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PERSPECTIVE

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Food for thought: The underutilized potential of tropical tree-sourced foods for 21st century sustainable food systems

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Abstract

1. The global food system is causing large-scale environmental degradation and is a major contributor to climate change. Its low diversity and failure to produce enough fruits and vegetables is contributing to a global health crisis.
2. The extraordinary diversity of tropical tree species is increasingly recognized to be vital to planetary health and especially important for supporting climate change mitigation. However, they are poorly integrated into food systems. Tropical tree diversity offers the potential for sustainable production of many foods, providing livelihood benefits and multiple ecosystem services including improved human nutrition.
3. First, we present an overview of these environmental, nutritional and livelihood benefits and show that tree-sourced foods provide important contributions to critical fruit and micronutrient (vitamin A and C) intake in rural populations based on data from sites in seven countries.
4. Then, we discuss several risks and limitations that must be taken into account when scaling-up tropical tree-based food production, including the importance of production system diversity and risks associated with supply to the global markets.
5. We conclude by discussing several interventions addressing technical, financial, political and consumer behaviour barriers, with potential to increase the consumption and production of tropical tree-sourced foods, to catalyse a transition towards more sustainable global food systems.

KEYWORDS

biodiversity conservation, climate mitigation, forest and landscape restoration, forest foods, global food system, natural climate solution, nutrition, sustainable food systems

1 | INTRODUCTION

Food systems are a major determinant of large-scale land transformation and degradation: globally ~43% of ice- and desert-free land is used for agriculture (Poore & Nemecek, 2018). Food production and consumption are also responsible for 26% of anthropogenic GHG emissions (Poore & Nemecek, 2018) while negatively altering ecosystem service provision (Foley et al., 2005). Especially in tropical landscapes, large-scale agricultural expansion has predominantly occurred at the expense of forestland (Gibbs et al., 2010). The recent increase in forest fires associated with agricultural expansion across the Amazon (Lizundia-Loiola et al., 2020) highlights the elevated risk for forestlands in rapidly growing economies in the global South (Hansen et al., 2016). The global food system is, at present, founded on extraordinarily low diversity, which is negatively affecting dietary quality. Almost half of the calories consumed by humans come from just four crops, namely wheat, rice, sugar and maize (FAOSTAT, 2018; Poore & Nemecek, 2018); consumed food is becoming more energy-dense and nutrient-poor (Khoury et al., 2014); and fruits and vegetables are under-consumed in all regions of the world, except for China, Japan and South Korea (Berners-Lee et al., 2018). Low intake of fresh fruits, vegetables, nuts and seeds and whole grains is associated with an increased risk of disease, especially cardiovascular disease, type II diabetes and cancer, and affects the poorest populations in particular (Afshin et al., 2019; Miller et al., 2017; Tilman & Clark, 2014). Another aspect regarding the sustainability of the global food system is the increased concentration of power among a few actors due to globalization and industrialization, which is leading to increased inequality within rural societies (Brown & Sander, 2007; Clapp & Fuchs, 2009; Pimbert et al., 2001). Reversing these trends requires a redesign of the global food system, which in turn necessitates a thorough understanding of which foods have the potential to simultaneously deliver environmental, nutritional and livelihood benefits at local and global levels.

Tree-sourced foods have this potential and can therefore be a critical part of the solution. Globally, tree diversity is enormous (Leigh Jr et al., 2004) with an estimated 60,000 species, most of which grow in tropical countries (Beech et al., 2017; Slik et al., 2015). Many species produce nutritious fruits, nuts, leaves and seeds. Traditionally, many tree-sourced foods are consumed by rural people (Asprilla-Perea & Díaz-Puente, 2018), who either collect them from the wild or grow them in agroforestry systems [e.g. in Southern India (Nair & Sreedharan, 1986) and Mali (Assé & Lassoie, 2011)]. However, many of these foods are only consumed locally in small geographical areas and are underutilized. Increased use of tree diversity can make a significant contribution to human nutrition (Fungo et al., 2019). A recent study found that 14 of the world's 100 most nutritious foods are derived from trees (Kim et al., 2015). Incorporating trees more in (local) agricultural systems can complement otherwise low-quality diets in poor rural areas (Correal et al., 2009; Gramza-Michałowska & Kmiecik, 2016), and can help address the global underconsumption of fruits (Berners-Lee et al., 2018). Planting trees, of the right species in the right place, is increasingly recognized for its co-benefits in mitigating climate change (Bastin et al., 2019; Griscom et al., 2017). The use of tree crops in agricultural landscapes (through agroforestry systems) provides many other environmental benefits like biodiversity conservation and improvement of soil, air and water quality (Jose, 2009). Tree crops can also help to enhance local livelihoods and combat poverty in the tropics, as incorporation of (native) tree crops at farms offers opportunities to diversify income streams and increase farmer autonomy (Leakey et al., 2005). An increase in tropical tree-based food production and consumption could have the potential to contribute to the redesign of our world food system towards a system that is more sustainable and socially equitable, provides better-quality diets, significantly contributes to tree-based restoration of ecosystem services, and helps to mitigate climate change.

