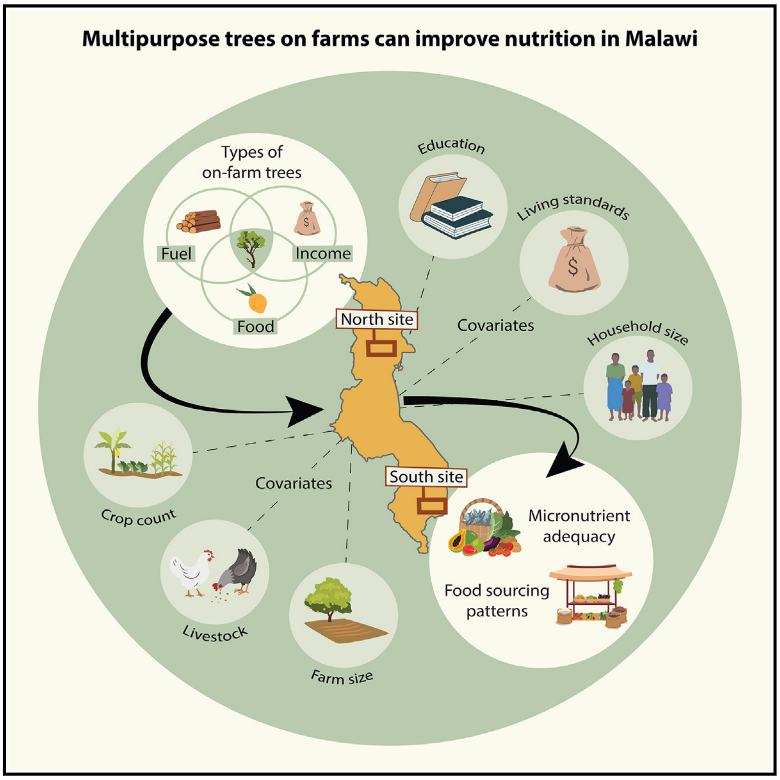
One Earth

Article

Multipurpose trees on farms can improve nutrition in Malawi

Graphical abstract



Highlights

- The contributions of trees on farms to dietary quality remain poorly quantified
- Food trees on farms are associated with a 7%–20% increase in micronutrient adequacy
- Food trees are also associated with higher consumption of other cultivated foods
- Additional uses of trees for fuel and income do not detract from dietary benefits

Authors

Emilie Vansant, Charlotte Hall, Bowy den Braber, Judith Kamoto, Matthias Geck, Florian Reiner, Laura Vang Rasmussen

Correspondence

ecv@ign.ku.dk

In brief

Trees on farms are an important source of micronutrient-rich foods, yet their contributions to people's diets remain poorly quantified. Using data collected in rural Malawi, this study shows how different uses of on-farm trees for food, income, and fuelwood are positively associated with women's micronutrient adequacy. Our findings highlight how promoting multipurpose tree systems can help target nutrient deficiencies in rural communities.

Vansant et al., 2025, One Earth *8*, 101165
February 21, 2025
https://doi.org/10.1016/j.oneear.2024.12.001

CellPress

One Earth

CellPress OPEN ACCESS

Article

Multipurpose trees on farms can improve nutrition in Malawi

Emilie Vansant,[1,5,*] Charlotte Hall,[1,2] Bowy den Braber,[1] Judith Kamoto,[3] Matthias Geck,[4] Florian Reiner,[1] and Laura Vang Rasmussen[1]
[1]Department of Geosciences and Natural Resource Management, University of Copenhagen, 1350 Copenhagen K, Denmark
[2]Department of Biological and Environmental Sciences, University of Stirling, Stirling, UK
[3]Forestry Department, Lilongwe University of Agriculture and Natural Resources, Lilongwe, Malawi
[4]World Agroforestry (ICRAF), Nairobi, Kenya
[5]Lead contact
*Correspondence: ecv@ign.ku.dk
https://doi.org/10.1016/j.oneear.2024.12.001

SCIENCE FOR SOCIETY Agricultural intensification can lead to simplified landscapes and simplified diets, especially in low- and middle-income countries. Trees on farms offer promising co-benefits for the environment and human health, with the potential to improve diets via providing food, income, and/or fuelwood. In this study, we measure how using trees on farms can support women's diets in rural Malawi. We find that using trees on farms to source food is positively associated with women's dietary quality in both dry and wet seasons. While we do not find any consistent additional benefits from using trees on farms for fuelwood or income, we find that multipurpose trees on farms—providing food, income, and fuel—can support diets while offering other livelihood benefits. This study therefore helps evidence multipurpose trees on farms as a viable pathway for addressing malnutrition in rural communities.

SUMMARY

In low- and middle-income countries, there is growing evidence that trees in landscapes can support healthy diets. Yet, the bulk of this evidence is based on broad-scale associations and thus fails to tease apart the contributions of different types of trees. Here, we examine how the use of on-farm trees for food, income, and fuel relates to micronutrient adequacy (vitamin A, zinc, iron, and folate) and food sourcing patterns in rural Malawi. We used data from socioeconomic, land use, and dietary surveys conducted with 460 women in both the dry and wet seasons. Our results illustrate that, compared to other uses, the use of on-farm trees for food is the most significant determinant of women's micronutrient adequacy across seasons. While this study does not find consistent dietary benefits from using on-farm trees for only fuel and income, our results suggest that multipurpose on-farm trees can support adequate intake of all measured micronutrients.

INTRODUCTION

Malnutrition in all of its forms is the number one risk factor in global morbidity.[1] One in seven premature deaths is attributable to child and maternal malnutrition and diet-related non-communicable diseases; this rate has only been exacerbated by the COVID-19 pandemic.[2] Though poor nutrition is a global crisis affecting approximately one-third of the population, the bulk of the burden is in low- and middle-income countries (LMICs), which host the majority of wasting (93%), low birthweight (83%), stunting (89%), and anemia (74%) cases worldwide.[3,4] With the same countries disproportionately experiencing the impacts of climate change,[5] there is an urgent need for food system transformations that support ecological and human health in tandem.[6,7]

Trees and forests have the potential to help achieve this dual agenda.[8] While landscape restoration has been a long-standing priority in climate change adaptation and mitigation efforts, the role of trees and forests in supporting dietary quality has only recently become prominent in high-level policy discourse.[9–11] In some cases, deforestation is associated with adverse nutritional effects, such as decreased dietary diversity and lower consumption of fruits and vegetables.[12,13] Such dietary changes can lead to micronutrient deficiencies, predominantly iron, zinc, vitamin A, and folate, which can have serious adverse health impacts, such as anemia, hindered child growth and development, and night blindness.[14]

