vegetation (wetland, grassland, salt flats, rocky outcrops and other non-forest formations) to calculate the forest cover percentage for each municipality. We grouped all types of native vegetation into one class (i.e., native vegetation cover) because people in the Caatinga derive many uses related to food security from all types of native vegetation and not only from forests (Albuquerque *et al.*, 2017). Then, we identified and spatialized the municipalities with synergies (win-win and lose-lose) and trade-offs (win-lose and lose-win) between forest cover and food security change, respectively. We considered all municipalities that gained food security from 2006 to 2017 as a 'win' group, irrespective of the scores' size, as well as 'lose' if the food security score was below zero.

Statistical analyses

We first principal components analyses to reduce dimensionality of our Multidimensional Food Security Index (MFSI). We used z-transformation to standardise scores of the principal components and calculate the MSFI. Because we changed the cardinality of the dimensions to always increase MFSI, the index is the sum of both positive (increasing security) and negative values (decreasing security). Because the dimensions were formed by different variables across years we provided a table to help readers interpret what drives food insecurity (Table S1). The absolute changes of values of MFSI and forest cover were used to create maps that help to understand spatial distribution of both changes in forest cover and food security. To understand the relationship between forest cover and MFSI and its two most important principal components in 2006 and 2017 we built spatial regression models with a quadratic term of forest cover when testing the effect of forest cover on MFSI and its first principal component (PC-1) and without quadratic term for the second PC. In all models, spatial error was included to check for nonlinear relationships. We used the *errorsalm* function from the package 'spdep' in the R environment. Moran I test, using the function *moran.test* was then used to test whether after accounting for spatial error, there was still spatial autocorrelation of the residuals.

Results

Multidimensional Food Security Index

Our proposed Multidimensional Food Security Index (MFSI) was composed of 12 dimensions (principal components) that cover very different aspects of food security and explained up to 70% of the whole variance contained within the 38 variables for both years (2006 and 2017, Table S1 and S2). Economic poverty was by far the most important dimension followed by socioeconomic inequality (see Table2 and Tables S1 and S2). More than half of the variance of the MFSI is attributed to the remaining 10 dimensions but with little contribution of each one, individually. There was a shift in the rank of importance of dimensions and small changes on the components - or variables, of each dimension between years. For example, the third most important dimension in 2006 was made by variables linked to the financial stability in food production alone, however, in 2017 gender inequality (an availability variable) had a more important role in this dimension. Environmental protection was placed at 12th dimension in 2006, increased its importance in 2017 and was ranked as the 4th most important dimension. Many other changes alike happened between years suggesting that food security can be secondarily influenced by many different drivers across time (Table 2).

Table 2. Principal Components of the food security index for 2006 and 2017 and the percentage of explained variance. Numbers refer to the order of importance of each principal component and the names are the author's interpretation of the subset of variables loaded for each principal component.

Name of Principal Component	Year	% of variance explained
1 – Poverty	2006	25.51%
1 – Poverty	2017	26.22%
2 – Inequality	2006	7.11%
2 – Inequality	2017	8.25%
3 – Farmer's Stability	2006	6.76%
3 – Gender inequality and stability	2017	5.76%
4 – Child Nutrition	2006	4.38%
4 – Forest cover in water bodies	2017	5.59%
5 – Goat herd	2006	4.30%
5 – Farmer's stability	2017	4.86%
6 – Availability	2006	4.26%
6 – Agricultural Production	2017	4.00%
7 – Agricultural intensification	2006	3.67%
7 – Child Nutrition	2017	3.72%
8 – Agricultural production	2006	3.51%
8 – Goat herd	2017	3.39%
9 – Cattle herd	2006	3.30%
9 – Forest cover in water bodies	2017	3.25%
10 – Protection of water resources	2006	3.16%
10 – Unemployment	2017	2.95%
11 – Utilisation	2006	2.79%
11 – Adult Nutrition	2017	2.78%
12 – Forest cover in water bodies	2006	2.66%
12 – Availability	2017	2.50%

Changes in forest cover and food security

Among the 525 municipalities that experienced net forest loss, deforestation averaged 4.04 ± 6.66% of the total vegetated area from 2006 to 2017. On the other hand, 616 municipalities had an increase in forest cover of 3.34 ± 3.22% in the same period. These values were surprisingly low but suggest small net loss of forest for the whole Caatinga. Only 19 municipalities experienced net forest gains greater than 10% while 39 lost more than 10% of forests between 2006 and 2017 (Fig. 2a). Regarding food security, 561 municipalities registered a decrease in food security while the remaining 580 improved this measure from 2006 to 2017. We found a large variability in food security change, that goes from small changes to three orders of magnitude (>32,000 %) of net gain or net loss (Fig. 2b). Overall, we found that 29% of the municipalities lost forest and gained food security (Fig. 3) between 2006 and 2017. These were followed by the municipalities that gained forest while losing food security (24 %). The worst scenario was registered for 25 % of the municipalities that lost both forest and food security in the time period. However, the optimal combination of gaining both forest cover and food security was registered in almost 22% of the municipalities (Fig. 3).