However, the global food system is highly heterogeneous, and is influenced by a diverse array of political, cultural, economic and environmental factors (Ericksen, 2008). The nutritional, environmental and social benefits that can be obtained with an increased focus on tropical tree-sourced foods will be equally heterogeneous. Traditional agroforestry systems are generally biologically diverse and include a variety of systems, for example, pastures with (non-planted) fruit-producing trees, woody hedgerows within agricultural fields, and multispecies tree gardens (Nair, 1985). These are generally smallholder systems that produce for subsistence, or to supply local or regional markets. In many areas, however, tree-based food production has either lost its diversity or has been replaced by annual crop production, in part due to agrarian reforms (Depommier, 2003; Mohri et al., 2013; Scherr, 1993; Sthapit et al., 2016). The tree plantations that are typically used to produce food for global markets, often fail to utilize the existing tropical tree-sourced food diversity and, perhaps more importantly, are often at odds with it (Blaser et al., 2017). Many of these systems focus on monocultures of cash crops – such as coffee (Nesper et al., 2017), tea and cacao (Higonnet et al., 2018) – in spite of their potential to be integrated with other valuable food species. The neglect of many current tree-based systems to integrate tree genetic resources and other crop diversity to generate biodiverse-rich agroforests strongly limits the potential environmental, nutritional and livelihood benefits of such systems (Achterbosch et al., 2014; Ickowitz et al., 2019; Tscharntke et al., 2011). Further, more diverse systems that take local knowledge and preferences for types of trees and food into account, can empower local communities to reinforce culturally important practices (Correal et al., 2009; Hegde et al., 2015).

Increasing the role of tropical tree-sourced foods in the world food system, requires interventions aimed at increasing demand for these foods, and creating the enabling conditions that would allow farmers to supply this demand sustainably. For example, significant barriers for implementation of tree-based food production systems include high initial investment costs and (perceived) insecure land tenure rights, especially for smallholders (Ding et al., 2017; Jacobi et al., 2017). On the consumer's side, we envision three groups that could both drive and benefit from an increase in production and diversification of tropical tree-sourced foods. A growing market of rural and national consumers would provide opportunities for production directly linked to regional skills and preferences and could increase the resilience of local food systems, which is increasingly important in the face of pandemics (Farrell et al., 2020). On the other hand, willingness to pay for more sustainable food is likely to be higher in high-income countries. There is evidence of an increase in the proportion of consumers in the global market willing to shift their choices to sustainable, ethical and healthy food products (Dowd & Burke, 2013). However, for the majority of consumers in middle- and high-income countries, we are seeing evidence of increasing consumption of unhealthy diets (Imamura et al., 2015; Willett et al., 2019). Thus, there is a need for interventions aimed at increasing the consumption of sustainable, ethical and healthy foods among different consumer groups.

We argue that better use of tropical tree diversity offers an underexplored opportunity to adjust our global food systems, to become more sustainable, equitable and nutritious. Doing this requires diversification and adaptation of many existing tree-based food production systems (while taking traditional ecological knowledge into account) and tackling several key barriers on both the supply and demand side of markets to increase consumption and production of tropical tree-sourced foods.

In this *Perspective* article, our intention is to illustrate this opportunity. We first provide an overview of the nutritional, environmental and livelihood benefits associated with tropical tree-based food production and demonstrate the nutritional importance of tropical tree-sourced foods using dietary intake data from rural sites in seven tropical low- and middle-income countries. Next, we discuss several risks and limitations that must be considered regarding the benefits tree-based food production can provide, including the importance of system diversity and risks associated with supply to the global market. We conclude with an overview of the key interventions needed and obstacles to overcome, both on the supply and demand side, so that an increase in the consumption of tropical tree-sourced foods can catalyse transformational change in the global food system, leading to increased consumption of nutritious, sustainably produced foods.

2 | THE MANY ADVANTAGES OF TROPICAL TREE-SOURCED FOODS

In this section, we provide an overview of the nutritional, environmental and livelihood benefits of tropical tree-sourced foods.

2.1 | Nutritional contribution to diets

A huge diversity of tropical tree-sourced foods has extraordinary nutritional characteristics. For example, camu-camu *Myrciaria dubia*, the fruit of a riverine shrub from the Amazon Basin, has a vitamin C content 54 times higher than that of oranges (Rodrigues et al., 2001). Brazil nuts *Bertholletia excelsa* contain an exceptionally high selenium content, an important antioxidant (Ip & Lisk, 1994). Currently, the global food production system does not produce enough fruit to meet dietary intake recommendations (Berners-Lee et al., 2018). Increased fruit production is thus a global imperative. Increasing the quantity, quality, diversity and efficiency of tree-based food production can play an important role in increasing world fruit production to match dietary recommendations.