Trees in forests and on farms provide micronutrient-rich fruits and vegetables that are undersupplied and under-consumed, with only 40 countries (36% of the global population) having adequate supplies of fruit and vegetables to meet people's needs, according to established dietary recommendations.[15] Recent research has found associations between tree cover and more diverse and nutritious diets,[12,16–18] with studies citing how trees may improve diets via different productive functions. Aside from the direct provision of nutrient-rich foods[19–21] (e.g., fruits and nuts), tree-based landscapes can also host wild green leafy vegetable growth as well as array of wild hunted bird, mammal, and insect species.[22–24] Second, trees can provide marketable products,[25] the income from which can enable market food purchases.[26] Third, trees supply fuelwood to facilitate the preparation of nutrient-dense foods with long cooking times (e.g., lentils).[27] In addition, ecosystem services from forests and trees can also indirectly support agricultural productivity of crops and livestock,[28,29] which can have downstream benefits for sustaining the dietary quality of rural households.[30]

However, there is less research explicitly examining the role of on-farm trees and the relative importance of each of these three direct contributions for people's micronutrient adequacy. This study assesses how different uses of on-farm trees for food, income, and fuelwood affect dietary quality. We focus on Malawi, where 52% of the population is classified as severely food insecure, and 34% of children under 5 are stunted.[3] Malawi has one of the least diversified economies in the world, with over 84% of the economically active population engaged in farming as a primary livelihood activity.[31] High demand for agricultural land and wood-based fuels has contributed to widespread deforestation in the past two decades, with a countrywide loss of over 16% (247 kha) of total tree cover since 2001.[32,33] Malawi is therefore an appropriate site to investigate this confluence of natural resource reliance, poverty, and malnutrition in the context of tree-diet linkages. Here, we use land use and dietary data collected from 460 households in the north and south of Malawi (during both dry and wet seasons) to compare the effects of different on-farm tree functions on women's adequacy levels of four key micronutrients: zinc, vitamin A, iron, and folate.

The inclusion of trees in farming systems is far from a new approach; trees are found on approximately 43% of global agricultural land,[34] although more recent estimates indicate that the prevalence might be much higher.[35] While emerging evidence suggests that on-farm trees can improve diets,[36] on-farm trees do not deliver universally positive or equal nutrition outcomes. The heterogeneous classifications for on-farm tree systems often vary with geographical and cultural contexts and do not often account for the ways in which the trees are used by the household. Accordingly, there is little research that teases apart the mechanisms by which on-farm trees are associated with dietary quality and that evaluates the relative efficacy of these mechanisms. This study further advances existing knowledge on landscape-diet linkages by (1) evaluating different uses of on-farm trees and (2) using detailed dietary quality metrics, assessing the micronutrient adequacy levels for each respondent across dry and wet seasons. By measuring how different uses of on-farm trees can affect people's diets, our results identify avenues for interventions targeting nutrient deficiencies in rural communities.

RESULTS

To test the relative importance of different uses of on-farm trees by households, we constructed linear models comparing women's micronutrient adequacy levels across different use categories (food, food + income, food + fuel, food + fuel + income, and fuel + income) while controlling for factors known to influence landscape-diet linkages (methods). Using the "no/other tree use" household category as a control, our results illustrate that, compared to other on-farm tree uses, the use of on-farm trees for food is the most significant determinant of women's micronutrient adequacy in both the dry and wet seasons. We find that use of on-farm trees for food is positively associated with women's micronutrient adequacy, likely due to the direct provision of nutrient-rich foods. To explore this further, we tested associations between on-farm tree use and household food consumption patterns. We see again that use of on-farm trees for food is associated with higher consumption of cultivated foods (from fields and trees), evidencing the "direct provision" pathway as a viable mechanism through which on-farm trees support diets.

Critically, we see that the use of on-farm trees only for income and fuelwood is generally not associated with changes in micronutrient adequacy. While our results do not indicate any additional benefits from fuel or income trees to dietary quality, we find that the benefits from food trees to micronutrient adequacy are maintained in multipurpose on-farm tree systems. This indicates that such farming systems can support dietary quality while potentially providing other livelihood benefits in the form of income or fuelwood. As this is a cross-sectional study with data from one point in time, we note that our estimated effects of different on-farm tree uses on micronutrient adequacy and food sources refer to associations in real-world settings. We therefore cannot make claims about causality.

On-farm food trees are positively associated with women's micronutrient adequacy

Sourcing food from on-farm trees is associated with increased adequacy levels of zinc, vitamin A, and folate. These effects are pronounced in both the dry and wet seasons. Given that the majority of food consumed by respondents is purchased (Table 1), such results point to the important contribution of even small amounts of tree-based foods to micronutrient adequacy. As tree-based foods have different nutritional values, the contributions of on-farm trees to people's micronutrient adequacy are likely to vary by species (Table S6). For example, in the dry season, on-farm food trees can increase women's folate adequacy by 15%–20% (Figure 1). In this season, while we observe the largest effect size for the household group that uses on-farm trees *only* for food, there is minimal effect change with additional uses of on-farm trees for income and/or fuel, suggesting that direct consumption of folate-rich tree foods (e.g., mangos, bananas, and guavas) is responsible for this increased micronutrient intake (Table S7). In our study areas, folate is a particularly limited micronutrient with an average adequacy rate of 64% in the dry season and 47% in the wet season across all household groups. This dry season pattern also holds for vitamin A and zinc; women in household groups that include on-farm food trees show higher adequacy levels for both micronutrients

Table 1. Summary statistics for control and outcome variables for each household grouping based on on-farm tree function

