Conceptual Links between Landscape Diversity and Diet Diversity: A Roadmap for Transdisciplinary Research

SARAH E. GERGEL, BRONWEN POWELL, FRÉDÉRIC BAUDRON, SYLVIA L. R. WOOD, JEANINE M. RHEMTULLA, GINA KENNEDY, LAURA V. RASMUSSEN, AMY ICKOWITZ, MATTHEW E. FAGAN, ERICA A. H. SMITHWICK, JESSICA RANIERI, STEPHEN A. WOOD, JEROEN C. J. GROOT, AND TERRY C. H. SUNDERLAND

Malnutrition linked to poor quality diets affects at least 2 billion people. Forests, as well as agricultural systems linked to trees, are key sources of dietary diversity in rural settings. In the present article, we develop conceptual links between diet diversity and forested landscape mosaics within the rural tropics. First, we summarize the state of knowledge regarding diets obtained from forests, trees, and agroforests. We then hypothesize how disturbed secondary forests, edge habitats, forest access, and landscape diversity can function in bolstering dietary diversity. Taken together, these ideas help us build a framework illuminating four pathways (direct, agroecological, energy, and market pathways) connecting forested landscapes to diet diversity. Finally, we offer recommendations to fill remaining knowledge gaps related to diet and forest cover monitoring. We argue that better evaluation of the role of land cover complexity will help avoid overly simplistic views of food security and, instead, uncover nutritional synergies with forest conservation and restoration.

Keywords: sustainable development, landscape approach, food security and nutrition, remote sensing, tropical forest conservation and restoration

Over two billion people suffer from deficiencies in essential vitamins and minerals, a problem known as *hidden hunger* (Development Initiatives 2018). Improving diet quality is part of overcoming micronutrient deficiencies while also contributing to better health outcomes. Poor quality diets (such as low consumption of whole grains, fruits and vegetables, or high consumption of red meat, processed foods, salt, fat, and/or added sugars) are associated with higher risk for many chronic diseases and are now among the leading modifiable risk factors for mortality globally (Development Initiatives 2018, Afshin et al. 2019).

Dietary diversity is associated with higher dietary quality (Ruel 2003, Kennedy et al. 2011). When considering not just calories alone but diet quality and diversity, forests are an important contributor to human diets (Ickowitz et al. 2014, Rowland et al. 2017), particularly for those living in proximity to forests. For example, forests and trees are sources of several food groups containing micronutrients of global nutrition concern including iron, zinc, vitamin A, and folate (Powell et al. 2013a). These food groups include dark green leafy vegetables, fruits, and meat. A growing body of evidence links tree cover (i.e., the percentage of the land area under tree canopy) to dietary quality and diversity, along with other indices of nutrition (Johnson et al. 2013, Ickowitz et al. 2014, Galway et al. 2018, Rasolofoson et al. 2018, Hall et al. 2019, Lo et al. 2019). For example, across 21 countries, Ickowitz and colleagues (2014) demonstrated that the dietary diversity of children was positively correlated with the percentage of tree cover surrounding their communities. For 27 developing countries, Rasolofoson and colleagues (2018) estimated that living in highly forested areas increased the dietary diversity of children by 25% compared with those in less forested areas. Across 15 African countries, Galway and colleagues (2018) showed that child dietary diversity was negatively correlated with forest loss. However, the mechanistic pathways explaining these relationships remain poorly resolved.

In current debates about how to feed the world's growing population, a focus on yields and calories has placed a pervasive emphasis on agriculture, livestock, and fisheries (Ickowitz et al. 2019). We argue that this has contributed to blind spots in the role of landscape diversity, especially

where agriculture is situated within a mosaic of trees and forest. Although ten crops account for two-thirds of global cropland (Dawson et al. 2019), their perceived advantage relies heavily on measures of yield and less on nutrition (Remans et al. 2014, DeFries et al. 2015). Such a singular focus on agricultural yields and calories arguably over-simplifies food–forest–conservation debates. As a result, forests and trees are rarely integrated into food security, nutrition, and agricultural development strategies (Ruel and Alderman 2013, HLPE 2017, Downs et al. 2020). We posit that diet and nutrition, particularly dietary diversity, can benefit from a broader landscape perspective that not only addresses agriculture but also integrates forest conservation and restoration. Approaches that place dietary quality and nutrition more centrally and that seek to understand diet–landscape relationships are integral to meeting twenty-first century nutrition and food security goals, especially in many low-income rural regions of the world (Remans et al. 2011, DeFries et al. 2015, Powell et al. 2015, Ickowitz et al. 2019, Sunderland et al. 2019).

In the present article, we aim to foster the integration of forests into strategic thinking about agriculture, nutrition, and food security in rural tropical regions. To do so, we first explore the empirical basis of how forests, tree cover, and landscape diversity help support dietary diversity. We then identify remaining knowledge gaps with respect to the role of landscape diversity in enhancing dietary diversity. Finally, to strengthen research, we present a conceptual framework for guiding synthesis on the role of forests and diverse landscapes in enhancing dietary diversity. In addition to filling this conceptual gap, we also propose ways to fill remaining knowledge gaps through enhanced monitoring of forests and diets. We conclude by connecting our perspectives to synergistic outcomes for conservation and forest restoration. Taken together, we frame a comprehensive research agenda to help answer the question *How might forests and landscape diversity support dietary diversity?*

## Empirical basis for the role of forests and trees in dietary diversity

Forest foods. Significant evidence is emerging that forests, agroforestry systems, home gardens, and trees on farms provide nutritional benefits to millions of people, complementing other agricultural production systems (Kumar 2006, Powell et al. 2013a). *Forests*—defined as areas with tree canopy cover exceeding 10% and larger than 0.5 hectares (FAO 2010)—contribute to nutrition through a variety of direct and indirect mechanisms that have only recently become more widely acknowledged (HLPE 2017). Forests contribute directly to diverse, nutritious diets (pathway 1 in figure 1) by serving as a source of wild foods, the most commonly consumed being vegetables, mushrooms, fruit, insects, and wild meat, including birds and fish (Boedecker et al. 2014, Powell et al. 2015, Tata et al. 2019). Forests also contain habitat for a variety of wildlife species (bushmeat and fish)

that provide critical micronutrients (e.g., iron; Fa et al. 2003, Blaney et al. 2009, Golden et al. 2011, Nasi et al. 2011, Lo et al. 2019). Furthermore, women rely on forest products differently from how men do (Sunderland et al. 2014), with far-reaching effects on household diets, given women's decision-making and control over food provisioning (Herforth and Ahmed 2015, Malapit and Quisumbing 2015).

Tree-based agricultural systems. *Agroforestry* is the deliberate retention or integration of trees on farms, either alongside crops or in rotation (Leakey 1996). Trees in agroforestry systems produce food directly (via fruits and nuts) but also support the productivity of crops and livestock via ecosystem service benefits (Reed et al. 2017) that include moderating harsh microclimates (Sida et al. 2018a), promoting the return of organic matter to soils (via litterfall and root turnover), and improving soil fertility (Kumar 2006). Deep tree roots can also mobilize nutrients and access water deep below ground and can reduce erosion (Garrity 2004, Kumar 2006, Jamnadass et al. 2013, Zomer et al. 2014). Forests and trees in agricultural systems also provide habitats for natural enemies of crop and livestock pests (Bianchi et al. 2006). As a result of these types of regulating and supporting ecosystem services (pathway 2 in figure 1), some crops grown in agroforestry combinations achieve higher yields (Kumar 2006, Sida et al. 2018a). And further, soils with increased nutrients can translate into micronutrients in food (Frossard et al. 2000, Lal 2009, Arhin and Kazapoe 2017, Wood et al. 2018). The inclusion of fruit trees in agroforestry systems is also important to improving fruit consumption (McMullin et al. 2019).

Home gardens are small plots of cultivated land typically located close to the homestead (Powell et al. 2015). They often include overstory trees, crops, and a mix of wild and semidomesticated species (Freedman 2015). The biotic diversity of home gardens, along with their close proximity to homesteads, makes them an important source of nutritionally important food (Kumar and Nair 2004, Powell et al. 2015). Four separate reviews of the affects of agricultural interventions on nutrition outcomes (Tontisirin et al. 2002, Berti et al. 2004, Girard et al. 2012, Masset et al. 2012) each noted that home garden interventions are one of the most successful types of agricultural interventions for improving diet and nutrition (Powell et al. 2015). The type and diversity of home gardens have been found to be more important for diet quality than the size of the garden (Bloem et al. 1996). Home gardens are particularity important in marginal arid lands, which are home to 33% of the global population (Hori et al. 2012). In such landscapes, the nutrient flux from surrounding forests and trees not only maintains agriculture (such as row crops and livestock) but can also provide nutrient inputs that support home garden soils (Baudron et al. 2017).