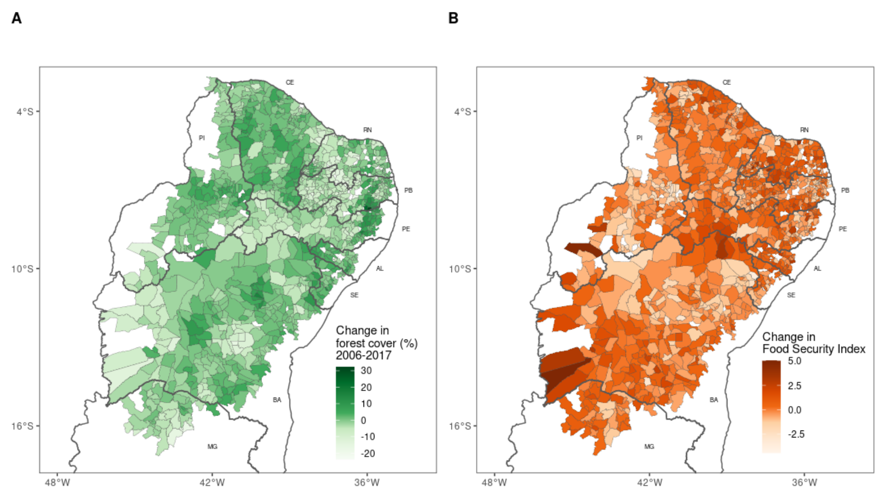

Figure 2. Map of the 1114 municipalities of the Caatinga region showing variation in forest cover (a) and food security index (b) between the years of 2006 and 2017.

Also, the correlation between forest cover and food security was complex and spatially structured (all models performed better with spatial error) and, as expected, presented a boom-bust pattern described by a weak but significant quadratic function for both years (for 2006; $z = -2.40$, $p=0.016$ and for 2017; $z = -3.13$, $p = 0.001$). Briefly, food security tends to increase in mid-deforested and reaches its peak around 50% of deforestation when it comes to drop again to similar levels of food security found in highly forested municipalities. A deeper analysis suggests that this pattern is mostly driven by economic poverty that presents a u-shaped curve in response to forest cover for both years (Fig 4.) However, the second most important dimension (PC 2) of food security presented a direct relationship with forest cover suggesting that inequality increases in more forested areas. As a result, low levels of food security can be grouped in two types: 1) poor people living in forested areas with social inequality and; 2) poor people living in deforested areas with smaller social inequality. In our study, the tradeoffs (gain-lose or lose-gain) group the poorest municipalities, but the ones losing forest and gaining food security are more unequal (in terms of income) while the ones gaining forest and losing food security are less unequal.

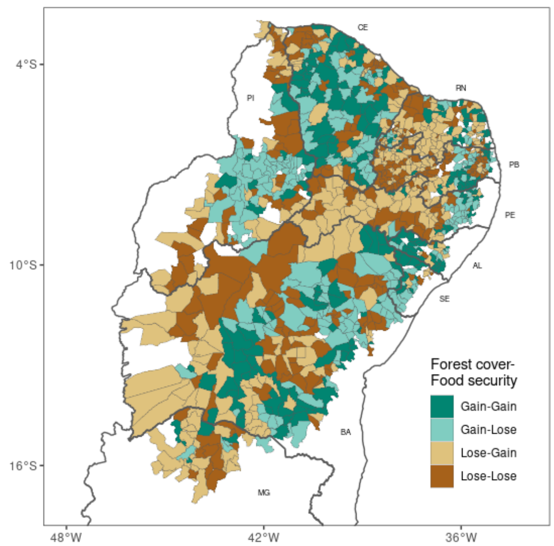

Figure 3. Geographical distribution of municipalities that experienced combinations of either gains or losses of forest cover and food security, between the years of 2006 and 2017. In the legend levels, first word always refers to forest cover and the second word, after hyphen, refers to food security (either gain or lose).