Our analysis across sites in seven tropical countries identified 90 foods from trees (including both woody species and other long-lived plants with tree-like properties, see Table S1 of the Supporting Information for the full list of species). On average, tree-sourced foods from these sites provided 11% of daily food intake (in grams), while accounting for 31% of the average daily intake for vitamins A and C (Table 1). Tree-sourced foods provided four times as much vitamin C and nine times as much vitamin A as other foods (Table 1), and comprised 100% and 97% of the total intake (in grams) of the 'vitamin A-rich fruits' and 'other fruits' food groups respectively (Table 2). Tree-sourced foods thus provide important contributions to meeting

TABLE 1 Nutrient density and contribution to nutrient intake of tropical tree-sourced foods in rural communities in sites in seven developing countries

	Nutrient density, tree-sourced foods	Nutrient density, other foods	Relative difference in nutrient density	Proportion nutrient intake, tree-sourced foods	Contribution of tree-sourced foods to average daily Nutrient Adequacy Ratio	Nutrient Adequacy Ratio total
Ca	0.252 mg/g	0.418 mg/g	0.603	0.061	0.030	0.455
Fe	0.006 mg/g	0.016 mg/g	0.394	0.047	0.055	0.929
Zn	0.003 mg/g	0.010 mg/g	0.259	0.027	0.026	0.879
Folate	0.198 μg/g	0.228 μg/g	0.867	0.081	0.051	0.580
Vitamin C	0.219 mg/g	0.055 mg/g	3.961	0.307	0.177	0.758
Vitamin A	4.644 RE/g	0.517 RE/g	8.989	0.306	0.281	0.744

Note: Results are based on analysis of 5,005 24-hr dietary recalls. Values represent the average of different sites, with equal weight for each site. Tree-sourced foods include woody species and other long-lived plants with tree-like characteristics (see Methods S1 of the Supporting Information for details).

TABLE 2 Contribution of tropical tree-sourced foods to different food groups in the diets of rural communities in sites in seven developing countries (Benin, Cameroon, Democratic Republic of the Congo, Ecuador, Kenya, Sri Lanka and Vietnam)

Food group	Proportion of food intake, tree-sourced foods	Number of tree-sourced foods in food group	Total number of foods in food group
Dark green leafy vegetables	0.032	6	31
Fats and oils	0.909	2	5
Herbs, spices, condiments, drinks	0.167	18	42
Legumes, nuts and seeds	0.007	5	19
Other fruits	0.970	36	42
Other vegetables	0.367	9	45
Starchy staples	0.017	1	18
Vitamin A-rich fruits	1.000	8	8
Vitamin A-rich vegetables	0.000	0	4

Note: Results are based on an analysis of 5,005 24-hr dietary recalls. Food intake was measured in grams. Tree-sourced foods include foods sourced from woody species and other long-lived plants with tree-like characteristics (see Methods S1 of the Supporting Information for details).

fruit and average daily nutrient intake requirements of vitamins A and C in the rural communities in these study sites, highlighting the critical role of tree-sourced foods for nutrition. The methods we used for the analysis are presented in Methods S1 of the Supporting Information. This analysis was based on seven publicly available datasets corresponding to the seven countries (Bechem et al., 2017; Hunter & Ratnasekera, 2017; Penafiel et al., 2017; Raneri, 2017; Termote et al., 2017; Termote & Ntandou-Bouzitou, 2017; Termote & Oduor Odhiambo, 2017). A description of the combined dataset and a general description of the diet between and across each site is reported elsewhere (Lachat et al., 2018).

While highly prevalent in developing countries, micronutrient deficiencies are a global issue, affecting over two billion people (Willet et al., 2019). For example, vitamin A intake is below recommended intake in almost all countries (World Health Organization, 2009) and the prevalence of vitamin C deficiency varies from close to 74% in India, down to 7% in the US (Maxfield & Crane, 2020) and can be relatively common in some low-income populations due to limited access to fresh fruit and vegetables (Mosdøl et al., 2008). Our results suggest that tree-sourced foods can provide an important source of vitamins A and C that could help tackle these deficiencies, both in rural communities and among consumers globally.

A diverse diet is one that is made up of a variety of foods from different food groups. Our data show the importance of tree-sourced foods in contributing to diverse diets, through the provision of several key food groups (FAO & FHI 360, 2016) including fruits and vegetables (especially vitamin A-rich species), fats and oils and to a lesser extent herbs and spices, and legumes, nuts and seeds. Fruits, vegetables and nuts are under-consumed in almost all regions across the world, and this is negatively affecting global health (Afshin et al., 2019; Berners-Lee et al., 2018; World Health Organization, 2017). Producing more tree-sourced foods in rural communities could therefore yield important dietary benefits, including providing protection against non-communicable diseases. This is supported by studies on the importance of forests and forest trees for dietary quality (Fungo et al., 2019). Tree cover was found to have a positive association with fruit and vegetable consumption and diet diversity of children in a study of 21 countries in sub-Saharan Africa (Ickowitz et al., 2014). Children's dietary diversity, iron intake and vitamin A intake have been found to be significantly higher when communities have access to forests (Rasolofoson et al., 2018). In areas where overnutrition is a public health concern, promoting dietary changes that replace sugars, simple carbohydrates and ultra-processed foods with tree-sourced fruits, vegetables and nuts would significantly improve the quality of the diet and reduce the prevalence of overweight, obesity and non-communicable diseases (Afshin et al., 2019; Louzada et al., 2015). A recent study finds that even a small increase in nut consumption reduces overweight and obesity in adults (Liu et al., 2019).

Tree-sourced foods, such as fruits, leaves and nuts are high in fibre. Globally, on average, fibre intakes meet optimal level of intake, but are generally insufficient in Asia, Australia, Western Europe and Southern Latin America (Afshin et al., 2019). Insufficient fibre intake has been associated with non-communicable diseases such as cardiovascular disease, type-2 diabetes and cancer (Aune et al., 2011; Keum & Giovannucci, 2019; Kim & Je, 2016; Mattei et al., 2012; Mirmiran et al., 2018). Logically, the promotion of tree-sourced foods in diets should provide the protective health benefits associated with high-fibre diets. Low fruit consumption is among the leading dietary risk factors for death globally (Afshin et al., 2019), likely driven by a combination of the high antioxidant, micronutrient and fibre content of fruits. Further research is needed to better understand to what extent tree-sourced foods can contribute to high-fibre diets that provide protective effects for non-communicable diseases.