Types of on-farm trees:	None/other	Food	Food + fuel	Food + fuel + income	Food + income	Fuel + income
N	43	83	116	126	35	57
Covariates						
Tree cover (% in 1-km radius)	8 (15)	16 (13)	17 (14)	27 (15)	28 (13)	3 (4)
MPI living standards (range 0–1)	0.69 (0.18)	0.57 (0.20)	0.58 (0.18)	0.55 (0.20)	0.46 (0.20)	0.54 (0.20)
Education level (% none, % primary, % secondary]	7, 70, 23	4, 71, 25	3, 75, 22	1, 76, 23	0, 67, 33	4, 81, 15
Household size	4.63 (2.05)	5.23 (1.82)	5.68 (2.35)	6.77 (3.53)	6.09 (2.15)	5.79 (1.92)
Farm size (acres)						
Dry season	0.67 (0.5)	1.17 (1.02)	1.39 (1.23)	1.71 (1.08)	1.73 (0.91)	1.19 (1.08)
Wet season	0.59 (0.50)	0.93 (0.76)	1.27 (1.11)	1.15 (0.71)	1.30 (1.04)	0.98 (0.82)
Crop count						
Dry season	3.09 (1.21)	3.20 (1.13)	4.16 (1.99)	4.75 (2.04)	4.40 (1.94)	4.04 (1.16)
Wet season	3.88 (1.89)	3.66 (1.73)	4.78 (1.93)	4.85 (1.87)	4.89 (1.95)	4.75 (1.91)
Livestock (TLU)						
Dry season	0.02 (0.05)	0.13 (0.37)	0.12 (0.17)	0.17 (0.26)	0.12 (0.31)	0.06 (0.10)
Wet season	0.02 (0.05)	0.10 (0.24)	0.12 (0.20)	0.15 (0.26)	0.15 (0.28)	0.05 (0.09)
Outcome variables						
Micronutrient adequacy levels						
Vitamin A						
Dry season	0.84 (0.23)	0.96 (0.12)	0.95 (0.14)	0.95 (0.12)	0.94 (0.16)	0.87 (0.22)
Wet season	0.84 (0.23)	0.95 (0.13)	0.95 (0.13)	0.96 (0.11)	0.95 (0.12)	0.90 (0.16)
Zinc						
Dry season	0.70 (0.22)	0.88 (0.16)	0.89 (0.16)	0.87 (0.18)	0.88 (0.21)	0.76 (0.22)
Wet season	0.56 (0.25)	0.71 (0.25)	0.73 (0.25)	0.74 (0.24)	0.72 (0.28)	0.62 (0.28)
Iron						
Dry season	0.70 (0.28)	0.74 (0.23)	0.73 (0.23)	0.79 (0.22)	0.71 (0.24)	0.68 (0.26)
Wet season	0.66 (0.30)	0.64 (0.28)	0.61 (0.26)	0.66 (0.26)	0.65 (0.28)	0.61 (0.25)
Folate						
Dry season	0.54 (0.26)	0.71 (0.22)	0.66 (0.24)	0.64 (0.22)	0.64 (0.22)	0.59 (0.24)
Wet season	0.38 (0.16)	0.47 (0.16)	0.47 (0.18)	0.53 (0.21)	0.53 (0.24)	0.40 (0.17)
Sources of food consumed						
Cultivated (own farm)						
Dry season	0.07 (0.10)	0.28 (0.19)	0.28 (0.19)	0.31 (0.18)	0.38 (0.18)	0.09 (0.16)
Wet season	0.19 (0.18)	0.35 (0.23)	0.33 (0.22)	0.36 (0.18)	0.39 (0.21)	0.22 (0.16)
Purchased						
Dry season	0.89 (0.11)	0.69 (0.20)	0.70 (0.18)	0.67 (0.18)	0.59 (0.19)	0.87 (0.18)
Wet season	0.74 (0.19)	0.62 (0.22)	0.64 (0.21)	0.62 (0.18)	0.59 (0.21)	0.75 (0.16)
Wild						
Dry season	0.04 (0.07)	0.03 (0.06)	0.02 (0.05)	0.02 (0.04)	0.03 (0.05)	0.04 (0.06)
Wet season	0.07 (0.08)	0.03 (0.05)	0.03 (0.05)	0.02 (0.03)	0.02 (0.05)	0.03 (0.07)

Values are presented as the mean value with the standard deviation in parentheses unless otherwise noted. Temporally independent variables (collected at one point in time) are merged across seasons. Tree cover is measured as the percentage within a 1-km radius around each household (Note S1). For each household grouping, percentages of food consumed from each source add up to 100% in each season.

than women in the fuel + income household group. For zinc, the average dry season adequacy level across all respondents is 83%. Therefore, a 17% increase in micronutrient adequacy in the dry season (as modeled for food and food + fuel household groups) would result in sufficient micronutrient intake for those women (i.e., an adequacy level >100%). In the case of vitamin A, these relatively modest increases could still make the difference between whether or not someone met their daily nutrient requirement, as the average intakes, though inadequate, were already quite high, with an average adequacy level of 93% in both seasons.

Notably, we found no differences in dietary quality between households without on-farm trees and households with only fuel and/or income trees. Vitamin A in the wet season is the

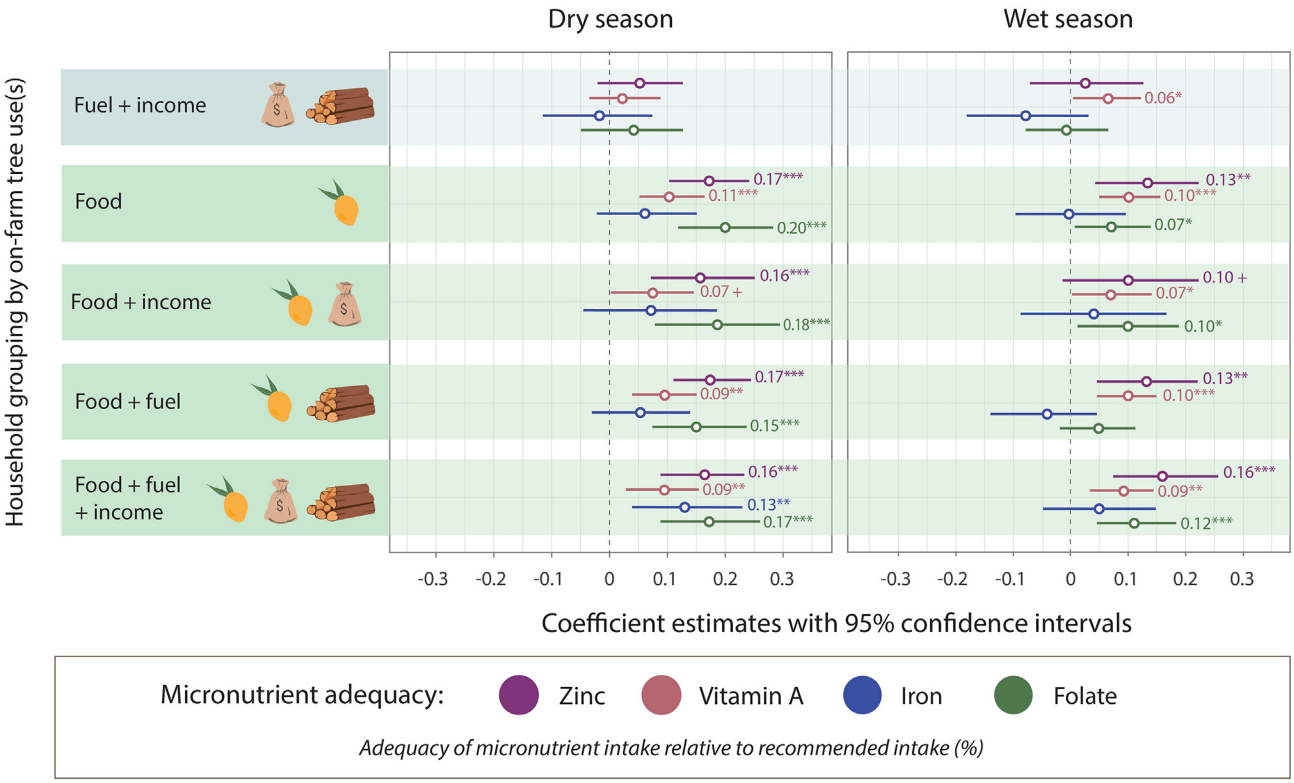


Figure 1. Associations between different on-farm tree uses and women's micronutrient adequacy for the dry and wet seasons
Model results are presented as coefficient estimates with 95% confidence intervals. All effect sizes represent the change from the "no/other" tree use group (control) to a group defined by one or more uses of on-farm trees. ***$p < 0.001$, **$p < 0.01$, *$p < 0.05$, +$p < 0.10$.