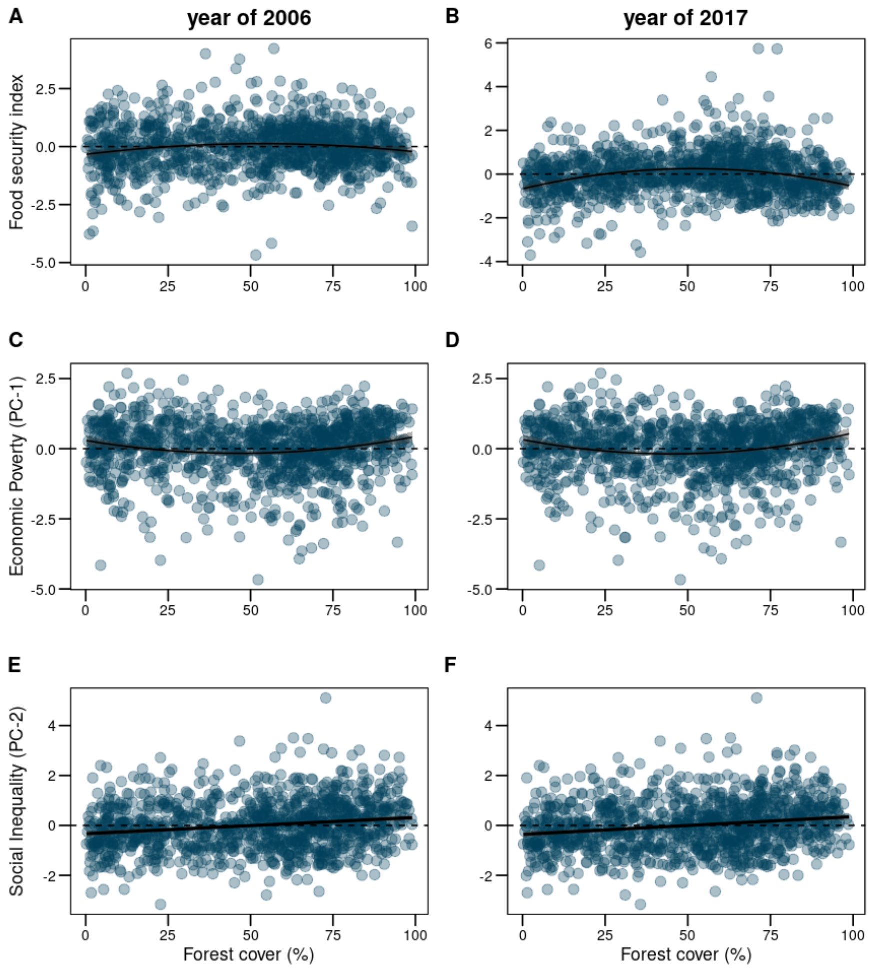

Figure 4. Relationships between the percentage of forest cover per municipality and the values of food security index (A and B) and its main components (C to F) for the years of 2006 (left column) and 2017 (right column).

Discussion

The relationship between our multidimensional index of food security and forest cover is complex but highlights that current models of development based on deforestation do not guarantee food security. Adopting a multidimensional index of food security brings both challenge and elucidation of hidden relationships between natural vegetation that adds to established measures of food security based on food availability. Although economic poverty and inequality remain constant between years as the main drivers of our proposed index, other dimensions shifted in importance suggesting high dynamism in both environmental and socioeconomic components of the index. All kinds of combinations between forest cover and food security were observed for the 1113 municipalities and both positive (win-win) and negative (lose-lose) synergies, as well as tradeoffs are almost equally likely to take place, however, clumped in space and therefore with strong influence of local context. Ultimately, we found two main types of food insecurity: the first is a sort of "green food insecurity" formed by a group of economically disadvantaged municipalities with high forest cover and low social evensess. The second one is a "grey food insecurity" formed by poor municipalities with low forest cover and more social inequality. In between these extremes, there is a zone of relatively high food security and intermediate forest cover with less poor people and intermediate levels of social inequality.

Multidimensional food security index (MFSI)

Clearly, the access variables were the most important for our MFSI and are mostly related to socioeconomic conditions of the population. Monetary poverty is a historical and widespread problem for the Caatinga population and as well as in other parts of the world, it is among the most important drivers of food insecurity (Fan & Brzeska, 2016; Nahid *et al.*, 2021). On the other hand, the role of socioeconomic inequality is not clear but wealth concentration can also mean generalised low access to food (Klassen & Murphy, 2020). The interplay of the other dimensions and their variation in the degree of importance between years precludes the search for general patterns and lead to the notion that a great number of factors can shift in importance to determine food security over time (FAO, 2022). One important lesson is the prevalence of access variables within the dimension of the index we created. Stability of food production also had some influence and highlighted the importance of collective association of farmers and the long-term protection of water resources (Parraguez-Vergara*et al.*, 2018). Surprisingly, neither utilisation nor availability variables contributed significantly to our index, reinforcing the rationale that food security is less influenced by food production or capacity to process food (Barrett, 2010). Yet, our results concur that access is far more important than the other dimensions to determine a population's food security (Barrett, 2010; FAO, 2020) even in high-income countries, such as the U.S. (O'Hara & Toussaint, 2021).