2.2 | Environmental benefits

Two of the most important and widely recognized environmental benefits of an increase in tropical tree-based food production and consumption are its potential contributions to atmospheric carbon dioxide drawdown and biodiversity conservation. Tree planting is one of the most effective nature-based solutions for mitigating climate change (Griscom et al., 2017). Smallholder agroforestry systems in the tropics have been estimated to store carbon at a rate of 1.5–3.5 Mg C ha^{-1} $year^{-1}$ (Montagnini & Nair, 2004). Currently, trees contribute to more than 75% of global carbon storage on agricultural land, while only 43% of agricultural land has a tree cover of >10% (Zomer et al., 2016); this illustrates the enormous potential of tree-sourced agriculture to contribute to climate change mitigation (Griscom et al., 2017), and to provide other well-recognized environmental services (Baral et al., 2016). Agroforests have been shown to generally have a higher floral, faunal and soil microbial diversity compared to monoculture agricultural systems (Udawatta et al., 2019). Agroforests provide habitat for species that can tolerate certain levels of disturbance, conserve germplasm of useful species, reduce conversion of natural habitat while increasing ecological connectivity, and enhance ecosystem service provision (Jose, 2012). Other environmental benefits include in many cases enrichment and restoration of soil properties (Dollinger & Jose, 2018; Jose, 2009), and provision of more habitat for pollinators (Pavageau et al., 2018) compared to monoculture agriculture. Further, agroforests have been suggested to play a potentially import role in hydrological cycles and associated water security (van Noordwijk et al., 2016), in part due to the importance of trees and forests for transportation of water over terrestrial surfaces and the associated influence on rainfall patterns (Davidson et al., 2012; Ellison et al., 2017).

2.3 | Livelihood benefits

Aside from nutritional and environmental benefits, tree-based food production can benefit local livelihoods, thereby enhancing the resilience of rural communities. Farmers in poor areas plant indigenous fruit trees because of their contribution to domestic food security and their potential to contribute to household income (Hegde et al., 2017). For example, a study in Cameroon and Nigeria found that the domestication of two indigenous fruit tree species contributed to poverty reduction and income generation (Schreckenberg et al., 2006). Greater diversity of tree-sourced foods can help diversify income streams and sustain revenues throughout the year, as different species fruit at different times and some (such as papaya and banana) are often available year-round. Moreover, certain species play critical roles in farmers' livelihoods because they yield fruit when household granaries are low or exhausted, and/or when particular seasonal expenses need to be made. For instance, the shea tree *Vitellaria paradoxa* fruits during the lean season, when school fees must be paid. The sale of shea butter and fruit at this time enables women to settle these fees and to extend their household's food supply through food purchases (Elias & Carney, 2005). The processing and sale of tree-sourced foods can be particularly important for marginalized groups and women, whose limited access to land, credit and other assets limit their livelihood opportunities (Hasalkar & Jadhav, 2004). Although potentially commercial tree species planted in farmers' fields, such as mango *Mangifera indica*, are sometimes marketed by men (Faridah Aini et al., 2017), women can play a key role in the collection and sale of products from indigenous tree species that are not planted but which grow spontaneously or for which natural regeneration can be managed, such as shea *Vitellaria paradoxa*, néré *Parkia biglobosa* or safou *Dacryodes edulis* (Ingram et al., 2016). Further, the production of tree-sourced foods with international market potential can increase employment and business opportunities in rural areas, which in turn can reduce rural-to-urban migration (Deotti & Estruch, 2016). Diversified employment opportunities can further be generated by accompanying increased production of tropical tree-sourced foods with investments in the creation of value adding activities to the products (Waarts et al. 2019). Tree-based food production can thus provide opportunities for gender empowerment, improve equitable and sustainable development options, and provide more resilient livelihood options, depending on local culture and gendered tenure rights to land and trees (Ingram et al., 2015; Table 3).

TABLE 3 Overview of the nutritional, environmental and livelihood benefits that can be obtained with increased tree-sourced food consumption and production

Nutritional benefits	• Filling global fruit production gap • Contribution to diversified diets through several additional food groups, including vegetables, fats and oils, nuts and seeds • Contribution to lowering micronutrient intake deficiencies, mainly Vit A and C (Vit A important for all consumers groups, Vit C especially important for low-income countries where access to fresh fruits is low)
Environmental benefits	• Carbon dioxide drawdown • Biodiversity conservation • Soil restoration • Pollinator habitat provision • Water security/transportation water over terrestrial surfaces
Livelihood benefits	• Poverty reduction and increased livelihood resilience due to system diversification • Gender empowerment (especially with naturally grown/tended trees) • Sustainable development options and employment opportunities • Improved domestic food security

3 | WHAT TO TAKE INTO ACCOUNT WHEN SCALING-UP TROPICAL TREE-BASED FOOD PRODUCTION?