exception to this with increases in micronutrient adequacy seen for all households that maintain on-farm trees for any productive function. These results suggest that improvements in vitamin A adequacy could be due to trees in agricultural production systems rather than the consumption of tree-based foods specifically. Across household groups, we observed higher consumption of dark green leafy vegetables (such as pumpkin leaves) from farms in the wet season than in the dry season. On-farm trees have been shown to increase ground vegetation/undergrowth by providing shade and improving soil quality through increased residual moisture and reduced erosion.[37,38] We can posit that on-farm trees in our study areas can indirectly support greater abundance of green leafy vegetables, thereby providing wild sources of vitamin A in the otherwise "lean" pre-harvest season.

Finally, we note that the maintenance of on-farm trees for any purpose seems to have no effect on iron adequacy, with the exception of using trees for a combination of food, fuel, and income in the dry season. This could be due to the relatively low iron content of commonly consumed tree-based foods across seasons (e.g., bananas, mangos, guavas, and avocados). It also speaks to households' potential reliance on purchased foods for iron intake (e.g., legumes and animal-source foods), although we observe that, on average, women had relatively low levels of iron adequacy (61%–79%) across all household groupings and seasons (Table 1).

On-farm trees are associated with how households source their food

Reinforcing our hypothesis that direct consumption from on-farm trees contributes to dietary quality, we find that households that have on-farm food trees consume more food from their own cultivation (food from trees and annual crops) than households without food trees, with income trees having little to no effect on household consumption of purchased foods (Figure 2). For example, in the dry season, households with on-farm food trees, on average, consume 18% more from their own farms and purchase 19% less food from the market. This pattern holds across all household groupings, except for households that use on-farm trees only for fuel and income. Use of on-farm trees for food seems to have a clear positive association with the consumption of cultivated foods overall and a negative association with the consumption of purchased foods. This also hints at a link between on-farm food trees and overall agricultural productivity, as households with food trees appear to be better able to meet their consumption needs through subsistence farming.

In the wet season, the decision to use on-farm trees for food provision only or food and fuelwood provision is associated with increased household consumption of cultivated foods from trees and annual crops. Critically, in this season, the use of on-farm trees for income does not have any effect on the amount of food that households are purchasing. This could be due to (1) limited productivity of on-farm trees in the wet season

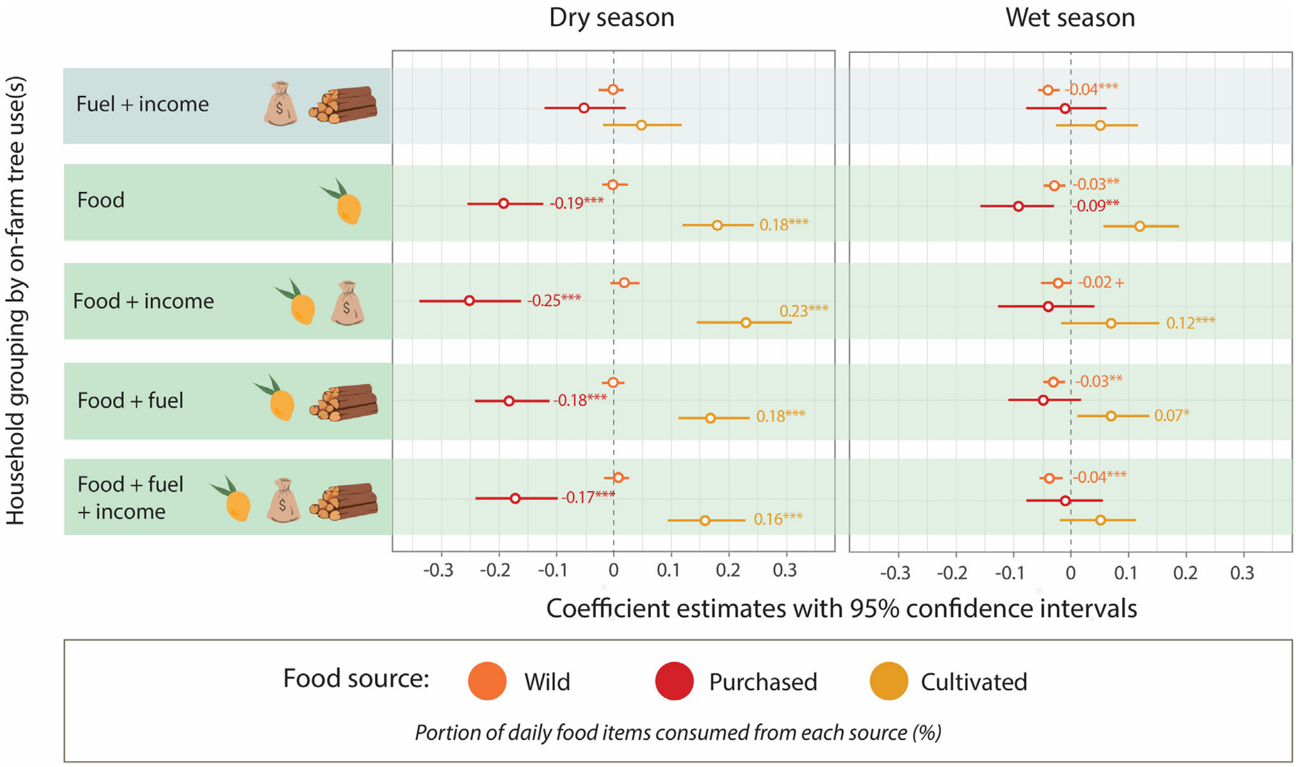


Figure 2. Associations between different on-farm tree uses and household food sourcing patterns
Model results are presented as coefficient estimates with 95% confidence intervals. All effect sizes represent the change from the "no/other" tree uses group (control) to a group defined by one or more uses of on-farm trees. $^{***}p < 0.001$, $^{**}p < 0.01$, $^{*}p < 0.05$, $+p < 0.10$.

or (2) the decision to use the income from on-farm trees for non-food purchases, such as school fees or medical expenses. According to our field survey (see the methods section), the most common income tree species include mango (*Mangifera indica)*, banana (*Musa paradisiaca)*, eucalyptus (*Eucalyptus maidenii)*, and guava *(Psidium guajava)* (Table S1). All of these species were also recorded as some of the most common food and/or fuelwood trees, indicating that households did not usually cultivate on-farm trees exclusively for income purposes. This is likely why we do not see any effect of income trees on food consumption, contrary to other studies in different LMIC contexts that examine the effects of income from tree crop systems (e.g., oil palm and rubber) on diets and food security.[39–41]