Food security and forest cover in Caatinga

We found a nuanced scenario with both synergies (win-win and lose-lose) and trade-offs (win-lose and lose-win) between food security and forest cover occurring in nearly similar proportions in the Caatinga. The combination represented by the negative synergy (lose-lose) between forest cover and food security is thought to be the worst scenario where an increasing food insecurity can be worsened by loss of natural resources (Meyfroidt, 2018). Many of these municipalities are located in a northeastern-to southwestern axis which is experiencing an expansion of a commodity-driven economy (fruit plantation and soybean) that exerts a pressure of deforestation and concentrates wealth (Weinhold *et al.*, 2013). Double positive scenarios where both forest cover and food security increases may represent development moments when poverty alleviation and politics for reducing inequality are decoupled from deforestation and must probably rely on services and industry rather than agricultural expansion, combined with forest protection policies (Liu *et al.*, 2017). Municipalities that lost forest and gained food security are probably experiencing the initial phases of commodity-driven development when a rapid increase in socioeconomic indicators derive from the establishment of new agricultural frontiers as already shown for the Amazon deforestation frontier (Rodrigues *et al.*, 2009). The other side of this tradeoff where municipalities present net gains of forest cover but food security decreases may represent the "bust" phase of commodity-driven economy when land abandonment occurs due to the displacement of agricultural frontiers to cheaper lands leaving behind a poor and unequal society (Barbier & Hochard, 2018). Both types of tradeoffs resemble the initial and final phases of "boom-and-bust" development, respectively (Barbier, 2020).

The role of forests for food security

Although our results do not address the role of forest to food security directly, there are some indirect connections that can be made based on the established literature. Forest goods and services are considered an important source of poverty alleviation as they provide vegetables, bushmeat, and work as rangelands for husbandry and provide nutrient cycling needed for shifting agriculture (Baudron *et al.*, 2019). Our index of food security could not grasp such services because this kind of data is hardly available on the scale of our analyses. However, the fact that the highest values of food security were registered in intermediate levels of forest cover suggest that a combination of basic "grey" and enough "green" infrastructure offer more opportunities for poverty alleviation and increase access to natural goods and services that ultimately reduce food insecurity. Our results indicate that improving socioeconomic conditions (i.e. reducing poverty and inequality) can be more effective to increase food security than stimulating food production through agricultural land expansion. Positive associations between forest cover and several nutrition indicators have been reported elsewhere in the literature (Ickowitz *et al.*, 2014; Johnson *et al.*, 2013; Powell *et al.*, 2011) whereas a significant inverted-U relationship between tree cover and fruit and vegetable consumption was registered in a study that compiled data from 21 African countries (Ickowitz *et al.*, 2014). Forests can play an important role as a safety net for low-income people, particularly by providing family income complement (Miller & Hajjar, 2020). In rural Malawi, for example, forests play an important role for poor rural farmers while coping with food shortages during climate shocks, either by providing a direct source of food or through the selling of forest goods (Fisher *et al.*, 2010).

Future direction

Fifteen percent of the Caatinga municipalities (n = 210) had forest cover lower than 20%. Forest restoration is a legal obligation in rural properties in Caatinga when native vegetation covers less than 20% of the property area, or when the buffer areas of forest around water-resources (i.e., Areas of Permanent Preservation - APP) are degraded (Brasil, 2012). The legal obligation can be seen as an opportunity to promote co-benefits between restoration and food security by the generation of jobs and income related to forest restoration (Mesquita *et al.*, 2010). Forest restoration should directly support food security since it can promote stability for food production through water and soil protection (Soares-Filho *et al.*, 2014) or improve the availability of food resources through agroforestry systems (Chamberlain *et al.*, 2020) . Variables related to protection of forests appear as one of the dimensions of our index (PC 10 in 2006 and PC 3 and 4 in 2017 - Table 2 and Supplementary Table 2 and 3) while variables related to the lack of protection contributed negatively to food security (PC 12 in 2006 and PC 9 in 2017). Thus, forest restoration in municipalities can help to increase food security mainly if productive restoration such as agroforests are implemented (Yang *et al.*, 2020). Then, it is possible to restore many deforested areas without competing with food production and also creating opportunities to improve access and stability of food systems. The priority of restoration should be given to low-income farmers and to municipalities with high levels of poverty and deforestation, since these are the places where it should have the greatest positive impact in increasing food security and also as a matter of environmental justice (Cousins, 2021; Reij & Garrity, 2016).

On the other hand, promoting restoration in municipalities with high forest cover could lead to more trade-offs with food security than co-benefits. In this situation, policies aiming to increase food security should attack social inequality (Misselhorn *et al.*, 2012) and take advantage of large tracts of native vegetation to maintain it under legal protection, whereas protected areas can help to improve people's well-being and food security (Naidoo *et al.*, 2019).