Landscape diversity. Despite their nutritional advantages, many diverse agriculture systems that include trees are
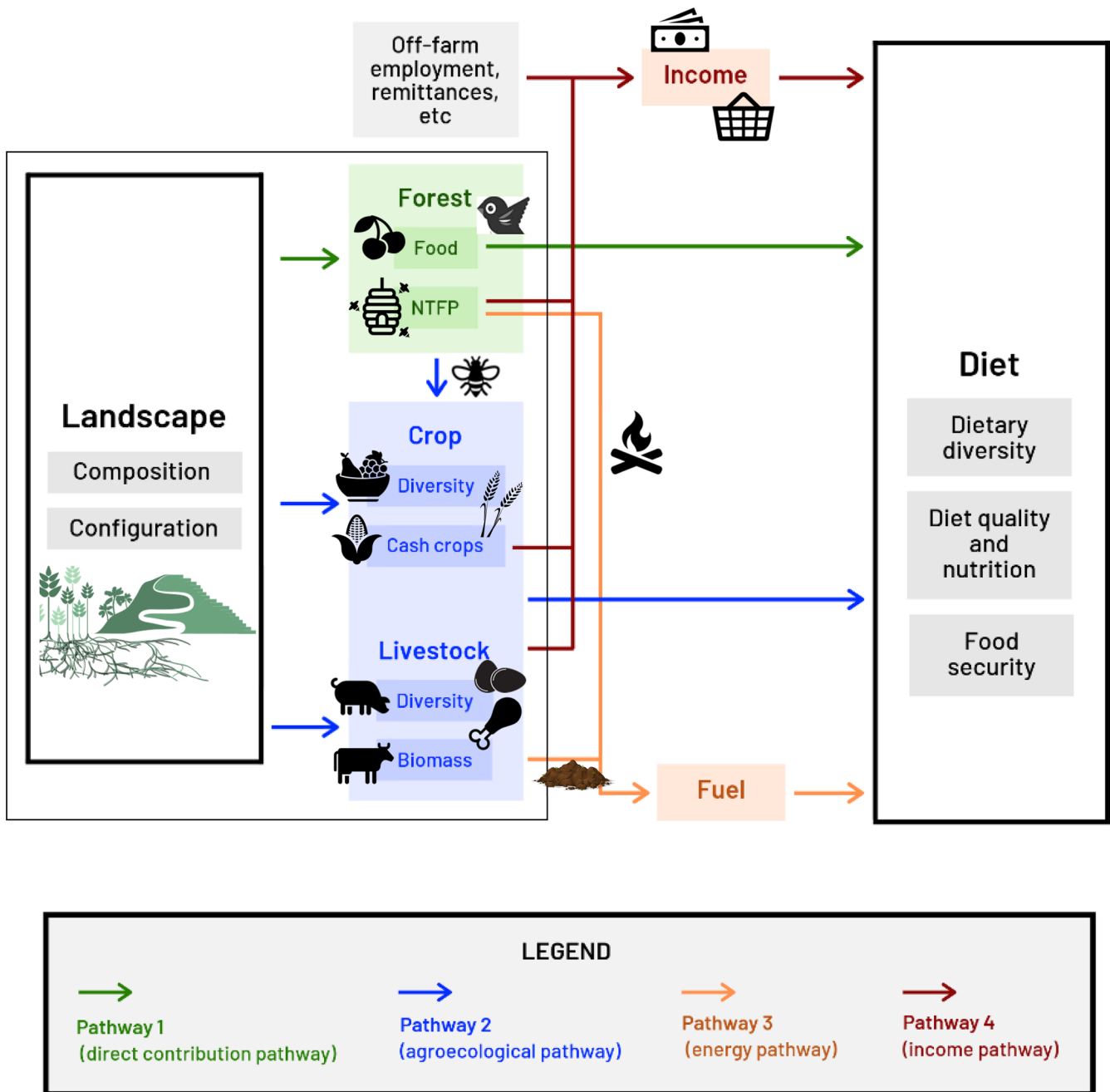
Figure 1. Landscape diversity can contribute to dietary diversity through four complex interacting pathways. Although forests make direct contributions to diets, landscape mosaics composed of forests and agriculture also interact to contribute to dietary diversity through several indirect pathways. The direct forest pathway can be critical during seasonal lean periods for agriculture and can provide income that enables purchase from markets. Market access can result in both beneficial and detrimental impacts on the quality of human diets. In an ideal situation for nutrition and dietary diversity, markets enable purchase of diverse nutritious foods. In a less than ideal situation, landscapes producing only a few commercial crops can give rise to local markets with fewer fresh foods and more highly processed, less healthy foods.

increasingly being replaced by commercial monocultures (Kumar and Nair 2004, Padoch and Sunderland 2014), with complex effects on nutrition. In some regions, access to cash income enables households to purchase foods that diversify their diets (Sibhatu et al. 2015, Remans et al. 2014).

Also, a number of studies have shown market access to be associated with greater dietary diversity (Sibhatu et al. 2015, Jones 2017). However, higher household cash flows may also be associated with more numerous, frequent, and larger-quantity purchases of highly processed and

micronutrient-poor foods (Popkin 2004, Reyes-Garcia et al. 2019). For example, in Ghana, the introduction of commercial cacao production was associated with lower nutritional diversity (Anderman et al. 2014, Remans et al. 2014). As such, a view toward the interaction of forests with various forms of agriculture nearby is needed.

Landscape diversity—the number and types of different land cover and their spatial distribution (Gergel and Turner 2017)—is an emerging and essential component of nutrition-sensitive landscapes (Powell et al. 2013a). Nutrition interventions alone, such as supplementation and fortification of single nutrients in single crops, cannot meet global targets for reducing all forms of malnutrition. This has led to increasing calls for cross-sectoral attention to nutrition and diet quality, especially in agriculture (Ruel and Alderman 2013). As a result, nutrition-sensitive landscapes are gaining attention, with the goal of building ecological and nutritional diversity into landscape policy and planning (Powell et al. 2013a). The approach aspires to provide multiple sources of nutrients to people along with other ecosystem services (Reed et al. 2017). To achieve this goal, nutrition would be necessarily integrated into policies and programs that are also cognizant of environmental targets. Wild forest foods, for example, would be assessed in hunger and poverty alleviation programs, as well as in protected area management. However, this new appreciation of food–forest–landscape dynamics lacks a full understanding of how various configurations of forests, trees, and fields interact to buoy dietary diversity (Rasmussen et al. 2019).

We argue that operationalizing the concept of landscape diversity with regards to diet and nutrition is underdeveloped from both conceptual and technical perspectives. In the present article, taking a broader landscape perspective, we place particular emphasis on the availability of and access to forests and trees, as well as their type, stand age, and travel distance, all of which potentially influence the ways forests and trees affect diverse diets. Concepts and approaches from landscape ecology and spatial analysis are well suited for providing insights into how landscape structure and configuration can support dietary diversity.

Food for thought: Hypotheses to deepen our understanding of the nutritional function of landscapes

Building on the evidence base above, we further integrate landscape ecological principles into four landscape-level hypotheses (H1–H4) that provide a rich arena for additional research, refinement, and evaluation.

Disturbed and secondary forests play an underappreciated role in providing wild foods. Younger recently disturbed forests and those regenerating after disturbance likely support dietary diversity in different ways than older or more intact forests because their function, structure, and composition differ (Brown and Zarin 2013, Tropek et al. 2014, Sutherland et al. 2016, Watson et al. 2018). For example, in Tanzania, wild leafy greens collected from disturbed forests are an important source of nutrition largely unavailable in primary forests (Powell et al. 2013b, Magnago et al. 2015). Many wild foods are found within forest fallows (i.e., young regenerating forests on previously cropped fields; Brookfield and Padoch 1994, Broegaard et al. 2017). Fallows support legacy species from prior cultivation, as well as from previously discarded pits and seeds (Wood et al. 2016), along with intentionally planted species (Sanchez 1999). Fallows and secondary forests are often important sites for hunting (Naughton-Treeves 2002, Smith 2005, Nasi et al. 2011). Initial evidence suggests that landscapes that include fallows and swidden agroforestry are associated with higher consumption of micronutrient-rich food groups than are landscapes with simplified agricultural systems (Ickowitz et al. 2016).

These relationships are complex, however. In the Brazilian Amazon, primary forests could sustainably provide more wild meat (per hectare) than secondary forests (Parry et al. 2009). However in the Bolivian Amazon, the density of useful plant species was lower in mature forests than in secondary forests (Toledo and Salick 2006). In the Peruvian Amazon, young fallows provided fewer useful species than secondary forest, but their total monetary value was greater (Gavin 2004). Finally, tree species composition within planted and regenerating stands likely affects their function, in part, because of the simplified forest structure of some forest plantations and managed secondary forests that have less diversity of tree and understory species (Nájera and Simonetti 2010). As an example, within some Amazonian riparian areas, extensive açaí palm forest management has produced monodominant forests (Weinstein and Moegenburg 2004).

Forest edge habitats as nutritional ecotones. Over 70% of the world's remaining forests are within 1 kilometer of a forest edge (Haddad et al. 2015). *Forest edge ecotones*—where forests meet other land cover types—consist of altered light, moisture, and nutrient conditions and are characterized by higher species diversity of plants and animals. This fundamental edge effect principle of ecology (Saunders et al. 1991, Haddad et al. 2015) potentially influences the type and amount of forest foods available near forest edges. Species preferring high light environments, such as pioneer or weedy species, thrive at forest edges (Magnago et al. 2015). Guava (*Psidium guajava*) serves as a prime example; it can be invasive along forest edges but provides an important fruit resource for people and animals (Berens et al. 2008). Forest edges also provide improved access points into forest interiors from which wildlife (for bushmeat) and fuelwood (for cooking) can be extracted.