It also appears that households that use on-farm trees for any material purpose rely marginally less on wild foods in the wet season than households with no or "non-productive" trees on farm (the "no/other" tree use group). This period, also known as the pre-harvest lean season, is a time where smallholder households have less purchasing power due to reduced agricultural income. Our interviews with farmers suggest that forests and fallows remain a source of food, fuelwood, and income for households (Table S2). Therefore, households with simplified production systems (no trees or only non-productive trees on farms) might be more reliant on uncultivated landscapes to supplement their food consumption via collecting wild foods, such as mushrooms, green leafy vegetables, fruits, and insects, which are more abundant in the wet season. Such foods, even though consumed in limited quantities (Table 1), can be important sources of nutrients for households, especially in periods of low agricultural production.

DISCUSSION

An integrated approach to improving dietary quality via on-farm trees

Despite mounting evidence showing that on-farm trees can contribute to improved food and nutrition security,[42] there is a lack of targeted investments to leverage these linkages.[43] By teasing apart the mechanisms by which different uses of on-farm trees can affect household food consumption, our analysis can support initiatives optimizing on-farm tree systems for better nutrition. In terms of improving zinc, vitamin A, and folate intake, the larger trends in our findings reflect how cultivating on-farm trees for income or fuel is less effective than using trees for food that can be consumed directly. Our results underscore the importance of maintaining on-farm trees that provide food, which can benefit women's micronutrient adequacy in both dry and wet seasons. A reasonable application of these results would be to singularly encourage the cultivation of on-farm trees for household subsistence. However, while our findings indeed prove the efficacy of the "direct food provision" pathway in improving micronutrient intake as compared to the "income pathway," they also show that the benefits of on-farm food trees to dietary quality are not diminished by using on-farm trees for additional purposes, such as income and/or fuelwood, which can provide supplementary livelihood benefits.

Our results call into question the capacity of household diets to benefit from on-farm trees through increased income to purchase foods (via tree-based products) or cook foods (via increased supplies of fuelwood). While a household can choose to source food from their own on-farm trees, their ability to source foods of similar micronutrient value from the market is dependent on larger, underlying structural aspects of the enabling economic, social, and political environment. Accordingly, nutrition-oriented initiatives must address tree-diet linkages at the farm, regional, and national scales with the objective of making nutritious foods accessible to households through monetary *and* non-monetary means. Intervention areas include (1) supporting on-farm tree production by providing smallholders with optimal multipurpose species while reducing potential negative tree-crop trade-offs (such as lower yields), (2) increasing the availability and accessibility of nutrient-rich foods in local markets, and (3) re-orienting policy incentives to support the production and consumption of nutritious, tree-based foods.

Farm level: Identifying optimal on-farm tree species and reducing tree-crop trade-offs

Our results show how on-farm trees can contribute to people's diets across seasons. While we find use of on-farm trees for food to be the greatest contributor to micronutrient adequacy, we note that the households using on-farm trees for food, fuel, and income are the only group to experience gains in micronutrient adequacy across all four micronutrients (in the dry season) (Figure 1). Optimizing a portfolio of indigenous and exotic tree species with staggered harvest periods is a strategy to ensure year-round availability of micronutrient-rich foods on farms.[19] This is especially crucial in rural areas with limited access to trading networks; healthier, perishable foods (i.e., fruits, vegetables, and dairy) suffer from seasonal fluctuations in prices and availability in local markets.[44] Our field survey revealed that households commonly managed a mix of indigenous (e.g., *Strychnos spinosa*, *Annona senegalensis*, *Uapaca kirkiana*) and exotic species (e.g., *M. indica*, *P. guajava*, and *Persea americana)* that fruit at different times of the year, which can buffer households against market shocks (Table S1). Such trees also play a role in climate resilience; with their deep and extensive root systems, trees can better endure extreme climatic events than annual crops. As evidenced from research in other parts of Africa, forests and trees can supplement food consumption in times of climatic stress.[20,45] In particular, cultivation of indigenous fruit and nut trees can be a strategy for providing smallholders with seedlings of species adapted to both the local agroclimate and farmers' consumption preferences.[46] This could also serve to diversify on-farm tree systems, as we note that most of the common species cultivated for food, income, and fuelwood by our surveyed households are exotic (Table S1). In Malawi, breeding programs for indigenous fruit trees have resulted in accelerated fruit production, substantially reducing the time lag between planting and harvest of indigenous fruits such as baobab (*Adansonia digitata*), safou (*Dacryodes edulis*), and wild loquat (*Uapaca kirkiana*).[47]

While such innovations can incentivize wider adoption of indigenous on-farm trees, extension services must also encourage maintenance practices to reduce negative trade-offs between trees and annual crops. Trees planted in agricultural plots may both support and hinder crop growth. For example, field studies in Ethiopia and Rwanda found that trees in fields had a negative effect on maize yields, but this impact was mitigated by agronomic measures to suppress competition from weed and tree roots or pruning/leaf litter recycling.[48,49] At a larger scale, however, tree cover in agricultural landscapes is positively associated with crop productivity, with one meta-analysis from sub-Saharan Africa finding average yields of staple crops to be higher in agroforestry systems compared to yields in treeless systems.[50] Indeed, research in other African contexts finds that mechanisms operating at the landscape scale can, to some extent, enhance and override local negative effects of individual on-farm trees on crop yield.[29]

Our results indicate that nutritional benefits of on-farm trees are maintained in multipurpose systems, i.e., from on-farm trees that provide food, and/or income, and/or fuel. Indeed, the most commonly cultivated tree species recorded in our field survey were reportedly used for multiple purposes; for example, mango (*M. indica*) was cited as the most common food, income, and fuelwood tree (Table S2). Such multifunctional species can be critical for not only supplying households with nutritious food but providing supplementary benefits in the form of income and fuelwood. The latter can be a critical resource for household heating and cooking, as 90% of Malawi's overall energy demand is met with biomass fuels (wood, charcoal, twigs, and leaves).[51] The near-universal dependence on fuelwood for cooking means that, if the household is not sourcing fuelwood from their on-farm trees, then they are likely purchasing it at the market or collecting it from surrounding landscapes. Maintaining on-farm trees as sources of both food and fuelwood can (1) reduce the need to spend income on fuelwood and/or (2) reduce the impact of biomass harvesting from the local landscape, a primary cause of deforestation and ecosystem degradation in Malawi.[52] Until alternative, more efficient energy sources are made available, sustainable fuelwood production from multipurpose on-farm trees can be a strategy for smallholders to co-address dietary and household energy needs.