Even though tree-based food production can clearly provide nutritional, environmental and livelihood benefits, several risks and limitations have to be taken into account when scaling-up tropical tree-based food production. Food system transformation that lacks consideration of local ecological, sociological and political realities might negatively impact livelihoods, the environment and/or create conflict. In this section, we provide an overview of several of such risks and limitations.

3.1 | The importance of biological diversity within food production systems

Environmental and livelihood benefits, and to some extent nutritional benefits, are strongly dependent on the biological diversity of the production system. More diverse systems (especially when they are largely based on native species) generally have a greater carbon sequestration capacity due to greater efficiency in resource use (nutrients, light and water) and often contribute more to maintaining biodiversity (Guillemot et al., 2018; McNeely, 2004; Ramachandran Nair et al., 2009; Wilson et al., 2017). More diverse systems also strongly contribute to diet quality, especially when the system includes access and utilization of wild and semi-wild foods, including from forests (Jones et al., 2014, 2019; Powell et al., 2013, 2015). Tree-plantations in monoculture on the other hand, can have negative effects on water security, by negatively affecting groundwater recharge (Jackson et al., 2005), and increase vulnerability of smallholders to price fluctuations, climate change and pandemics (Waarts et al., 2019; Kahiluoto, 2020). Thus, if scaling-up of tropical tree-based food production is primarily based on monoculture plantations, the environmental, livelihood and nutritional benefits that can be obtained are limited.

3.2 | Supplying international markets

Increased global demand for tropical tree-sourced foods and associated expansion of production can lead to conversion of forest to farmland, especially in places where there is a lack of land-use planning, tenure insecurity and weak policy implementation (Roth et al., 2017). The conversion of forest to farmland can cause significant carbon emissions (see e.g. Carlson et al., 2012) and increase drought (Staal et al., 2020). For example, the establishment of large industrial cacao plantations in West Africa and palm oil plantations in Asia to supply increased international demand for these products, have contributed to deforestation and carbon emissions (Carlson et al., 2012; Ruf et al., 2015).

Increased global demand for tree-sourced foods can influence producer prices of these foods, which can affect farmer livelihoods and/or create conflict. For example, strong price increases can attract organized crime as has happened in Mexico when avocado prices increased strongly (Ornelas, 2018; Osorno-Covarrubias et al., 2018), while strong decreases in producer prices can impact farmer livelihood and even children's health, as has happened during the 1990 cacao crisis in Ivory Coast (Cogneau & Jedwab, 2012).

Supply to global markets can in some cases, depending on the crop, be associated with rapid transformation of traditional production systems towards industrialized monocultures, which, as discussed above, can reduce the environmental, nutritional and livelihood benefits of tree-based food production. In addition, many (traditional) smallholders lack the financial means or labour capacity to invest in new production models necessary to supply the global market or cannot bear the risks that involve these new investments (Waarts et al., 2019). If powerful actors and large-scale farmers then take over and replace small farms, this can increase inequality and potentially exacerbate poverty (Altieri & Nicholls, 2008; Brown & Sander, 2007; Markelova et al., 2009). Further, despite many attempts to integrate and empower smallholders in sustainable agricultural commodity value chains (such as with fair trade certification), most such value chains remain buyer-driven, in which buyers have a powerful position to establish stringent price policies and govern the chain, limiting the options for alleviating poverty and increasing livelihood resilience (Brown & Sander, 2007).

3.3 | Other considerations

Tropical tree-sourced foods cannot address all existing nutritional challenges. For example, nutritional iron deficiency affects about two billion people world-wide (Zimmermann & Hurrell, 2007). Our analysis shows that tree-sourced foods (or at least the ones in our dataset) contain relatively less of the micro-nutrients Ca, Fe, Zn and Folate compared to other foods (Table 1). Also, perishability of fresh tree-sourced fruits limits transport options, which could be a limitation for provision of these products to global markets [although this can partly be overcome by applying innovative processing techniques such as solar powered desiccation units or by producing purees and pulps (Bello et al., 2012)].

The carbon footprint of food consumption is affected by the distance of markets, with regional markets resulting in a lower carbon footprint compared to global markets. However, it should be noted that transportation is usually only a small part of the carbon footprint, especially if products are transported over land or sea and not by air (Wakeland et al., 2012). The carbon that is stored in the production system strongly depends on the planted species, system age and previous land-use. Large tree species have a much higher above-ground carbon storage potential than shrubs and other smaller perennials, and carbon stocks of agroforestry systems gradually increase with age (Kim et al., 2016). There is also still much uncertainty about the contribution of agroforests to the emission of other greenhouse gasses (Kim et al., 2016). Care must be taken when designing a polyculture agroforestry system, such that yield reductions due to resource competition are prevented (Van Noordwijk et al., 2015). Finally, we do not advocate growing trees everywhere on the planet since clearly not all lands are suitable for the growth of food-producing trees (Albrecht & Kandji, 2003; Table 4).