Forests also affect adjacent agricultural lands (Mitchell et al. 2015) and, in doing so, can indirectly influence dietary diversity by affecting agricultural productivity. Among the most well understood positive influences is the impact of forests on crop pollination (Ricketts et al. 2004, Bailey et al. 2014). Roughly a third of global food comes from pollinated

crops, many of which are also nutrient dense (Eilers et al. 2011). Insects at forest edges can enhance pest control (via natural enemies) or result in damaging crop herbivory (Bianchi et al. 2008). Raiding of crops and livestock by forest wildlife can create significant vulnerabilities for food security of rural households, however (Dorresteijn et al. 2014). Other disservices may include negative impacts on agricultural yields through competition for light, water, and nutrients (Akbar et al. 1990, Reynolds et al. 2007, Sida et al. 2018b). On balance, edge effects on agricultural production appear to be positive (González et al. 2016).

Interestingly, the total amount and arrangement of forest edge habitats can alter ecosystem services and disservices provided by forest–agricultural landscape mosaics, and the impacts may be perceived differently among various households (Dorresteijn et al. 2014). Furthermore, the total amount and arrangement of forest edge habitats can function in nonlinear ways to affect ecosystem services in landscapes composed of forest and agriculture (Yang et al. 2020). Because edge influences can permeate forest interiors to a depth of 100 meters or more (Laurance 1997, Chaplin-Kramer et al. 2015), a substantive area of the world's forests is potentially subject to edge influences. Therefore, recognizing trade-offs among ecosystem services and disservices is critical for human well-being (Shackleton et al. 2016, Power 2010), and this challenge may be particularly acute near forest edges.

Access mediates the impact of forests on dietary diversity. Households further from forests and trees may have less diverse diets because they lack routine access to forest foods. As the distance to a forest increases, forest foods are likely to be more costly to obtain (in terms of both time and effort; Baudron et al. 2017). In contrast, close proximity to forests can provide opportunistic access to bushmeat species abundant at the forest edges, whereas fruit-bearing trees planted near villages may attract a variety of animal species (rodents and monkeys; Berens et al. 2008, Sunderland and Rowland 2019). Importantly, people may travel much further or deeper into the forest interior for hunting, fishing, or specialty forest foods (e.g., orchid tubers and mushrooms; Cunningham 2011). Although travel distances and movements can be very site specific and are affected by cultural food preferences and terrain, the distance to forests and trees likely affects consumption of forest foods.

In addition to location, permissions and land rights affect access and therefore mediate the role of forests in influencing dietary diversity. For example, despite the high availability of wild foods in protected forests (Ratsimbazafy et al. 2012), National parks and protected areas with restrictions on access or extraction may result in fewer dietary benefits than accessible communal areas (Sylvester et al. 2016). Similarly, rules governing access and extraction rights around private or community-managed forests can limit the harvest of resources (Robinson and Lokina 2011, Jagger et al. 2014). Importantly in some landscapes, forest resources serve as an economic equalizer, making disproportionate contributions to livelihoods for resource-poor, land-poor, or female-headed households (Kamanga et al. 2009). Therefore, the loss of access may disproportionally affect such households and their diets. Thus, the presence of forest within landscapes may not be a straightforward predictor of improved dietary diversity if the local people do not have access (Naidoo et al. 2019).

Landscape diversity can bolster dietary diversity. When considered collectively, the aforementioned patterns suggest that diverse heterogeneous landscapes may be better equipped to support diverse diets, particularly in rural landscapes in which market access is low. Where local landscapes—landscapes on which people rely—provide reasonable access to the ecosystems and land cover types needed for diverse foods, it is more likely people will have access to diverse diets. For example, in Tanzania, many of the vegetables consumed grow as wild species along forest edges or within fallows (Powell et al. 2013b). Consumption of fruit relies on agroforests, scattered trees, and disturbed or edge forest (Powell et al. 2015). Meanwhile, home gardens often support species not found elsewhere (Powell et al. 2015). In many parts of the world, meat consumption requires access either to large forest tracts with wild game or to areas producing feed or fodder for domesticated animals. Finally, grains, legumes, and some roots or tubers require farmed land.

Simply put, different species and food groups require different ecological niches, but rarely are all these drivers of dietary diversity examined in a unified way. However, such diversity in local landscapes can enhance dietary diversity by providing a variety of nutrient-dense food items in addition to what can be procured in markets. It is precisely in such rural landscapes where forest and biodiversity loss are of concern (Dawson et al. 2019), along with food security and poverty alleviation, further emphasizing the need to clarify the significance of forests in concert with other land cover types.

In addition to landscapes composed of many land cover types, the type and spacing of agricultural fields may also provide an indication of available dietary diversity (Kumar et al. 2015, Herrero et al. 2017,). Larger fields (i.e., clumped, unified parcels) comprising inedible cash crops or monocultures (e.g., palm oil) are typically indicative of specialization. Specialized production systems and monoculture-dominated landscapes are less likely to directly provide diverse dietary resources, especially to local residents. In contrast, landscapes with smaller fields are more likely to include traditional forms of agriculture, involving intercropping, rotations, and mixed crop–livestock production, as well as agroforestry and, therefore, a potentially greater range of agricultural products (Fanzo 2017, Herrero et al. 2017).

The majority of fruits, vegetables, and pulses are produced in more diverse agricultural landscapes (Herrero et al. 2017), and the majority of food in sub-Saharan Africa, Southeast Asia, South Asia, and China is produced in small farms (Herrero et al. 2017). Therefore, there is evidence that small,

diverse farms are key for supplying nutrient-rich foods in many regions of the world. Incorporating more complex aspects of landscape diversity, both within and beyond agriculture, takes a step further in generating an understanding of landscape features important in diet diversity. Fully recognizing the role of landscape diversity could help integrate the various aspects of forests, trees, and farms capable of supporting diverse diets.

A way forward for filling knowledge gaps

Several conceptual and methodological gaps currently stymie our ability to uncover the role of landscape diversity in supporting dietary diversity. We propose several ways forward to help better understand these relationships.

Less compartmentalized approaches are needed to understand the many pathways to dietary diversity. First and foremost, a guiding framework to support transdisciplinary approaches is essential because landscapes can contribute to dietary diversity through many interacting pathways (figure 1), and the understanding of each requires expertise from many disciplines. The direct pathway from forests to dietary diversity (pathway 1 in figure 1) captures the known direct contributions of forests to diets in the form of wild or forest-sourced foods, ranging from fruits and vegetables to fish and bushmeat (Fa et al. 2003, Vinceti et al. 2008, Nasi et al. 2011, Termote et al. 2011, Powell et al. 2013b). In addition, forests also affect dietary diversity via less direct agroecological pathways (pathway 2) through which forests support agriculture. The agroecological pathway includes a wide variety of ecosystem services that support agricultural production (including the maintenance of soil fertility, pollination, and pest control; Ricketts et al. 2004, Bianchi et al. 2006, Reed et al. 2017, Wood et al. 2018). Furthermore, forests serve as a source of feed and fodder for livestock, which then produces animal products for direct consumption (meat, milk, eggs), as well as soil amendments (manure) for row crops and home gardens (Baudron et al. 2017). The fuels pathway (pathway 3) highlights how forests and agroecological pathways can ameliorate energy poverty for households with insufficient energy to cook or for those spending hours on fuelwood collection (Wan et al. 2011, Baudron et al. 2017). Fuelwood from forests, along with dung from livestock, not only facilitates cooking a range of foods for many households but also supports the preparation of nutrient-dense foods with long cooking times, such as legumes (Powell et al. 2015).

Market access can either amplify or counteract the dietary benefits of forests. Finally, the role of income and market access (pathway 4) in supporting higher dietary diversity is complicated in rural forested areas, with important caveats and trade-offs (Pfund et al. 2011, Angelsen et al. 2014). Forest-adjacent communities are often some of the most remote and poorest in a country or region. Despite the many forest products that can be sold to generate income, the importance of income from forest products relative to other sources is mitigated by

market access and other factors. The relative importance of income from the sale of forest products may change in times of crises (e.g., drought, illness, or other shocks). Although the sale of forest products can provide rural households with an income safety net (Shackleton and Shackleton 2004, Shackleton et al. 2007, Arnold et al. 2011), other coping strategies may be more common (Wunder et al. 2014). In Honduras, the sale of forest products, although it is not the most common coping mechanism to deal with hurricane related crop loss, was used most commonly by young, poor, and land-poor households (McSweeney 2004).

Whether or not increased market access or income will improve diets depends on aspects of the nearby markets. In rural areas in which local infrastructure (electricity, refrigeration, transportation, etc.) is not well developed, highly perishable foods (such as fresh fruits, vegetables, fish, and meat) do not travel long distances. In such places, markets may only supply locally produced perishable foods, in addition to nonperishable processed foods from regional or global markets (Ickowitz et al. 2019). Because of this, greater market access can be associated with higher access to and consumption of processed foods (Reyes-Garcia et al. 2019), which are micronutrient poor and high in energy, salt, sugar, and fat. Therefore, although markets can enhance dietary diversity by providing access to a wider range of foods, there are complex interactions among forests, market access, and nutrition that have yet to be well understood.