Policy level: Stimulating supply and demand of nutritious, tree-based foods

Recent research has highlighted the relative importance of markets in supporting the dietary quality of farming households in LMIC contexts.[53] Indeed, some empirical studies find positive associations between market access and dietary diversity in Malawi, with increased consumption of purchased foods leading to better nutrition outcomes.[54–56] However, our findings reveal that increases in the proportion of consumed cultivated foods (including tree foods) and decreases in the proportion of consumed purchased foods mirror improvements in micronutrient adequacy (Figure 1). This pattern could indicate that households may not always be able to source nutritious food at the market. Our observed trends therefore challenge the policy assumption that increased purchasing power *de facto* translates into better diets for smallholders. Future research on tree-diet linkages would benefit from market analyses to disentangle these mechanisms.

At the macro level, there is also a need to reorient policy incentives that currently support the production of calorie-rich staples to instead encourage the production and consumption of nutritious tree-based foods. While more than 70% of Malawians live under the international $1.9/day poverty line,[57] 96% of Malawians cannot afford to purchase a healthy diet on a daily basis.[3] Despite having limited purchasing power, the farmers we interviewed indicated a high reliance on food purchases, citing climate change and deforestation as primary reasons why they cannot source the resources they need from their farms or the wider landscape (Table S2). Due to strong dependence on agriculture for livelihoods, these same factors that drive market reliance paradoxically also hinder farmers' income-earning potential and, consequently, market participation. Our interviewed farmers described how climatic variations (i.e., irregular rainfall, floods, and extreme temperatures) reduced their agricultural production, while deforestation reduced the availability of marketable forest products, such as fruits, mushrooms, and timber (Table S2). Therefore, there is a need for policies that can simultaneously (1) address climate change and deforestation and (2) increase farmers' economic and ecological resilience by diversifying means of agriculture-based income.

Multipurpose on-farm trees can provide perennial sources of food, income, and fuelwood, simultaneously providing households with a reliable means of market participation while also ensuring non-monetary avenues to improving dietary quality across seasons. However, the Malawian Government has adopted a contrasting approach, addressing low agricultural earnings through maize and input subsidies that encourage agricultural simplification. The Farm Input Subsidy Program, enacted in 2005, was engineered to boost surplus maize harvests, and therefore food availability, on farms and in markets.[58] Evidence suggests that these subsidies effectively increased maize production,[59] but household-level program evaluations find no effect on participant dietary diversity.[60] An analysis of changes in Malawians' food consumption from 2004–2011 found that maize seed subsidies led to a decline in real maize prices relative to other, more nutritious food products, such as pulses and green leafy vegetables.[61] They partially attributed an observed decline in iron and vitamin A consumption to these relative price changes and recommended coupling poverty alleviation measures with economic incentives that increase affordability of pulses, fruits, and vegetables relative to calorie-rich staples. While such subsidy policies have been effective in increasing calorie consumption, the current state of malnutrition in Malawi highlights a need to better leverage agricultural strategies to tackle micronutrient deficiencies. Our findings here suggest that multipurpose on-farm trees can be an effective solution. Strategies that expand existing social protection systems to include investment in on-farm tree systems via subsidized tree seedlings and enhanced silvicultural training could help ensure household access to nutrient-rich foods both on farms and in markets. Further research is needed to evaluate which factors influence the adoption or retention of certain on-farm tree species for different uses, focusing on important dimensions such as whether the biophysical conditions favor specific species, household access to agroforestry extension services and knowledge about specific species, and household participation in cash transfer programs enabling purchase of seedlings.[62,63] Without data in these domains, it is difficult to estimate what makes farmers pursue on-farm tree retention and use and, thus, design tailored policy programs promoting on-farm trees. A study that looks more broadly at why households adopt certain on-farm trees and then, in turn, examines the effect of maintaining those trees on dietary quality would be a promising direction for future investigation.

METHODS

Research ethics

We conducted this study within the framework of the FORESTDIET project, funded by the European Research Council (ERC) under the European Union's Horizon 2020 Research and Innovation Program. The ERC and the Research Ethics Committee for Science and Health at the University of Copenhagen (hosting institution) approved this project.

Data collection

We collected data from 460 households in two distinct study areas in Malawi, located in the north (Nkhata Bay district) and in the south (Mulanje district). Household survey sites in both areas were selected to represent varying degrees of tree cover on customary land and within varied distances to a forest reserve (Figure S1). Surveys were carried out both in the dry season (October 2021) and wet season (March 2022), allowing us to account for seasonal differences in food intake. Households were systematically sampled on the basis of village size, and women with children between the ages of 2 and 5 years were interviewed as the primary respondents. The underlying assumption for our analysis is that women's food consumption patterns reflect those of the household at large, as in Malawi women are traditionally responsible for the sourcing, preparation, and provisioning of food for the household. For example, women's dietary diversity has been shown to closely parallel household dietary diversity in low- and middle-income contexts, indicating that women are reliable representatives of household dietary quality.[64] In both seasons, we gathered information on respondent characteristics as well as socioeconomic, land use, and forest use data at the household level (Note S1). The first-round dry season survey was conducted with 515 households; in the wet season, we returned to 460 households. Our analysis was therefore based on the combined sample of 460 households for which we have data across dry and wet seasons.[65]

On-farm tree data

In the household survey, respondents were asked to identify whether they had on-farm trees, and if so, self-report the species (including both wild and cultivated). Following the precedent set by Miller et al.,[20] we defined trees as woody perennials (>2 m) with elongated stems that can support leaves and branches, including bananas due to their similar productive functions and management as fruit trees. Only responses that corresponded to our scientific definition of a tree were recorded. Respondents were then asked to list how they used their on-farm trees (e.g., for food, commercial purposes, fuelwood, medicine, shade, etc.), and responses were assigned to a list of corresponding, pre-determined categories or "other." For the analysis, households were grouped based on whether/how they use their on-farm trees. Groupings were determined by assessing the three most common uses reported in our household survey: food provision, income (marketable products), and fuelwood.

Mutually exclusive categories were therefore determined by the single or multiple material contributions of on-farm trees: food, food + income, food + fuelwood, food + income + fuelwood, income + fuelwood, no trees/other trees. This last category, used as a control, encompasses households that only used the trees on/around their farmland for non-productive purposes (e.g., shade, windbreak, etc.). We acknowledge that non-productive trees can contribute to improved crop yields by providing ecosystem services (e.g., microclimate regulation, erosion control, and enhanced pollination services) and thus may indirectly support household dietary quality.[30]

In the dry season, a field survey was conducted with a subsample of 60 households, employing a mix of forestry and ethnobotanical techniques to measure the on-farm tree prevalence, diversity, and uses of specific on-farm tree species (corresponding to the same categories as the principal household survey, n = 460). Three field plots (average size, 0.44 acres) were selected randomly for measurement from each sampled household (a field plot was defined as a demarcated zone under cultivation, often delineated by a field border or footpath). All trees with a diameter at breast height >10 cm were counted and identified with the help of a local taxonomist in order to calculate on-farm tree density (trees per acre) and species diversity (per acre). Specimens were collected if the species could not be identified on site. A member of the household was then asked to identify whether and how each species was used by the household. These data on species-specific tree uses, while not included in our statistical analysis due to the lower sample size, provides useful insights for the interpretation of our results (Table S1). To gain a historical perspective of how food sourcing patterns have changed over time, field survey respondents were also asked open-ended questions pertaining to their reasoning behind changes in how they use (1) forests and trees in the landscape and (2) local markets (Table S2).