Conclusion

We highlighted that native vegetation should be taken into account when thinking about food security and sustainable food systems. Forests play an important role in maintaining the stability and productivity of the local food system (Chamberlain *et al.*, 2020; Melo *et al.*, 2020), but are not usually addressed in food security studies (FAO 2013; Ozturk 2015; Gubert *et al.* 2017; but see Vysochyna *et al.* 2020). Our approach shows that there are no intrinsic, unavoidable trade-offs between forest cover increase and food security. In fact, as poverty and inequality were the main source of food insecurity in Caatinga, well-designed ecological restoration programmes can help to alleviate poverty by creating jobs and promoting more income to rural families. Although restoration is an important ally to reduce poverty, this is not a solution for food insecurity in Caatinga and other drylands. There is still an urgent need for social policies that directly aim to reduce poverty in all its dimensions (UNDP & OPHI, 2020) which will greatly improve food security. Those policies should promote ways out of poverty that do not compromise the already over-pressured natural systems (see Chamberlain *et al.* 2020; Cousins 2021 for examples), they should be focused in the most socially vulnerable and environmentally degraded municipalities, such the ones with low forest cover and low food security or the ones that had negative synergies (lose-lose) between forest and food. Otherwise, those policies might not reduce poverty and food insecurity where it is most needed.

References

Albuquerque UP de, Araújo EL, Castro CC, Alves RRN. 2017. People and Natural Resources in the Caatinga. *Caatinga: The Largest Tropical Dry Forest Region in South America*. Springer: Cham, Switzerland

Alencar L, Rodrigues, AA, Parry L, Melo FPL. 2022. Forest security as a fourth dimension of the water-energy-food nexus: empirical evidence from the Brazilian Caatinga. *The Water-Energy- Food NEXUS: What the Brazilian Research has to Say*. University of São Paulo: São Paulo, Brazil

Alexander P, Rounsevell MDA, Dislich C, Dodson JR, Engström K, Moran D. 2015. Drivers for global agricultural land use change: The nexus of diet, population, yield and bioenergy. *Global Environmental Change* **35**: 138–147. DOI: 10.1016/j.gloenvcha.2015.08.011

Andrade EM de, Aquino D do N, Chaves LCG, Lopes FB. 2017. Water as Capital and Its Uses in the Caatinga. *Caatinga: The Largest Tropical Dry Forest Region in South America*. Springer: Cham, Switzerland

Antongiovanni M, Venticinque EM, Fonseca CR. 2018. Fragmentation patterns of the Caatinga drylands. *Landscape Ecology* **33**: 1353–1367. DOI: 10.1007/s10980-018-0672-6

Antongiovanni M, Venticinque EM, Matsumoto M, Fonseca CR. 2020. Chronic anthropogenic disturbance on Caatinga dry forest fragments. *Journal of Applied Ecology* **57**: 2064–2074. DOI: 10.1111/1365-2664.13686

Arroyo-Rodriguez V, Fahrig L, Tabarelli M, Watling JI, Tischendorf L, Benchimol M, Cazetta E, Faria D, Leal IR, Melo FPL, Morante-Filho JC, Santos BA, Arasa-Gisbert R, Arce-Pena N, Cervantes-Lopez MJ, Cudney-Valenzuela S, Galan-Acedo C, San-Jose M, Vieira ICG, Slik JWF, Nowakowski AJ, Tscharntke T. 2020. Designing optimal human-modified landscapes for forest biodiversity conservation. *Ecology Letters*. DOI: 10.1111/ele.13535

Bahar NHA, Lo M, Sanjaya M, Van Vianen J, Alexander P, Ickowitz A, Sunderland T. 2020. Meeting the food security challenge for nine billion people in 2050: What impact on forests? *Global Environmental Change* **62**: 102056. DOI: 10.1016/j.gloenvcha.2020.102056

Barbier EB. 2020. Long run agricultural land expansion, booms and busts. *Land Use Policy***93**: 103808. DOI: 10.1016/j.landusepol.2019.01.011

Barbier EB, Hochard JP. 2018. Land degradation and poverty. *Nature Sustainability***1**: 623–631. DOI: 10.1038/s41893-018-0155-4

Barrett CB. 2010. Measuring Food Insecurity. *Science* **327**: 5

Baudron F, Tomscha SA, Powell B, Groot JCJ, Gergel SE, Sunderland T. 2019. Testing the Various Pathways Linking Forest Cover to Dietary Diversity in Tropical Landscapes. *Frontiers in Sustainable Food Systems* **3**. DOI: 10.3389/fsufs.2019.00097

Brasil. 2012.*Lei de Protecao da Vegetacao Nativa*.