Because the majority of fruits, vegetables, and pulses are produced in diverse agricultural landscapes (Herrero et al. 2017), markets are also key for ensuring that nutrient-rich foods reach consumers outside of such origin or production landscapes. Therefore, markets bring some of the benefits of the nutrient-rich foods from diverse landscapes to other consumers (beyond the landscapes in which the food was produced) in both rural and urban landscapes. To fully appreciate the role of markets, nutrition-sensitive landscapes should be studied as socioecological systems (Kalaba 2014) that involve the choices of local farmers and their relations with other beneficiaries (either directly or indirectly through markets or teleconnections). Such perspectives are critical to understanding the dynamics between rural areas and growing urban centers, inform debates on local versus global food sourcing, and indicate the scale and intensity of land use required to feed the global population with a diversified healthy diet.

Improvements in future monitoring and research methods

To understand these four pathways and evaluate the strength of evidence supporting or negating each, several monitoring gaps must be filled. Methods for improving the empirical assessment of forest cover and dietary information are explained next.

Filling gaps in measures of dietary intake

Evaluating the direct contribution of forests to diet (as in pathway 1 in figure 1) requires an understanding of the

origin of food products. Unfortunately, several methodological issues surrounding collection of dietary intake data limit our ability to understand the importance of this pathway. First, research on dietary intake does not routinely determine the origin of food, be it nearby forests, a farmer's own fields, or markets. Food from markets may also be of indeterminate origin (fields or forests) or may come from different countries. Because very few studies gather this level of detail, most studies cannot provide direct attribution of forest-sourced foods, much less the type of forest from which a food was collected. Many large, publicly available data sets contain information at the food group level (fruit, meat, dairy, etc.) and therefore lack the species or varietal information needed to trace a food's origin (e.g., https://dhsprogram.com). Such coarse levels of information hinder our understanding of forests' contribution to nutrition.

Seasonality affects the availability and use of forest foods; therefore, diet diversity can change seasonally (Waswa 2016, Stevens et al. 2017). In Malawi and Zambia, the proportion of women meeting minimum diet diversity requirements fluctuated widely depending on the month of data collection (Ahern and Kennedy 2018). In contrast, dietary diversity did not change across seasons in Tanzania; however, the *source* of foods did change, whereby wild food consumption was greater during the food-insecure season (Powell et al. 2013b). Although consumption of wild foods is highly seasonal, it is unclear whether this is driven by need or availability (Powell et al. 2015). Seasonal nutritional patterns must be better characterized if we are to understand the contributions of forests to nutrition.

A greater depth and nuance in dietary diversity metrics could also improve our understanding of landscape-diet relationships. Diversity indices are quite well developed and routinely used in ecology to characterize species and land cover diversity, probing well beyond just total species counts. For example, tracking identities (species, cultivars, and varieties) would be useful in determining how local (alpha) diversity is generated. Furthermore, the benefit of using more complex diversity indices would enable analysis of diversity differences among households (such as beta diversity), and their contributions to the total diversity in a landscape (gamma diversity). Lachat and colleagues (2018) used dietary species richness (DSR) to explore diversity beyond food groups, thus capturing the biological diversity of diets. DSR has been validated and shown to be positively correlated with micronutrient intake and diet quality across multiple countries (Lachat et al. 2018). Nutritional functional diversity has also been linked to dietary quality (Lachat et al. 2018) and lower incidence of child malnutrition at the national scale (Remans et al. 2011). Because some such metrics can be challenging to interpret, Wood (2018) developed the potential nutritional adequacy score, a simplified but intuitive indicator capturing multiple dimensions of nutritional diversity. It has been used to assess how different production systems contribute to nutritional needs in Senegal (Wood 2018).

In summary, to better understand the contribution of diverse landscapes to dietary diversity, dietary intake assessments must pay more attention to food origin, seasonal variation, and consider a greater more creative range of diet diversity metrics.

Improved monitoring and mapping of trees and forests

Advances in remote sensing could help evaluate the attributes of forests, woody vegetation, and scattered trees which are important to diets but are not typically captured in routine forest cover mapping. Several knowledge gaps could be filled by the use of high spatial resolution imagery, a better characterization of seasonal forest phenology, and a clear understanding of historical forest change.

Unfortunately, many definitions of forest used in monitoring not only underestimate tree cover (Chazdon et al. 2016) but potentially underestimate forest types of value to nutrition, as well as to ecosystem services (Gross et al. 2017). As such, the definitions of *forest* and *nonforest* used in satellite remote sensing (Chazdon et al. 2016) are important to reconsider in light of forests' role in food security and dietary diversity. For example, minimum thresholds for tree canopy cover and forest patch size are often used in mapping to delimit an area as forest. Notably, over 40% of agricultural lands worldwide have more than 10% canopy cover (Zomer et al. 2014), coincidentally exceeding the 10% canopy threshold often used to define an area as *forest* (FAO 2010). Use of 0.5-hectare minimum patch size thresholds (as in http://mapbiomas.org) disregards small forests fragments and remnants, such as sacred forest patches, home gardens, narrow riparian forests, live fences, and scattered fruit trees. Such fine-scale features are generally missed by the spatial resolution of sensors on satellites in routine use historically (such as 30-meter Landsat), making such features difficult to monitor (Gergel 2007). Such forest mapping criteria influence the detection, classification, and characterization of landscape diversity, particularly so in places with sparse tree cover or small forest fragments (Chazdon et al. 2016). Although food resources from small forest patches and scattered trees have largely been overlooked by the development community (Kumar 2006), they are, in addition, simply not well captured in routine forest monitoring.

The use of high spatial resolution satellite imagery (e.g., WorldView-3, Quickbird, SPOT, and RapidEye) can capture individual trees (Li et al. 2017), riparian forests (Johansen et al. 2007), and sparse savanna tree cover (Boggs 2010). Colgan and colleagues (2012) successfully combined high spatial resolution aerial imagery and lidar to map tree species in South African savannas. High resolution imagery has been used to generate settlement maps across several developing countries (e.g., Tatem et al. 2007), which could be used to estimate the occurrence of home gardens. Although the ecological importance of large scattered trees is appreciated (Manning et al. 2006), understanding the role of scattered trees or sparse woody vegetation in nutrition will

necessitate the use of higher spatial resolution approaches to capture fine-scale attributes because fruit consumption relies on agroforests, scattered trees, and home gardens (Powell et al. 2015).

Temporal aspects of food–forest dynamics require forest tracking across different timeframes from the short term to the longer term. Throughout much of Africa, vegetation greenness varies dramatically across the year (Zhang et al. 2018) affecting forest resources. For example, in Burkina Faso, edible leaves from trees (such as the baobab tree, *Adansonia digitata*) provide up to 60% of consumed vegetables. As a deciduous species that loses its leaves in the dry season, its availability to produce food is highly seasonal. As a result, to ensure vegetable consumption in the dry season, people must either dry tree leaves or have access to irrigated gardens (Mertz et al. 2001, Lykke et al. 2002). Such phenological changes present challenges for deriving accurate consistent vegetation information because satellite imagery often provides coverage at either high spatial resolution over infrequent intervals or at frequent intervals but with coarse resolution. Among possible solutions include use of high spatial resolution imagery to train more frequent moderate resolution imagery (e.g., Brandt et al. 2018), as well as the inclusion of mapping targets (such as buildings) that lack phenological variability.

Distinguishing between older forest remnants and newly established forests is not only important for ecological reasons (Chazdon et al. 2016) but, as was previously discussed, is potentially of great importance to nutrition. The structure and composition of new tree cover and younger forests differ from those of older forests (Brown and Zarin 2013, Sutherland et al. 2016). Although many regions of the world now lack large tracts of primary undisturbed forest, many forest assessments do not distinguish between planted and naturally regenerated forests or between stands of different age. Without such distinctions, the expansion of plantations may be portrayed as a gain (or no net loss) of forests (Puyravaud et al. 2010, Chazdon et al. 2016, Petersen et al. 2016). Even Hansen's extremely useful and ambitious map of global deforestation classifies rubber, oil palm plantations, and other monocultures as forest cover (Hansen et al. 2013, Tropek et al. 2014). Gaining a deeper perspective of forest trajectories and how they affect forest foods will necessitate longer-term image time series from sources such as Landsat (Hansen et al. 2013) or historical archival aerial photography (Morgan et al. 2010).

In summary, detailed tracking of forest landscape mosaics over time could be a powerful approach for prioritizing nutrition-based interventions. However, evaluation of nutrition-sensitive landscapes will remain challenging until such mapping is refined.

Implications for land-use planning, conservation, and forest restoration

Our efforts to theorize and monitor the pathways leading from landscape diversity to dietary diversity can contribute to the goals of several emerging landscape approaches in land-use planning (Sayer et al. 2014, Laestadius et al. 2015) and have implications for conservation, agriculture, and forest restoration, as well as human well-being. Understanding landscape diversity and improving the tools used to measure it will improve our ability to balance the multiple functions and multiple stakeholders that landscapes must support (Sayer et al. 2014).