Food source and dietary data

The household survey (n = 460) was combined with a 24-h dietary recall to gather detailed, quantitative data on women's food intake the previous day, including the quantity and source of all items consumed. The amount of each food item was recorded in local units using serving size aids (bowls, plates, and cups). For each round of fieldwork, the dietary recall survey was conducted on two non-consecutive days within a 7-day period. We conducted the follow-up dietary recall survey with an attrition rate of 3% (n = 16 of 515) and 2% (n = 9 of 460) in the dry and wet seasons, respectively.

All food consumption data were converted from local units into grams using weighted equivalents of single food items and recipes recorded during the fieldwork. Using corresponding food composition tables, we estimated the dietary intake of four critical micronutrients: zinc, vitamin A, iron, and folate (Note S1). The multiple source method[66] was used to calculate the individual estimated usual intake (EUI) of target micronutrients during dry and wet seasons. We then compared the EUI against the WHO recommended nutrient intake values for each micronutrient,[67] adjusting for each respondent's age, breastfeeding, and pregnancy status (Table S3). The resulting nutritional adequacy ratios (NAR) values (spanning from 0%–100%) compares any respondent's usual intake of a micronutrient to what the WHO deems as "adequate" intake. The NAR values for each micronutrient of interest were therefore our primary outcome variables to assess the degree to which respondents achieved their recommended intakes of key micronutrients in different seasons. For example, women from households with only food trees on their farmland had an average vitamin A NAR of 0.96 in the dry season (Table 1), meaning they almost meet the adequacy threshold of 1. By contrast, women without on-farm trees had an average vitamin A NAR of 0.84 in the dry season (Table 1), indicating less adequate intakes of vitamin A in this season across respondents.

The sources for all food items recorded in the 24-h dietary recall (including recipe ingredients when applicable) were grouped into three general categories: cultivated, purchased, and wild. We co-developed definitions for each source category during the trial phase of the survey. "Cultivated" encompassed all food (from on-farm trees and fields) that was planted and managed by the household. "Purchased" encompassed any food that was obtained via monetary exchange (from the market, vendor, neighbor, etc.). "Wild" accounted for all foods that "grow on their own" (from the forest, bush, rivers, farmland, etc.), following the local definition of wild (Note S1). For each respondent, the percentage of food items from each source was calculated from an aggregate dataset spanning two recall surveys in each season. Therefore, the source data for each respondent are recorded as proportions and not real amounts. The reason for this is because when the respondent reported having consumed a meal (e.g., pumpkin leaves with tomato and onion), we would ask where they sourced each ingredient. However, we could not reliably disaggregate the recipe to determine the amount of each ingredient consumed per source. As most recipes recorded had documented nutrition information (or close proxies) in food composition tables, it was, however, possible to estimate the amount of nutrients consumed from these data (Note S1).

Statistical analysis

We explored links between on-farm tree use, food source, and micronutrient adequacy to tease apart the pathways by which on-farm trees affect dietary quality. Using linear models, we tested the effect of each on-farm tree grouping on micronutrient adequacy and food sources in both the dry and wet seasons (Figures 1 and 2), controlling for percentage of tree cover around the household, study region, household size, education level, living standards (using the multidimensional poverty index [MPI]),[68] crop count (last growing season), farm size (acres cultivated in the last growing season), and livestock holdings (measured in tropical livestock units [TLUs])[69] (for covariate selection, see Note S1). In the models testing for the effect on food source, we also controlled for the respondent's estimated usual caloric intake (kcal). All models were based on our dataset with 460 households, with the detailed field surveys (n = 60) serving to improve model interpretation. We ran models to compare the effects of on-farm tree groupings on micronutrient adequacy (4 outcome variables) and percentage of food intake by source (3 outcome variables) for both dry and wet season data (full model outputs can be found in Tables S4 and S5). The effect sizes represent the difference by which the outcome for each household grouping deviates from the control (households with "no/other tree uses" on farms). To aid in the interpretation of our results, we conducted an additional series of models testing the effect of tree species ownership (for the most commonly cultivated species reported in our household survey) on micronutrient adequacy (Table S7).

RESOURCE AVAILABILITY

Lead contact

Requests for resources and further information should be directed to the lead contact, Emilie Vansant (ecv@ign.ku.dk).

Materials availability

This study did not generate new unique materials.

Data and code availability

Anonymized versions of data and scripts can be accessed at Vansant, Emilie, 2024, Replication data and code for: "Multipurpose trees on farms can improve nutrition in Malawi," (Harvard Dataverse: https://doi.org/10.7910/DVN/OMZU3V).

ACKNOWLEDGMENTS

The authors gratefully acknowledge the research assistants from the Lilongwe University of Agriculture and Natural Resources who conducted the household and dietary surveys: Rahim Liguluwe, Aaron Posiano, Temwa Luhanga, Franscisa Khoropa, Grace Ntholo, and Jonathan Chautsi. This study was funded by the European Research Council (ERC) under the European Union's Horizon 2020 Research and Innovation Program (grant agreement 853222 FORESTDIET).

AUTHOR CONTRIBUTIONS

E.V., conceptualization, methodology, formal analysis, investigation, writing – original draft, writing – review & editing, and visualization; C.H., methodology, validation, supervision, and writing – review & editing; B.d.B., methodology, validation, formal analysis, and writing – review & editing; J.K., conceptualization, and resources, writing – review & editing; M.G., writing – review & editing; F.R., resources and writing – review & editing; L.V.R., conceptualization, methodology, writing – original draft, writing – review & editing, supervision, project administration, and funding acquisition.

DECLARATION OF INTERESTS

The authors declare no competing interests.

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.oneear.2024.12.001.