Burchi F, De Muro P. 2016. From food availability to nutritional capabilities: Advancing food security analysis. *Food Policy* **60**: 10–19. DOI: 10.1016/j.foodpol.2015.03.008

Chamberlain JL, Darr D, Meinhold K. 2020. Rediscovering the Contributions of Forests and Trees to Transition Global Food Systems. *Forests* **11**: 1098. DOI: 10.3390/f11101098

Cousins JJ. 2021. Justice in nature-based solutions: Research and pathways.*Ecological Economics* **180**: 106874. DOI: 10.1016/j.ecolecon.2020.106874

Cutter SL, Boruff BJ, Shirley WL. 2003. Social Vulnerability to Environmental Hazards*.*Social Science Quarterly* **84**: 242–261. DOI: 10.1111/1540-6237.8402002

de Fraiture C, Wichelns D. 2010. Satisfying future water demands for agriculture.*Agricultural Water Management* **97**: 502–511. DOI: 10.1016/j.agwat.2009.08.008

Devendra C. 1999. Goats: Challenges for Increased Productivity and Improved Livelihoods. *Outlook on Agriculture* **28**: 215–226. DOI: 10.1177/003072709902800404

Devereux S. 2016. Social protection for enhanced food security in sub-Saharan Africa. *Food Policy* **60**: 52–62. DOI: 10.1016/j.foodpol.2015.03.009

Ericksen PJ. 2008. Conceptualizing food systems for global environmental change research. *Global Environmental Change* **18**: 234–245. DOI: 10.1016/j.gloenvcha.2007.09.002

Fan S, Brzeska J. 2016. Sustainable food security and nutrition: Demystifying conventional beliefs. *Global Food Security* **11**: 11–16. DOI: 10.1016/j.gfs.2016.03.005

FAO (ed). 2013. *The multiple dimensions of food security.* FAO: Rome

FAO. 2022. *The State of Food Security and Nutrition in the World 2022.* FAO. DOI: 10.4060/cc0639en

FAO I. 2020. *The State of Food Security and Nutrition in the World 2020: Transforming food systems for affordable healthy diets.* FAO, IFAD, UNICEF, WFP and WHO: Rome, Italy. DOI: 10.4060/ca9692enAlso Available in:Chinese Spanish Arabic French Russian

Fisher M, Chaudhury M, McCusker B. 2010. Do Forests Help Rural Households Adapt to Climate Variability? Evidence from Southern Malawi. *World Development* **38**: 1241–1250. DOI: 10.1016/j.worlddev.2010.03.005

Foley JA, Ramankutty N, Brauman KA, Cassidy ES, Gerber JS, Johnston M, Mueller ND, O'Connell C, Ray DK, West PC, Balzer C, Bennett EM, Carpenter SR, Hill J, Monfreda C, Polasky S, Rockstrom J, Sheehan J, Siebert S, Tilman D, Zaks DPM. 2011. Solutions for a cultivated planet. *Nature* **478**: 337–342. DOI: 10.1038/nature10452

Godfray HC, Beddington J, Crute I, Haddad L, Lawrence D, Muir J, Pretty J, Robinson S, Thomas S, Toulmin C. 2010. Food Security: The Challenge of Feeding 9 Billion People. *Science* **327**

Gubert MB, dos Santos SMC, Santos LMP, Perez-Escamilla R. 2017. A Municipal-level analysis of secular trends in severe food insecurity in Brazil between 2004 and 2013. *Global Food Security* **14**: 61–67. DOI: 10.1016/j.gfs.2017.03.004

Hummell BM, Cutter SL, Emrich CT. 2016. Social Vulnerability to Natural Hazards in Brazil. *International Journal of Disaster Risk Science* **7**: 111–122. DOI: 10.1007/s13753-016-0090-9

IBGE (ed). 2017. *Classificacao e caracterizacao dos espacos rurais e urbanos do Brasil: uma primeira aproximacao.* IBGE, Instituto Brasileiro de Geografia e Estatistica: Rio de Janeiro

Ickowitz A, Powell B, Salim MA, Sunderland TCH. 2014. Dietary quality and tree cover in Africa. *Global Environmental Change* **24**: 287–294. DOI: 10.1016/j.gloenvcha.2013.12.001

IPBES. 2019. *The global assessment report on biodiversity and ecosystems services.* IPBES secretariat: Bonn, Germany

Jagger P, Cheek JZ, Miller D, Ryan C, Shyamsundar P, Sills E. 2022. The Role of Forests and Trees in Poverty Dynamics. *Forest Policy and Economics* **140**: 102750. DOI: 10.1016/j.forpol.2022.102750

Johnson KB, Jacob A, Brown ME. 2013. Forest cover associated with improved child health and nutrition: evidence from the Malawi Demographic and Health Survey and satellite data. *Global Health: Science and Practice* **1**: 237–248. DOI: 10.9745/GHSP-D-13-00055

Kah HK. 2017. 'Boko Haram is Losing, But so is Food Production': Conflict and Food Insecurity in Nigeria and Cameroon. *Africa Development* 20

Khan S, Hanjra MA, Mu J. 2009. Water management and crop production for food security in China: A review. *Agricultural Water Management* **96**: 349–360. DOI: 10.1016/j.agwat.2008.09.022