High spatial resolution mapping and monitoring has the potential to not only aid nutritional planning but also yield benefits to conservation and restoration initiatives often occurring within the same landscapes (Fisher and Christopher 2007), ensuring nutrition and human well-being are not ignored. For example, tracking small linear forests that provide waterway protection or remnant forest patches and scattered trees that support habitat conservation and connectivity are also useful in planning for landscapes that can support diverse diets. High spatial resolution remote sensing needed to inform landscape pattern and connectivity assessments for conservation could simultaneously contribute information about the types of foods potentially available in a landscape.

Over 500 million smallholder farming households rely on their local landscapes for much of their nutrition (Lowder et al. 2016). Furthermore, small farms in diverse landscapes are producing the majority of the world's food, especially in terms of fruits, vegetables, and important micronutrients (Herrero et al. 2017). However, declining farm sizes in many low-income countries (Lowder et al. 2016), along with transitions to large-scale corporate agricultural production, is placing these farming landscapes under increasing pressure. Higher land-use intensity has been associated with lower use of wild foods (Cooper et al. 2018). Therefore, with increasing land-use intensity, the diets of farming households producing the world's food may change irreplaceably (Ickowitz et al. 2019). Finally, in the face of climate variability, landscape diversity may play an increasingly important role in coping with food shortages (Koffi et al. 2016).

Some nutritionally important foods may be more dependent on ecosystem services such as pollination (Gallai et al. 2009, Eilers et al. 2011, Smith et al. 2015), and as a result, land-use change and homogenization could lead to their decline (Reed et al. 2017). Fortuitously, in the case of forest restoration, there is a growing emphasis on landscape approaches. The term *forest landscape restoration* encompasses a broader view that recognizes diverse options for both forestry and agriculture (Laestadius et al. 2015). The approach looks beyond site-level technical interventions toward balancing multiple benefits and mitigating trade-offs across landscapes (Laestadius et al. 2015). In fact, the IUCN (International Union for Conservation of Nature) has recently recommended that the World Bank consider landscape approaches in reviews of forest policy (Laestadius et al. 2015). Despite the integral importance of forests to diets, forest resources are not well integrated into poverty alleviation or into nutrition strategies (Oksanen and Mersmann

2003, Powell et al. 2015), but the opportunity exists for their improved integration. Therefore, a landscape perspective on nutrition is both timely and commensurate with emerging priorities for forest restoration.

Conclusions

Understanding the role of landscape diversity in supporting diet diversity, diet quality, and nutrition is a research imperative. Tackling this challenge requires better integration of expertise that spans multiple disciplines and newly available geospatial information to rigorously evaluate landscape–diet relationships. In the present article, we offer a way forward in addressing the complex interactions between landscape diversity and that of human diets in the rural tropics. First, we summarized the state of knowledge regarding diets obtained from forests, trees, and agroforests. We then hypothesized how specific forest types, as well as overall landscape diversity, can function in supporting dietary diversity. In doing so, we built a framework illuminating four pathways (direct, agroecological, energy, and market pathways) connecting forested landscapes to diet diversity. Finally, we offered recommendations to enhance monitoring of human diets and forest cover designed to help illuminate these pathways.

Biodiversity conservation, climate change, land-use change, agriculture, human health, and nutrition are all integrally affected by landscape structure and diversity. The conceptual and technical approaches we have presented can improve the way competing demands for land are contextualized when food security and nutrition are considered along with forest conservation. The nutrition community is increasingly attentive to issues of sustainability in global diets and dietary recommendations (Hirvonen et al. 2019, HLPE 2019, Willett et al. 2019). Commitments such as the United Nations' decade of action on nutrition note synergies between the goals of global nutrition and conservation. Also highlighted is the need to move away from an overemphasis on increasing production of staple crops and calories without due attention to diet quality, protection of poor farmers, and sustainability. Along with the United Nation's decade of ecosystem restoration for 2021–2030, such growing national and international commitments across research and policy communities demand transdisciplinary and integrated approaches. Therefore, an opportunity exists to use national and global dietary recommendations to improve the sustainability of food production landscapes around the world while also achieving forest conservation solutions. Truly finding balanced solutions for the multiple functions needed from landscapes will require understanding how landscapes shape diverse nutritious diets.

References cited

Afshin A, et al. 2019. Health effects of dietary risks in 195 countries 1990–2017: A systematic analysis for the Global Burden of Disease Study 2017. Lancet 393: 1958–1972.

Ahern M, Kennedy G. 2018. The use of dietary surveys across seasons to identify patterns of seasonality in dietary intake and opportunities to diversify diets of women of reproductive age in Zambia and Malawi. Scientific poster presented at the Africa Nutritional Epidemiology Conference (ANEC) Addis Ababa, Ethiopia.

Akbar G, Ahmad M, Rafique S, Babar KN. 1990. Effect of trees on the yield of wheat crop. Agroforestry Systems 11: 1–10.

Anderman TL, Remans R, Wood SA, DeRosa K, DeFries RS. 2014. Synergies and tradeoffs between cash crop production and food security: A case study in rural Ghana. Food Security 6: 541–554.

Angelsen A, Jagger P, Babigumira R, Belcher B, Hogarth NJ, Bauch S, Börner J, Smith-Hall C, Wunder S. 2014. Environmental income and rural livelihoods: A global-comparative analysis. World Development 64: S12– S28.

Arhin E, Kazapoe R. 2017. Selenium in locally produced food crops and implications on healthy eating: A case study at the Talensi district of Ghana. Ecronicon Nutrition 8.3: 85–92.

Arnold M, Powell B, Shanley P, Sunderland TCH. 2011. Forests, biodiversity and food security. The International Forestry Review 13: 259–264.

Bailey S, Requier F, Nusillard B, Roberts SPM, Potts SG, Bouget C. 2014. Distance from forest edge affects bee pollinators in oilseed rape fields. Ecology and Evolution 2014 4: 370–80.

Baudron F, Chavarría J-YD, Remans R, Yang K, Sunderland T. 2017. Indirect contributions of forests to dietary diversity in Southern Ethiopia. Ecology and Society 22 (art. 28).

Berti PR, Krasevec J, Fitzgerald S. 2004. A review of the effectiveness of agriculture interventions in improving nutrition outcomes. Public Health Nutrition 7: 599–609.

Berens DG, Farwig N, Schaab G, Böhning-Gaese K. 2008. Exotic Guavas are Foci of Forest Regeneration in Kenyan Farmland. Biotropica 40: 104–112.

Bianchi FJJA, Goedhart PW, Baveco JM. 2008. Enhanced pest control in cabbage crops near forest in The Netherlands. Landscape Ecology 23: 595–602.

Bianchi F, Booij C, Tscharntke T. 2006. Sustainable pest regulation in agricultural landscapes: A review on landscape composition, biodiversity and natural pest control. Proceedings of the Royal Society B 273: 1715–27.

Blaney S, Beaudry M, Latham M. 2009. Contribution of natural resources to nutritional status in a protected area of Gabon. Food and Nutrition Bulletin 30: 49–62.

Bloem MW, Huq N, Gorstein J, Burger S, Kahn T, Islam N, Baker S, Davidson F. 1996. Production of fruits and vegetables at the homestead is an important source of vitamin A among women in rural Bangladesh. European Journal of Clinical Nutrition 50: S62–S67.

Boedecker J, Termote C, Assogbadjo AE, Van Damme P, Lachat C. 2014. Dietary contribution of Wild Edible Plants to women's diets in the buffer zone around the Lama forest, Benin: An underutilized potential. Food Security 6: 833–849.

Boggs G. 2010. Assessment of SPOT 5 and QuickBird remotely sensed imagery for mapping tree cover in savannas. International Journal of Applied Earth Observation and Geoinformation 12: 217–224.

Brandt M, et al. 2018. Reduction of tree cover in west african woodlands and promotion in semi-arid farmlands. Nature Geoscience 11: 328–328.

Broegaard RB, Rasmussen LV, Dawson N, Mertz O, Vongvisouk T, Grogan K. 2017. Wild food collection and nutrition under commercial agriculture expansion in agriculture–forest landscapes. Forest Policy and Economics 84: 92–101.

Brookfield H, Padoch C. 1994. Appreciating agrodiversity: A look at the dynamism and diversity of indigenous farming practices. Environment: Science and Policy for Sustainable Development 36: 6–45.

Brown S, Zarin D. 2013. What Does Zero Deforestation Mean? Science 342: 805–807.

Canella DS, Levy RB, Martins APB, Claro RM, Moubarac J-C, Baraldi LG, Cannon G, Monteiro CA. 2014. Ultra-processed food products and obesity in brazilian households (2008–2009). PLOS ONE 9 (art. e92752).

Chaplin-Kramer R, et al. 2015. Degradation in carbon stocks near tropical forest edges. Nature Communications 6: 10158–10158.