TABLE 4 Overview of the importance of biological diversity within production systems, risks associated with supply to global markets, and other considerations related to increased production and consumption of tropical tree-sourced foods

Importance of diverse production systems	• More environmental benefits (including carbon sequestration and biodiversity conservation) • Higher contribution to domestic food security • Higher livelihood and climate resilience • Greater resilience to shocks from pandemics
Risks when supplying to global markets	• Increased deforestation • Transition to monocultures • Loss of traditional production systems • Price changes and conflict emergence • Low capacity smallholders to compete within international trade (leading to increased socio-economic inequality and poverty)
Other considerations	• Not all nutritional challenges can be addressed by increased tropical tree-based food production • Carbon footprint of tree-sourced foods is influenced by transport distance • Carbon sequestration potential varies between agroforest systems • Limited knowledge on emissions of other greenhouse gasses within agroforests • Yield reductions possible if agroforest system not properly designed • Not all lands are suitable for tree planting

4 | JOINING UP THE DOTS TO TRANSFORM THE GLOBAL FOOD SYSTEM

In the previous sections, we presented evidence that enhancing the production and consumption of tropical tree-sourced foods provides an excellent opportunity to diversify and improve the nutritional quality of both local and global diets, and meet tropical landscape management objectives, but that several risks and limitations have to be taken into account. In this section, we discuss which key interventions are needed and which obstacles have to be overcome, both on the supply and demand side, so that an enabling environment can be created to drive restoration and sustainable development based on tropical tree-based food production, without creating unwanted side effects.

4.1 | Consumer demand

In order to increase demand for tropical tree-sourced foods, more information about these foods needs to reach consumers. Many tropical tree-sourced foods are relatively unknown and underutilized outside of rural communities. For example, only 34 of the 90 tree-sourced foods in our dataset are in the FAO trade database (FAOSTAT, 2018). To radically change diets, extensive behavioural change campaigns will likely be necessary, especially to increase the consumption of underutilized nutritious and healthy foods (i.e. currently undomesticated and only regionally known foods). Consumer behaviour depends on many factors related to the social and physical environment of people, and effectively changing consumer behaviour requires simultaneously influencing the capability, motivation and opportunity of people to change behaviour (van der Vliet et al., 2018). Lowering taxes on healthy, sustainable and/or carbon-positive foods (or increasing taxes on foods that do not have these characteristics) could make such foods more accessible, and motivate both domestic and international consumers to consume more of these foods (Lee, 2016). Additional interventions could include campaigns to raise consumer awareness about the nutritional and environmental benefits of tropical tree-sourced foods (e.g. through the use of different types of media and/or incorporation in educational programs, e.g. McGuire, 2015), while so-called 'nudging', using positive reinforcement to influence consumer behaviour, could provide a non-obtrusive enabling environment for consumers to shift their choices towards more sustainable foods (Vandenbroele et al., 2020). In combination with the global trend of increased consumer willingness to make diets more diverse, healthy and sustainable (Dowd & Burke, 2013), this could make the diversity of tropical tree-sourced foods a more important element of global diets, and as such become a driver of large-scale sustainable land-use in the tropics.

The potential large-scale impact on land-use from changes in consumer behaviour is well illustrated by historic consumption patterns of tree crops like cacao, avocado and cashew, which quickly gained popularity and have become more accessible over the last decades. Analysing FAOSTAT production area data (excluding countries with incomplete data, FAOSTAT, 2018), we show that the production area of both cacao and avocado have doubled over the last three decades, and that of cashew has increased fivefold (Figure 1a–c). Between 1985 and 2016, the combined production areas of these products grew from about 4 million ha to 14 million ha, showing the significance of changes in consumer's choices on land-use. If diverse tree-sourced foods were better integrated as part of sustainable diets at local, national and global level, this could be a driver of large-scale sustainable land-use in the tropics and profoundly enhance the functionality of tropical landscapes to become more environmentally sustainable and provide higher quality diets. However, as we discuss below, this will require several major interventions by states, markets and civil society, which will facilitate tropical tree-based food production, guarantee that this is done sustainably, and that increased consumption does not lead to negative side effects, as has often happened in the past and is currently still happening (see e.g. Carlson et al., 2012; Ruf et al., 2015).

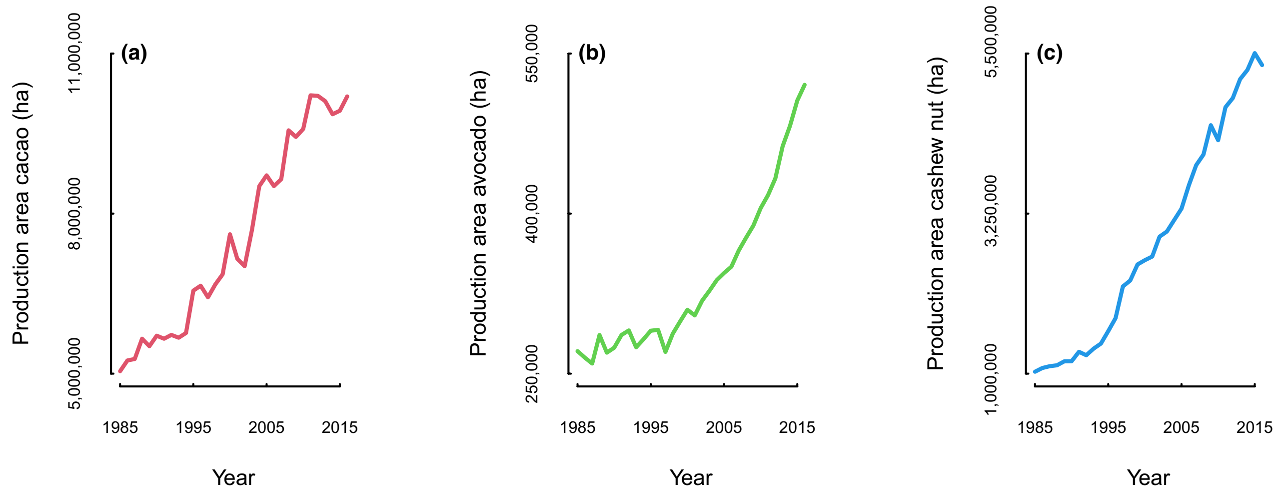

FIGURE 1 Historical changes over time in production area of the tree-sourced foods (a) cacao, (b) avocado and (c) cashew nuts. All data shown are FAOSTAT data (FAOSTAT, 2018). Countries with incomplete production area data were excluded