Klassen S, Murphy S. 2020. Equity as both a means and an end: Lessons for resilient food systems from COVID-19. *World Development* **136**: 105104. DOI: 10.1016/j.worlddev.2020.105104

Lambin EF, Gibbs HK, Heilmayr R, Carlson KM, Fleck LC, Garrett RD, le Polain de Waroux Y, McDermott CL, McLaughlin D, Newton P, Nolte C, Pacheco P, Rausch LL, Streck C, Thorlakson T, Walker NF. 2018. The role of supply-chain initiatives in reducing deforestation. *Nature Climate Change***8**: 109–116. DOI: 10.1038/s41558-017-0061-1

Latawiec AE, Strassburg BB, Brancalion PH, Rodrigues RR, Gardner T. 2015. Creating space for large-scale restoration in tropical agricultural landscapes.*Frontiers in Ecology and the Environment*

Liu J, Liang M, Li L, Long H, De Jong W. 2017. Comparative study of the forest transition pathways of nine Asia-Pacific countries. *Forest Policy and Economics* **76**: 25–34. DOI: 10.1016/j.forpol.2016.03.007

Melo FPL. 2017. The Socio-Ecology of the Caatinga: Understanding How Natural Resource Use Shapes an Ecosystem. *Caatinga: The Largest Tropical Dry Forest Region in South America.* Springer: Cham, Switzerland

Melo FPL, Parry L, Brancalion PHS, Pinto SRR, Freitas J, Manhaes AP, Meli P, Ganade G, Chazdon RL. 2020. Adding forests to the water–energy–food nexus.*Nature Sustainability.* DOI: 10.1038/s41893-020-00608-z

Melo FPL, Parry L, Brancalion PHS, Pinto SRR, Freitas J, Manhaes AP, Meli P, Ganade G, Chazdon RL. 2021. Adding forests to the water–energy–food nexus.*Nature Sustainability* **4**: 85–92. DOI: 10.1038/s41893-020-00608-z

Mesquita CAB, Holvorcem CGD, Lyrio CH, de Menezes PD, da Silva Dias JD, Azevedo JF. 2010. COOPLANTAR: A Brazilian Initiative to Integrate Forest Restoration with Job and Income Generation in Rural Areas. *Ecological Restoration* **28**: 199–207. DOI: 10.3368/er.28.2.199

Meyfroidt P. 2018. Trade-offs between environment and livelihoods: Bridging the global land use and food security discussions. *Global Food Security***16**: 9–16. DOI: 10.1016/j.gfs.2017.08.001

Miller DC, Hajjar R. 2020. Forests as pathways to prosperity: Empirical insights and conceptual advances. *World Development* 13

Miller DC, Ordonez PJ, Brown SE, Forrest S, Nava NJ, Hughes K, Baylis K. 2020. The impacts of agroforestry on agricultural productivity, ecosystem services, and human well-being in low-and middle-income countries: An evidence and gap map.*Campbell Systematic Reviews* **16**. DOI: 10.1002/cl2.1066

Misselhorn A, Aggarwal P, Ericksen P, Gregory P, Horn-Phathanothai L, Ingram J, Wiebe K. 2012. A vision for attaining food security. *Current Opinion in Environmental Sustainability* **4**: 7–17. DOI: 10.1016/j.cosust.2012.01.008

Nahid N, Lashgarara F, Farajolah Hosseini SJ, Mirdamadi SM, Rezaei-Moghaddam K. 2021. Determining the Resilience of Rural Households to Food Insecurity during Drought Conditions in Fars Province, Iran. *Sustainability***13**: 8384. DOI: 10.3390/su13158384

Naidoo R, Gerkey D, Hole D, Pfaff A, Ellis AM, Golden CD, Herrera D, Johnson K, Mulligan M, Ricketts TH, Fisher B. 2019. Evaluating the impacts of protected areas on human well-being across the developing world. *Science Advances***5**: eaav3006. DOI: 10.1126/sciadv.aav3006

O'Hara S, Toussaint EC. 2021. Food access in crisis: Food security and COVID-19.*Ecological Economics* **180**: 106859. DOI: 10.1016/j.ecolecon.2020.106859

Ozturk I. 2015. Sustainability in the food-energy-water nexus: Evidence from BRICS (Brazil, the Russian Federation, India, China, and South Africa) countries. *Energy* **93**: 999–1010. DOI: 10.1016/j.energy.2015.09.104

Parraguez-Vergara E, Contreras B, Clavijo N, Villegas V, Paucar N, Ther F. 2018. Does indigenous and campesino traditional agriculture have anything to contribute to food sovereignty in Latin America? Evidence from Chile, Peru, Ecuador, Colombia, Guatemala and Mexico. 17