Chazdon RL, Brancalion PHS, Laestadius L, Bennett-Curry A, Buckingham K, Kumar C, Moll-Rocek J, Vieira ICG, Wilson SJ. 2016. When is a forest a forest? Forest concepts and definitions in the era of forest and landscape restoration. Ambio 45: 538–550.

Colgan M, Baldeck C, Feret J, Asner G. 2012. Mapping savanna tree species at ecosystem scales using support vector machine classification and BRDF correction on airborne hyperspectral and LiDAR data. Remote Sensing 4: 3462–3480.

Cooper M, Zvoleff A, Gonzalez-Roglich M, Tusiime F, Musumba M, Noon M, Alele P, Nyiratuza M. 2018. Geographic factors predict wild food and nonfood NTFP collection by households across four African countries. Forest Policy and Economics 96: 38–53.

Cunningham AB. 2011. Fungi and the future: Policy and practice for sustainable production and conservation. Pages 175–204 in Cunningham AB, Yang X, eds. Mushrooms in Forests and Woodlands: Resource Management, Values and Local Livelihoods. CRC Press.

Dawson I, Attwood S, Park S, Jamnadass R, Powell W, Sunderland T and Carsan S. 2019. Contributions of biodiversity to the sustainable intensification of food production. Global Food Security 21: 23–37.

DeFries R, Fanzo J, Remans R, Palm C, Wood S, Anderman TL. 2015. Metrics for land-scarce agriculture. Science 349: 238–40.

Development Initiatives, 2018. 2018 Global Nutrition Report: Shining a Light to Spur Action on Nutrition. Development Initiatives. https://globalnutritionreport.org/documents/352/2018_Global_Nutrition_Report.pdf.

Dorresteijn I, Hanspach J, Kecskés A, Latková H, Mezey Z, Sugár S, von Wehrden H, Fischer J. 2014. Human–carnivore coexistence in a traditional rural landscape. Landscape Ecology 29: 1145–1155.

Downs SM, Ahmed S, Fanzo J, Herforth A. 2020. Food environment typology: Advancing an expanded definition, framework, and methodological approach for improved characterization of wild, cultivated, and built food environments toward sustainable diets. Foods 9.4: 532.

Eilers EJ, Kremen C, Greenleaf, SS, Garber AK, Klein AM. 2011. Contribution of pollinator-mediated crops to nutrients in the human food supply. PLOS ONE 6 (art. e21363).

Fisher B, Christopher T. 2007. Poverty and biodiversity: Measuring the overlap of human poverty and the biodiversity hotspots. Ecological Economics 62: 93–101.

Fa JE, Currie D, Meeuwig J. 2003. Bushmeat and food security in the Congo Basin: Linkages between wildlife and peoples future. Environmental Conservation 30: 71–78.

Fanzo J. 2017. From big to small: The significance of smallholder farms in the global food system. Lancet Planetary Health 1: e15–e16.

[FAO] Food and Agriculture Organization of the United Nations. 2010. Forest Resource Assessment. FAO.

[FAO] Food and Agriculture Organization of the United Nations 2014. The State of Food and Agriculture: Innovation of Family Farming. FAO.

Freedman RL. 2015. Indigenous wild food plants in home gardens: Improving health and income—with the assistance of agricultural extension. International Journal of Agricultural Extension 3: 63–71.

Frossard E, Bucher M, MäChler F, Mozafar A, Hurrell R. 2000. Potential for increasing the content and bioavailability of Fe, Zn and Ca in plants for human nutrition. Journal of the Science of Food and Agriculture 80: 861–879.

Gallai N, Salles JM, Settele J, Vaissière BE. 2009. Economic valuation of the vulnerability of world agriculture confronted with pollinator decline. Ecological Economics 68: 810–821.

Galway LP, Acharya Y, Jones AD. 2018. Deforestation and child diet diversity: A geospatial analysis of 15 Sub-Saharan African countries. Health and Place 51: 78–88.

Garrity DP. 2004. Agroforestry and the achievement of the Millennium Development Goals. Agroforestry Systems 61: 5–17.

Gavin MC. 2004. Changes in forest use value through ecological succession and their implications for land management in the Peruvian Amazon. Conservation Biology 18: 1562–1570.

Gergel SE. 2007. New directions in landscape pattern analysis and links with remote sensing. Pages 173–208 In Wulder M, Franklin S, eds. Understanding Forest Disturbance and Spatial pattern: Remote Sensing and GIS Approaches. Taylor and Francis–CRC Press.

Gergel SE, Turner MG. 2017. Learning Landscape Ecology: A Practical Guide to Concepts and Techniques 2nd ed. Springer.

Girard AW, Self JL, Mcauliffe C, Olude O. 2012. The effects of household food production strategies on the health and nutrition outcomes of women and young children: A systematic review. Paediatric and Perinatal Epidemiology 26: 205–222.

Golden CD, Fernald LCH, Brashares JS, Rasolofoniaina BJR, Kremen C. 2011. Benefits of wildlife consumption to child nutrition in a biodiversity hotspot. Proceedings of the National Academy of Sciences 108: 19653–19656.

González E, Salvo A, Defagó MT, Valladares G. 2016. A moveable feast: Insects moving at the forest–crop interface are affected by crop phenology and the amount of forest in the landscape. PLOS ONE 11 (art. e0158836).

Gross D, Achard F, Dubois G, Brink A, Prins HHT. 2017. Uncertainties in tree cover maps of Sub-Saharan Africa and their implications for measuring progress towards CBD Aichi Targets. Remote Sensing in Ecology and Conservation 4: 94–112.

Haddad NM, et al. 2015. Habitat fragmentation and its lasting impact on Earth's ecosystems. Science Advances 1: e1500052.

Hall C, Macdiarmid JI, Matthews RB, Smith P, Hubbard SF and Dawson TP. 2019. The relationship between forest cover and diet quality: A case study of rural southern Malawi. Food Security 11: 1–16.

Hansen MC, et al. 2013. High-resolution global maps of 21st-century forest cover change. Science 342: 850–853.

Herforth A, Ahmed S. 2015. The food environment, its effects on dietary consumption, and potential for measurement within agriculture–nutrition interventions. Food Security 7: 505–520.

Herrero M, Thornton PK, Power B, Bogard JR, Remans R, Fritz S, Gerber JS, Nelson G, See L, Waha K. 2017. Farming and the geography of nutrient production for human use: A transdisciplinary analysis. Lancet Planetary Health 1: e33–e42.

Hirvonen K, Bai Y, Headey D, Masters WA. 2019. Affordability of the EAT–Lancet reference diet: A global analysis. Lancet Global Health 8: PE59–PE66.

[HLPE] High Level Panel of Experts. 2017. Sustainable forestry for food security and nutrition. Committee on World Food Security, Food and Agriculture Organization of the United Nations.

[HLPE] High Level Panel of Experts. 2019. Agroecological and other innovative approaches for sustainable agriculture and food systems that enhance food security and nutrition. Food and Agriculture Organization of the United Nations. www.fao.org/cfs/cfs-hlpe.

Hori Y, Stuhlberger C, Simonett O. 2012. Desertification: A Visual Synthesis. United Nations Convention to Combat Desertification.

Ickowitz A, Powell B, Salim MA, Sunderland TC. 2014. Dietary quality and tree cover in Africa. Global Environmental Change 24: 287–294.

Ickowitz A, Rowland D, Powell B, Salim MA, Sunderland T. 2016. Forests, trees, and micronutrient-rich food consumption in Indonesia. PLOS ONE 11 (art. e0154139).

Ickowitz A, Powell B, Rowland D, Jones A, Sunderland T. 2019. Agricultural intensification, dietary diversity, and markets in the global food security narrative. Global Food Security 20: 9–16.

Jagger P, Luckert MMK, Duchelle AE, Lund JF, Sunderlin WD. 2014. Tenure and forest income: Observations from a global study on forests and poverty. World Development 64: S43–S55.

Jamnadass R, Place F, Torquebiau E, Malézieux E, Iiyama M, Sileshi GW, Kehlenbeck K, Masters E, McMullin S, Dawson IK. 2013. Agroforestry for food and nutritional security. Unasylva 241: 23–29.

Johansen K, Coops NC, Gergel SE, Stange Y. 2007. Application of high spatial resolution satellite imagery for riparian and forest ecosystem classification. Remote Sensing of Environment 110: 29–44.

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.

Jones AD. 2017. Critical review of the emerging research evidence on agricultural biodiversity, diet diversity, and nutritional status in low- and middle-income countries. Nutrition Reviews 75: 769–782.

Kalaba FK. 2014. A conceptual framework for understanding forest socioecological systems. Biodiversity and Conservation 23: 3391–3403.

Kamanga P, Vedeld P, Sjaastad E. 2009. Forest incomes and rural livelihoods in Chiradzulu District, Malawi. Ecological Economics 68: 613–624.

Kennedy G, Ballard T, Dop MC. 2011. Guidelines for Measuring Household and Individual Dietary Diversity. Food and Agriculture Organization of the United Nations.

Koffi CK, Djoudi H, Gautier D. 2016. Landscape diversity and associated coping strategies during food shortage periods: Evidence from the Sudano-Sahelian region of Burkina Faso. Regional Environmental Change 17: 1369–1380.