4.2 | Institutional, policy and financing barriers

An important barrier to implementation of tree-based food production systems is insecure land tenure rights (Brancalion et al., 2017; Ding et al., 2017). Secure land tenure rights are particularly important for tree crops, as due to the long payback time they are usually not produced on land with (perceived) insecure tenure rights (e.g. Tenge et al., 2011). Securing land and tree tenure rights, especially for smallholders and rural communities, should be prioritized by governments to increase local tropical tree-based food production. Fortunately, an increasing number of state and non-state actors recognize the importance of tenure security of communities (indigenous and non-indigenous) for the pursuit of economic, social and environmental needs. More than 200 million hectares have been devolved to communities since 1985 (White & Martin, 2002), and 27% of forests in developing countries is managed by communities (Larson et al., 2010; Sunderlin et al., 2008). Through new tools, institutions and funding mechanisms, community land rights are being granted and strong multi-sectoral partnerships are helping to prevent possible rollbacks (Rights & Resources Initiative, 2017). The devolution of land rights cannot guarantee that these rights are secure, because they remain subject to the institutional framework and political powers. However, national and international legal provisions, combined with a strong civil society, can force political leaders to respect these rights (Rights & Resources Initiative, 2017).

For smallholders, a long delay between planting and harvesting of tree-sourced foods, in combination with high initial investment costs, can be a significant barrier to their production (Jacobi et al., 2017). This can partially be alleviated by intercropping with compatible annual food crops, or through payments for ecosystem services (PES) such as carbon sequestration, watershed management and soil restoration. In addition, because most agricultural subsidies are allocated to annual crop production systems (Jacobi et al., 2017), shifting (some of) these subsidies to enhance tropical tree-based food production could provide incentives to implement these systems. Direct investment requires the trust of investors that there will be significant financial returns; experiences from timber plantations have shown that, aside from resolving land tenure issues, the best way to gain trust of both investors and smallholders, is to develop an evidence base on financial returns for tropical tree-based food production systems. Impact investors, governments and philanthropic sources can play an important role in the financing of these initiatives (Ding et al., 2017), and targeting such investments to smallholders (e.g. in the form of micro credits) could contribute to multiple SDGs such as reducing poverty (Knoke et al., 2009) and improving gender equality.

Traditional food systems are key to more sustainable and nutritious food production. However, obtaining access to national or international markets can be a challenge – especially for smallholders – due to quantity, quality and certification requirements (Jacobi et al., 2017) and because value chains are mostly absent or weak. Moreover, smallholders often lack technical knowledge and have high transaction costs, among other limitations such as lack of basic infrastructure (Johns et al., 2013; Markelova et al., 2009). Experience with well-established tree-sourced foods (e.g. cacao, Brazil nuts) has shown that collective action, such as through producers' associations, can help overcome such barriers. External assistance is often needed, as farmer organizations rarely self-organize. Non-governmental organizations (NGOs) can support collective action for marketing. However, both the public and the private sectors are critical in enabling smallholders to access stable and competitive markets (Brown & Sander, 2007; Guariguata et al., 2017; Markelova et al., 2009; Pacheco et al., 2017).

4.3 | Technical and knowledge barriers

Propagation methods, planting techniques and post-harvest technologies such as drying or processing for storage have been developed and improved over time for some tree species; however, sufficient knowledge is lacking for many undomesticated trees. For successful implementation of tropical tree-based food production systems, the development of such methods, techniques and technologies is essential (Jacobi et al., 2017; Leakey, 1999). Investment in this development by both governments and the private sector for the tropical tree-sourced foods that have the highest nutritional, environmental and market potential, taking regional skills, traditional knowledge, local needs and preferences into account, can help generate this knowledge. Once techniques are developed, governmental programs and NGOs could help to develop a strategy with rural communities to adopt (or to incorporate) these innovations.

It is also important to invest in the conservation of the genetic resource base of what are currently relatively unknown/underutilized tropical tree-sourced foods. For many such species, this resource base is vulnerable to being lost as species become extinct (see e.g. Gaisberger et al., 2017). Not only are a huge number of tree species lacking conservation classification (60%), but in a recent survey of seed systems for seven Latin American countries, only a tiny fraction of the native trees have any formal seed delivery systems (Atkinson et al., 2018).

4.4 | Sustainable production

Probably the largest challenge related to promoting the consumption of more tree-sourced foods is to guarantee that increases in demand are supplied from sustainable production systems that are diverse (to maximize environmental, social and nutritional benefits), and that will not lead to large-scale deforestation or other unwanted side effects, as has previously happened with large increases in global demand for certain products (Carlson et al., 2012; Ruf et al., 2015).