Powell B, Hall J, Johns T. 2011. Forest cover, use and dietary intake in the East Usambara Mountains, Tanzania. *International Forestry Review* **13**: 305–317. DOI: 10.1505/146554811798293944

Pretty J, Bharucha ZP. 2014. Sustainable intensification in agricultural systems. *Annals of Botany* **114**: 1571–1596. DOI: 10.1093/aob/mcu205

Queiroz LP, Cardoso D, Fernandes MF, Moro MF. 2017. Diversity and Evolution of Flowering Plants of the Caatinga Domain. *Caatinga: The Largest Tropical Dry Forest Region in South America.* Springer: Cham, Switzerland

Rasmussen LV, Fagan ME, Ickowitz A, Wood SLR, Kennedy G, Powell B, Baudron F, Gergel S, Jung S, Smithwick EAH, Sunderland T, Wood S, Rhemtulla JM. 2020. Forest pattern, not just amount, influences dietary quality in five African countries. *Global Food Security* **25**: 100331. DOI: 10.1016/j.gfs.2019.100331

Reij C, Garrity D. 2016. Scaling up farmer-managed natural regeneration in Africa to restore degraded landscapes. *Biotropica* **48**: 834–843. DOI: 10.1111/btp.12390

Rodrigues ASL, Ewers RM, Parry L, Souza C, Verissimo A, Balmford A. 2009. Boom-and-Bust Development Patterns Across the Amazon Deforestation Frontier.*Science* **324**: 1435–1437. DOI: 10.1126/science.1174002

Rosenstock TS, Dawson IK, 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 AM, Sola P, Shepherd K, Steward P. 2019. A Planetary Health Perspective on Agroforestry in Sub-Saharan Africa. *One Earth* **1**: 330–344. DOI: 10.1016/j.oneear.2019.10.017

Sampaio EVSB, Menezes RSC, Sampaio, Y de SB, Freitas ADS de. 2017. Sustainable Agricultural Uses in the Caatinga. *Caatinga: the largest tropical dry forest region in South America.* Springer,: Cham, Switzerland

Schutz L, Gattinger A, Meier M, Muller A, Boller T, Mader P, Mathimaran N. 2018. Improving Crop Yield and Nutrient Use Efficiency via Biofertilization—A Global Meta-analysis. *Frontiers in Plant Science* **8**

Sena A, Freitas C, Feitosa Souza P, Alpino T, Pedroso M, Corvalan C, Barcellos C, Carneiro F. 2018. Drought in the Semiarid Region of Brazil: Exposure, Vulnerabilities and Health Impacts from the Perspectives of Local Actors. *PLoS Currents.* DOI: 10.1371/currents.dis.c226851ebd64290e619a4d1ed79c8639

Silva JMC da, Barbosa LC. 2017. Impact of Human Activities on the Caatinga. *Caatinga: the largest tropical dry forest region in South Americad.* Springer: Cham, Switzerland

Silva JMC da, Barbosa LC, Leal IR, Tabarelli M. 2017. The Caatinga: Understanding the Challenges. *Caatinga: The Largest Tropical Dry Forest Region in South America.* Springer: Cham, Switzerland

Soares-Filho B, Rajao R, Macedo M, Carneiro A, Costa W, Coe M, Rodrigues H, Alencar A. 2014. Cracking Brazil's Forest Code. *Science* **344**: 363–364. DOI: 10.1126/science.1246663

Swift TL, Hannon SJ. 2010. Critical thresholds associated with habitat loss: a review of the concepts, evidence, and applications. *Biological Reviews***85**: 35–53. DOI: 10.1111/j.1469-185X.2009.00093.x

Tabarelli M, Leal IR, Scarano FR, Silva JMC da. 2017. The Future of the Caatinga.*Caatinga: The Largest Tropical Dry Forest Region in South America.* Springer: Cham, Switzerland

Tendall DM, Joerin J, Kopainsky B, Edwards P, Shreck A, Le QB, Kruetli P, Grant M, Six J. 2015. Food system resilience: Defining the concept. *Global Food Security* **6**: 17–23. DOI: 10.1016/j.gfs.2015.08.001

UNDP, OPHI. 2020.*Global Multidimensional Poverty Index 2020.*

Vysochyna A, Stoyanets N, Mentel G, Olejarz T. 2020. Environmental Determinants of a Country's Food Security in Short-Term and Long-Term Perspectives. *Sustainability* **12**: 4090. DOI: 10.3390/su12104090

Weinhold D, Killick E, Reis EJ. 2013. Soybeans, Poverty and Inequality in the Brazilian Amazon. *World Development* **52**: 132–143. DOI: 10.1016/j.worlddev.2012.11.016

Yang KF, Gergel SE, Baudron F. 2020. Forest restoration scenarios produce synergies for agricultural production in southern Ethiopia. *Agriculture, Ecosystems & Environment* **295**: 106888. DOI: 10.1016/j.agee.2020.106888