Kumar BM. 2006. Agroforestry: The new old paradigm for Asian food security. Journal of Tropical Agriculture 44: 1–14.

Kumar BM, Nair PR. 2004. The enigma of tropical homegardens: New visitas in tropical agroforestry. Agroforestry Systems 61: 135–152.

Kumar N, Harris J, Rawat R. 2015. If they grow it, will they eat and grow? Evidence from Zambia on agricultural diversity and child undernutrition. Journal of Development Studies 51: 1060–1077.

Lachat C, et al. 2018. Dietary species richness as a measure of food biodiversity and nutritional quality of diets. Proceedings of the National Academy of Sciences 115: 127–132.

Laestadius L, Buckingham K, Maginnis S, Saint-Laurent C. 2015. Before Bonn and beyond: The history and future of forest landscape restoration. Unasylva 66: 11–18.

Lal R. 2009. Soil degradation as a reason for inadequate human nutrition. Food Security 1: 45–57.

Laurance WF, Laurance SG, Ferreira LV, Judy M, Rankin-de Merona, Gascon C, Lovejoy TE. 1997. Biomass collapse in Amazonian forest fragments. Science 278: 1117–1118.

Leakey R. 1996. Definition of agroforestry revisited. Agroforestry Today 8: 5.

Li W, Fu H, Yu L, Cracknell A. 2017. Deep learning based oil palm tree detection and counting for high-resolution remote sensing images. Remote Sensing 9: 22.

Lo M, Narulita S, Ickowitz A. 2019. The relationship between forests and freshwater fish consumption in rural Nigeria. PLOS ONE 14 (art. e0218038).

Lowder SK, Skoet J, Raney T. 2016. The number, size, and distribution of farms, smallholder farms, and family farms worldwide. World Development 87: 16–29.

Lykke, AM, Mertz O, Ganaba S. 2002. Food consumption in rural Burkina Faso. Ecology of Food and Nutrition 41: 119–153.

Malapit HJ, Quisumbing AR. 2015. What dimensions of women's empowerment in agriculture matter for nutrition-related practices and outcomes in Ghana? Food Policy 52: 54–63.

Magnago LFS, Rocha MF, Meyer L, Martins SV, Meira-Neto JAA. 2015. Microclimatic conditions at forest edges have significant impacts on vegetation structure in large Atlantic forest fragments. Biodiversity and Conservation 24: 2305–2318.

Manning AD, Fischer J, Lindenmayer DB. 2006. Scattered trees are keystone structures: Implications for conservation. Biological Conservation 132: 311–321.

Masset E, Haddad L, Cornelius A, Isaza-Castro J. 2012. Effectiveness of agricultural interventions that aim to improve nutritional status of children: Systematic review. British Medical Journal 344: d8222.

McSweeney, K. 2004. Forest product sale as natural insurance: The effects of household characteristics and the nature of shock in eastern Honduras. Society and Natural Resources 17: 39–56.

McMullin S, Njogu K, Wekesa, B, Gachuiri A, Ngethe E, Stadlmayr B, Jamnadass R, Kehlenbeck K. 2019. Developing fruit tree portfolios that link agriculture more effectively with nutrition and health: A new approach for providing year-round micronutrients to smallholder farmers. Food Security 11: 1–18.

Mertz O, Lykke AM, Reenberg A. 2001. Importance and seasonality of vegetable consumption and marketing in Burkina Faso. Economic Botany 55: 276–289.

Mitchell MGE, Suarez-Castro AF, Martinez-Harms M, Maron M, McAlpine C, Gaston KJ, Johansen K, Rhodes JR. 2015. Reframing landscape fragmentation's effects on ecosystem services. Trends in Ecology and Evolution 30: 190–198.

Morgan JL, Gergel SE, Coops NC. 2010. Aerial photography: A rapidly evolving tool for ecological management. BioScience 60: 47–59.

Nájera A, Simonetti JA. 2010. Enhancing avifauna in commercial plantations. Conservation Biology 24: 319–324.

Naidoo R, et al. 2019. Evaluating the impacts of protected areas on human well-being across the developing world. Science Advances 5: eaav3006.

Nasi R, Taber A, Vliet NV. 2011. Empty forests, empty stomachs? Bushmeat and livelihoods in the Congo and Amazon Basins. International Forestry Review 13: 355–368.

Naughton-Treves L. 2002. Wild animals in the garden: Conserving wildlife in Amazonian agroecosystems. Annals of the Association of American Geographers 92: 488–506.

Oksanen T, Mersmann C. 2003. Forests in poverty reduction strategies: An assessment of PRSP processes in Sub-Saharan Africa. Pages 121–158 in Oksanen T, Pajari B, Tuomasjukka, T eds. Forests in Poverty Reduction Strategies: Capturing the Potential. European Forest Institute. Proceedings no. 47.

Padoch C, Sunderland TCH. 2014. Managing landscapes for greater food security and improved livelihoods. Unasylva 64: 3–13.

Parry L, Barlow JOS, Peres CA. 2009. Hunting for sustainability in tropical secondary forests. Conservation Biology 23: 1270–1280.

Petersen R, Aksenov D, Esipova E, Goldman E, Harris N, Kurakina I, Loboda T, Manisha A, Sargent S, Shevade V. 2016. Mapping Tree Plantations with Multispectral Imagery: Preliminary Results for Seven Tropical Countries. World Resources Institute.

Pfund JL, et al. 2011. Understanding and integrating local perceptions of trees and forests into incentives for sustainable landscape management. Environmental Management 48: 334–349.

Popkin BM. 2004. The nutrition transition: An overview of world patterns of change. Nutrition Reviews 62: S140–S143.

Powell B, Ickowitz A, McMullin S, Jamnadass R, Padoch C, Pinedo-Vasquez M, Sunderland T. 2013a. The Role of Forests, Trees, and Wild Biodiversity for Nutrition-Sensitive Food Systems and Landscapes. Food and Agriculture Organization of the United Nations.

Powell B, Maundu P, Kuhnlein HV and Johns T. 2013b. Wild foods from farm and forest in the East Usambara Mountains, Tanzania. Ecology of Food and Nutrition 52: 451–478.

Powell B, Thilsted SH, Ickowitz A, Termote C, Sunderland T, Herforth A. 2015. Improving diets with wild and cultivated biodiversity from across the landscape. Food Security 7: 535–554.

Power AG. 2010. Ecosystem services and agriculture: Tradeoffs and synergies. Philosophical Transactions of the Royal Society B 365: 2959–2971.

Puyravaud JP, Davidar P, Laurance WF. 2010. Cryptic destruction of India's native forests. Conservation Letters 3: 390–394.

Rasmussen LV, et al. 2019. Forest pattern, not just amount, influences dietary quality in five African countries. Global Food Security (art. 100331).

Rasolofoson RA, Hanauer MM, Pappinen A, Fisher B and Ricketts TH. 2018. Effects of forests on children's diets in developing countries: A cross-sectional study. Lancet Planetary Health 2: S15.

Ratsimbazafy CL, Harada K, Yamamura M. 2012. Forest resources use, attitude, and perception of local residents towards community based forest management: Case of the Makira Reducing Emissions from Deforestation and Forest Degradation (REDD) Project, Madagascar. Journal of Ecology and the Natural Environment 4: 321–332.

Reed J, Van Vianen J, Clendinning J, Petrokoversusky G, Sunderland T. 2017. Trees for life: The ecosystem service contribution of trees to food production and livelihoods in the tropics. Forest Policy and Economics 84: 62–71.

Remans R, et al. 2011. Assessing nutritional diversity of cropping systems in African villages. PLOS ONE 6 (art. e21235).

Remans R, Wood S, Saha N, Anderman TL, DeFries RS. 2014. Measuring nutritional diversity of national food supplies. Global Food Security 3: 174–182.

Reyes-García V, Powell B, Díaz-Reviriego I, Fernández-Llamazares Á, Gallois S, Gueze M. 2019. Dietary transitions among three contemporary hunter–gatherers across the tropics. Food Security 11: 109–122.

Reynolds PE, Simpson JA, Thevathasan NV, Gordon AM. 2007. Effects of tree competition on corn and soybean photosynthesis, growth, and yield in a temperate tree-based agroforestry intercropping system in southern Ontario, Canada. Ecological Engineering 29: 362–371.

Ricketts TH, Daily GC, Ehrlich PR, Michener CD. 2004. Economic value of tropical forest to coffee production. Proceedings of the National Academy of Sciences 101: 12579–12582.

Robinson EJ, Lokina RB. 2011. A spatial–temporal analysis of the impact of access restrictions on forest landscapes and household welfare in Tanzania. Forest Policy and Economics 13: 79–85.

Rowland D, Ickowitz A, Powell B, Nasi R, Sunderland T. 2017. Forest foods and healthy diets: Quantifying the contributions. Environmental Conservation 44: 102–114.

Ruel MT. 2003. Is dietary diversity an indicator of food security or dietary quality? A review of measurement issues and research needs. Food and Nutrition Bulletin 24: 231–232.

Ruel MT, Alderman H. 2013. Nutrition-sensitive interventions and programmes: How can they help to accelerate progress in improving maternal and child nutrition? Lancet 382: 536–551.