A combination of interventions by states, markets and civil society across the supply chain (from producers to consumers) has the potential to positively impact the ecological, social and environmental aspects of supply chain sustainability (Newton et al., 2013). Interventions such as certification schemes, restrictions in access to credit, and embargos have shown to be effective in the past (Carlson et al., 2018; Nepstad et al., 2014). Increased consumer awareness (e.g. due to civil society led campaigns) can change consumer behaviour by dissuading people from buying products that cause deforestation (Giam et al., 2016), and several food companies have made commitments towards deforestation-free supply chains (Sen, 2017). However, such commitments do not yet always lead to impacts (Lambin et al., 2018). Further evaluation of which combination of interventions is most effective under which circumstances remains a subject for further study (Newton et al., 2013).

Changing existing farming systems and stimulating sustainable tree-based food production that promotes equality and environmental integrity, requires integrated approaches that meet the needs of both environment and rural communities. One of the best opportunities to link tropical landscape management and consumption of tropical tree-sourced foods lies in the establishment of mixed production systems on (abandoned and deforested) land with agricultural potential (see e.g. Bastin et al., 2019; Griscom et al., 2017). Tropical tree-based food systems have a high potential to be integrated into forest and landscape restoration (FLR) interventions (Stanturf & Mansourian, 2017), which aim to reconcile environmental and social objectives in degraded lands. To obtain maximum environmental and nutritional benefits, and as such to contribute to several Sustainable Development Goals – including SDG2: improved nutrition and sustainable production, SDG 11: sustainable cities and communities, SDG 12: responsible consumption and production, and SDG 15: Life on land – cash crops need to be combined with a diverse native shade canopy, including fruit and other food-producing trees (Mansourian, 2018). Promoting native tree species that are already known to local farmers could help them regain control over these resources and over the quality of food consumption (Johns et al., 2013). The success of such interventions lies in how well these are embedded in the larger social, political and economic dynamics that influence local realities. Understanding how different land-use systems balance societal benefits at landscape, national and international levels requires carefully designed interventions that are tailored to the socio-ecological context (Sayer et al., 2017; Table 5).

TABLE 5 Overview of several interventions that can take away barriers and enable upscaling of tropical tree-based food production

Increasing consumer demand
• Lowering taxes on healthy, sustainable and/or carbon-positive foods • Behavioural change campaigns (including consumer education and nudging)
Tackling institutional, policy & financing barriers

• Securing of land tenure rights for especially rural communities
• Alleviate high investment costs and long payback time by:
  ○ Intercropping with annual crops
  ○ Payment for ecosystem services
  ○ Shifting agricultural subsidies towards tree-based food production
  ○ Develop evidence base for increased investment
  ○ Micro-credit provision
• Policy development & NGO assistance to support supply chain development and market access

Tackling technical and knowledge barriers
• Development of propagation methods, planting techniques and post-harvest technologies for undomesticated trees • Investment in the conservation of tree genetic resources and the development of formal seed delivery systems
Interventions to guarantee sustainable production

• Interventions across supply chains to prevent deforestation, including:
  ○ Certification schemes
  ○ Consumer education
  ○ Embargos
  ○ Restrictions in access to credit
• Planting of tree-based food production systems on previously deforested and/or degraded lands
• Combining cash crops with a native shade canopy to maximize nutritional, environmental and livelihood benefits

5 | CONCLUSIONS

Tropical tree-based food production offers an excellent opportunity to simultaneously transform food systems and contribute to landscape restoration in developing tropical countries. Planting the right type of trees in the right place can provide nutritious foods to improve diets sustainably, while providing other valuable ecosystem services (e.g. carbon sequestration) as well as contributing to national and international initiatives, including SDGs related to poverty reduction, biodiversity conservation and food security. Leveraging the diversity and local knowledge of tree species in tropical landscapes offers an excellent nature-based solution to match the rising global demand for diversified, healthy and sustainable diets, and to re-valuate native tree species and local farming practices. Local, regional and global consumer markets have the potential to drive the large-scale adoption of such tropical tree-sourced food-producing landscapes, provided they are aware of their multiple benefits.

Overcoming current barriers to large-scale adoption of tropical tree-based food production systems requires a holistic approach that addresses technical, financing, political and consumer awareness barriers simultaneously. Policies to support a transformational sustainable change in food systems are essential. With this holistic approach, consumption of tropical tree-sourced foods could drive more sustainable global land-use that restores ecosystem services including carbon storage and biodiversity conservation, diversifies diets of both producers and consumers, and improves the livelihoods of smallholders in their production landscapes. In the face of increased shocks from events such as global pandemics, like COVID-19, diversification of the food system is urgently required to ensure greater resilience locally and globally.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

AUTHORS' CONTRIBUTIONS

M.J., C.J.K. and M.R.G. conceptualized the study; J.E.R. provided data; M.J. and J.E.R. performed data analysis and interpretation; M.J. prepared the original draft. All authors contributed extensively to review and editing of the text and gave final approval for publication.

DATA AVAILABILITY STATEMENT

The datasets we used to analyse the contribution of tree-sourced foods to diets in rural populations in seven countries, are publicly available (https://dataverse.harvard.edu/dataverse/DietarySpeciesRichness).

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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