Sanchez PA. 1999. Improved fallows come of age in the tropics. Agroforestry Systems 47: 3–12.

Saunders DA, Hobbs RJ, Margules CR. 1991. Biological consequences of ecosystem fragmentation: A review. Conservation Biology 5: 18–32.

Sayer J, et al. 2014. Landscape approaches: What are the pre-conditions for success? Sustainability Science 10: 345–355.

Shackleton C, Shackleton S. 2004. The importance of non-timber forest products in rural livelihood security and as safety nets: A review of evidence from South Africa. South African Journal of Science 100: 658–664.

Shackleton CM, Shackleton SE, Buiten E, Bird N. 2007. The importance of dry woodlands and forests in rural livelihoods and poverty alleviation in South Africa. Forest Policy and Economics 9: 558–577.

Shackleton CM, Ruwanza S, Sinasson GK, Bennet S, De Lacy P, Modipa R, Mtati N, Dalu MTB, Thondhlana G. 2016. Unpacking Pandora's Box: Understanding and categorising ecosystem disservices for environmental management and human wellbeing. Ecosystems 19: 587.

Sibhatu, KT, Krishna VV, Qaim M. 2015. Production diversity and dietary diversity in smallholder farm households. Proceedings of the National Academy of Sciences 112: 10657–10662.

Sida TS, Baudron F, Kim H, Giller KE. 2018a. Climate-smart agroforestry: *Faidherbia albida* trees buffer wheat against climatic extremes in the Central Rift Valley of Ethiopia. Agricultural and Forest Meteorology 248: 339–347.

Sida TS, Baudron F, Hagud K, Derero A, Giller KE. 2018b. Crop versus tree: Can agronomic management reduce trade-offs in tree–crop interactions? Agriculture Ecosystems and Environment 260: 36–46.

Smith MR, Singh GM, Mozaffarian D, Myers SS. 2015. Effects of decreases of animal pollinators on human nutrition and global health: A modelling analysis. Lancet 386: 1964–1972.

Smith DA. 2005. Garden game: Shifting cultivation, indigenous hunting and wildlife ecology in western Panama. Human Ecology 33: 505–537.

Stevens B, Watt K, Brimbecombe J, Clough A, Judd J, Lindsay D. 2017. The role of seasonality on the diet and household food security of pregnant women living in rural Bangladesh: A cross-sectional study. Public Health Nutrition 20: 121–129.

Sunderland T, Ickowitz A, Reyes-Garcia V, Shively G, Angelsen A, Babimigura R, Achdiawan R. 2014. Challenging perceptions about men, women, and forest resources: Results from the PEN global dataset. World Development 64: S56–S66.

Sunderland T, Rowland D. 2019. Forests, land use, and challenges to climate stability and food security. Pages 95–116 in Campanhola C, Pandey S, eds. Sustainable Food and Agriculture: An Integrated Approach. Elsevier.

Sunderland T, O'Connor A, Muir G, Nerfa L, Nodari G, Widmark C, Bahar N, Ickowitz A. 2019. SDG2: Zero hunger: Challenging the hegmony of monoculture agriculture for forests and people. Pages 48–71 in Katila P, Colfer C, de Jong W, Galloway G, Pacheco P, Winkel G, eds. Sustainable Development Goals: Their Impacts on Forests and People. Cambridge University Press.

Sutherland I, Bennett EB, Gergel SE. 2016. Recovery trends for multiple ecosystem services reveal non-linear responses and long-term tradeoffs from temperate forest harvesting. Forest Ecology and Management 374: 61–70.

Sylvester O, Garcia Segura AG, Davidson-Hunt IJ. 2016. The protection of forest biodiversity can conflict with food access for indigenous people. Ecology and Society 14: 279–290.

Tata CY, Ickowitz A, Powell B, Colecraft EK. 2019. Dietary intake, forest foods, and anemia in Southwest Cameroon. PLOS ONE 14 (art. e0215281).

Tatem A, Noor A, von Hagen C, Di Gregorio A, Hay S. 2007. High resolution population maps for low income nations: Combining land cover and census in east Africa. PLOS ONE 2 (art. e1298).

Termote C, Van Damme P, Dhed'a Djailo B. 2011. Eating from the wild: Turumbu, Mbole, and Bali traditional knowledge on non-cultivated edible plants, District Tshopo, DR Congo. Genetic Resources and Crop Evolution 58: 585–618.

Toledo M, Salick J 2006. Secondary succession and indigenous management in semideciduous forest fallows of the Amazon Basin 1. Biotropica: The Journal of Biology and Conservation 38: 161–170.

Tontisirin K, Nantel G, Bhattacharjee L. 2002. Food-based strategies to meet the challenges of micronutrient malnutrition in the developing world. Proceedings of the Nutrition Society 61: 243–250.

Tropek R, Sedláček O, Beck J, Keil P, Musilova Z, Šímová I, Storch D. 2014. Comment on High-resolution global maps of 21st-century forest cover change. Science 344: 981–981.

Vinceti B, Eyzaguirre P, Johns T. 2008. The nutritional role of forest plant foods for rural communities. Pages 63–93 in Colfer CJP, ed. Human Health and Forests: A Global Overview of Issues, Practice, and Policy. Earthscan.

Wan M, Colfer CJP, Powell B. 2011. Forests, women and health: Opportunities and challenges for conservation. International Forestry Review 13: 369–387.

Waswa LM. 2016. Improving Dietary Diversity and Nutritional Health of Women and Children under Two Years through Increased Utilization of Local Agrobiodiversity and Enhanced Nutrition Knowledge in Kenya. Dr. oec. troph. Dissertation. Justus-Liebig-University Giessen, Germany. http://geb.uni-giessen.de/geb/volltexte/2016/12194/pdf/WaswaLydiah_2015_12_15.pdf.

Watson JEM, Evans T, Lindenmayer D. 2018. The exceptional value of intact forest ecosystems. Nature Ecology and Evolution 2: 599–610.

Weinstein S, Moegenburg S. 2004. Açaí palm management in the amazon estuary: Course for conservation or passage to plantations? Conservation and Society 2: 315–346.

Willett W, Rockström J, Loken B, Springmann M, Lang T, Vermeulen S, Jonell M. 2019. Food in the Anthropocene: The EAT–Lancet Commission on healthy diets from sustainable food systems. Lancet 393: 447–492.

Wood SL, Rhemtulla JM, Coomes OT. 2016. Intensification of tropical fallow-based agriculture: Trading-off ecosystem services for economic gain in shifting cultivation landscapes? Agriculture, Ecosystems and Environment 215: 47–56.

Wood SA. 2018. Nutritional functional trait diversity of crops in south-eastern Senegal. Journal of Applied Ecology 55: 81–91.

Wood SA, Tirfessa D and Baudron F. 2018. Soil organic matters underlies crop nutritional quality and productivity in smallholder agriculture. Agriculture, Ecosystems, and Environment 266: 100–108.

Wunder S, Börner J, Shively G, Wyman M. 2014. Safety nets, gap filling and forests: A global-comparative perspective. World Development 64: S29–S42.

Yang KF, Gergel SE, Baudron F. 2020. Forest restoration scenarios produce synergies for agricultural production in southern Ethiopia. Agriculture, Ecosystems and Environment 295: e106888.

Zhang W, Brandt M, Tong X, Tian Q, Fensholt R. 2018. Impacts of the seasonal distribution of rainfall on vegetation productivity across the Sahel. Biogeosciences 15: 319–330.

Zomer RJ, Trabucco A, Coe R, Place F, Noordwijk MV, Xu J. 2014. Trees on farms: An update and reanalysis of agroforestry's global extent and socioecological characteristics. World Agroforestry Centre, Southeast Asia Regional Program. Working paper no. 179.

Sarah E. Gergel (sarah.gergel@ubc.ca), Jeanine M. Rhemtulla, Laura V. Rasmussen, and Terry C. H. Sunderland are affiliated with the Department of Forest and Conservation Sciences at the University of British Columbia, in Vancouver, Canada. Bronwen Powell and Erica A. H. Smithwick are affiliated with the Department of Geography and BP is also affiliated with the Departments of African Studies and Anthropology at Pennsylvania State University, in University Park, Pennsylvania. Frédéric Baudron is affiliated with the International Maize and Wheat Improvement Center CIMMYT-Southern Africa Regional Office, in Harare, Zimbabwe. Sylvia L. R. Wood is affiliated with the Future Earth Global Hub, in Montreal, Quebec, Canada. Gina Kennedy and Jessica Ranieri are affiliated with Bioversity International, in Rome, Italy. Amy Ickowitz and Terry C. H. Sunderland are affiliated with the Center for International Forestry Research, in Bogor, Indonesia. Matthew E. Fagan is affiliated with the Department of Geography and Environmental Systems at the University of Maryland—Baltimore County, in Baltimore, Maryland. Stephen A. Wood is affiliated with The Nature Conservancy, Arlington, Virginia, and with the School of Forestry and Environmental Studies at Yale University, in New Haven, Connecticut. Jeroen C. J. Groot is affiliated with the Department of Farming Systems Ecology, at Wageningen University and Research, in Wageningen, The Netherlands.