Received: May 2, 2024
Revised: October 12, 2024
Accepted: December 2, 2024
Published: December 26, 2024

REFERENCES

1. Han, X., Ding, S., Lu, J., and Li, Y. (2022). Global, regional, and national burdens of common micronutrient deficiencies from 1990 to 2019: A secondary trend analysis based on the Global Burden of Disease 2019 study. eClinicalMedicine *44*, 101299. https://doi.org/10.1016/j.eclinm.2022.101299.
2. Murray, C.J.L., Aravkin, A.Y., Zheng, P., Abbafati, C., Abbas, K.M., Abbasi-Kangevari, M., Abd-Allah, F., Abdelalim, A., Abdollahi, M., Abdollahpour, I., et al. (2020). Global burden of 87 risk factors in 204 countries and territories, 1990–2019: a systematic analysis for the Global Burden of Disease Study 2019. Lancet *396*, 1223–1249. https://doi.org/10.1016/S0140-6736(20)30752-2.
3. FAO, I. (2023). The State of Food Security and Nutrition in the World 2023: Urbanization, Agrifood Systems Transformation and Healthy Diets across the Rural–Urban Continuum (FAO). IFAD, UNICEF, WFP, WHO). https://doi.org/10.4060/cc3017en.
4. Global Nutrition Report (2022). 2022 Global Nutrition Report: Stronger commitments for greater action (Development Intiatives).
5. Birkmann, J., Liwenga, R., Pandey, E., Boyd, R., Djalante, F., Gemenne, W., Filho, W.L., Pinho, P.F., Stringer, L., and Wrathall, D. (2022). Poverty, Livelihoods and Sustainable Development. In Climate Change 2022: Impacts,Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, H.O. Portner, D.C. Roberts, E.S. Tignor, K. Poloczanska, A. Mintenbeck, M. Alergria, S. Craig, S. Langsdorf, V. Loschke, and A. Moller, et al., eds. (Cambridge University Press), pp. 1171–1274.
6. Ickowitz, A., McMullin, S., Rosenstock, T., Dawson, I., Rowland, D., Powell, B., Mausch, K., Djoudi, H., Sunderland, T., Nurhasan, M., et al. (2022). Transforming food systems with trees and forests. Lancet Planet. Health *6*, e632–e639. https://doi.org/10.1016/S2542-5196(22)00091-2.
7. Diversifying sustainable diets (2023). In One Earth, *6*, pp. 441–442. https://doi.org/10.1016/j.oneear.2023.05.004.
8. Rosenstock, T.S., Dawson, I.K., Aynekulu, E., Chomba, S., Degrande, A., Fornace, K., Jamnadass, R., Kimaro, A., Kindt, R., Lamanna, C., et al. (2019). A Planetary Health Perspective on Agroforestry in Sub-Saharan Africa. One Earth *1*, 330–344. https://doi.org/10.1016/j.oneear.2019.10.017.
9. HLPE (2020). Food security and nutrition: building a global narrative towards 2030.
10. UNEP (2021). Making Peace with Nature (United Nations).
11. Willett, W., Rockström, J., Loken, B., Springmann, M., Lang, T., Vermeulen, S., Garnett, T., Tilman, D., DeClerck, F., Wood, A., et al. (2019). Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems. Lancet *393*, 447–492. https://doi.org/10.1016/S0140-6736(18)31788-4.
12. Ickowitz, A., Powell, B., Salim, M.A., and Sunderland, T.C. (2014). Dietary quality and tree cover in Africa. Global Environ. Change *24*, 287–294. https://doi.org/10.1016/j.gloenvcha.2013.12.001.
13. Hall, C.M., Rasmussen, L.V., Powell, B., Dyngeland, C., Jung, S., and Olesen, R.S. (2022). Deforestation reduces fruit and vegetable consumption in rural Tanzania. Proc. Natl. Acad. Sci. USA *119*, e2112063119. https://doi.org/10.1073/pnas.2112063119.
14. Stevens, G.A., Beal, T., Mbuya, M.N.N., Luo, H., Neufeld, L.M., Adu-Afarwuah, S., Alayón, S., Bhutta, Z., Brown, K.H., et al.; Global Micronutrient Deficiencies Research Group (2022). Micronutrient deficiencies among preschool-aged children and women of reproductive age worldwide: a pooled analysis of individual-level data from population-representative surveys. Lancet Global Health *10*, e1590–e1599. https://doi.org/10.1016/S2214-109X(22)00367-9.
15. Mason-D'Croz, D., Bogard, J.R., Sulser, T.B., Cenacchi, N., Dunston, S., Herrero, M., and Wiebe, K. (2019). Gaps between fruit and vegetable production, demand, and recommended consumption at global and national levels: an integrated modelling study. Lancet Planet. Health *3*, e318–e329. https://doi.org/10.1016/S2542-5196(19)30095-6.
16. Galway, L.P., Acharya, Y., and Jones, A.D. (2018). Deforestation and child diet diversity: A geospatial analysis of 15 Sub-Saharan African countries. Health Place *51*, 78–88. https://doi.org/10.1016/j.healthplace.2018.03.002.
17. Rasolofoson, R.A., Hanauer, M.M., Pappinen, A., Fisher, B., and Ricketts, T.H. (2018). Impacts of forests on children's diet in rural areas across 27 developing countries. Sci. Adv. *4*, eaat2853. https://doi.org/10.1126/sciadv.aat2853.

18. Olesen, R.S., Hall, C.M., and Rasmussen, L.V. (2022). Forests support people's food and nutrition security through multiple pathways in low- and middle-income countries. One Earth *5*, 1342–1353. https://doi.org/10.1016/j.oneear.2022.11.005.

19. McMullin, S., Njogu, K., Wekesa, B., Gachuiri, A., Ngethe, E., Stadlmayr, B., Jamnadass, R., and 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 Secur. *11*, 1355–1372. https://doi.org/10.1007/s12571-019-00970-7.

20. Miller, D.C., Muñoz-Mora, J.C., Rasmussen, L.V., and Zezza, A. (2020). Do Trees on Farms Improve Household Well-Being? Evidence From National Panel Data in Uganda. Front. For. Glob. Change *3*, 101. https://doi.org/10.3389/ffgc.2020.00101.

21. Powell, B., Hall, J., and Johns, T. (2011). Forest cover, use and dietary intake in the East Usambara Mountains, Tanzania. int. forest. rev. *13*, 305–317. https://doi.org/10.1505/146554811798293944.

22. Broegaard, R.B., Rasmussen, L.V., Dawson, N., Mertz, O., Vongvisouk, T., and Grogan, K. (2017). Wild food collection and nutrition under commercial agriculture expansion in agriculture-forest landscapes. For. Policy Econ. *84*, 92–101. https://doi.org/10.1016/j.forpol.2016.12.012.

23. Powell, B., Maundu, P., Kuhnlein, H.V., and Johns, T. (2013). Wild Foods from Farm and Forest in the East Usambara Mountains, Tanzania. Ecol. Food Nutr. *52*, 451–478. https://doi.org/10.1080/03670244.2013.768122.

24. Tata Ngome, P.I., Shackleton, C., Degrande, A., Nossi, E.J., and Ngome, F. (2019). Assessing household food insecurity experience in the context of deforestation in Cameroon. Food Pol. *84*, 57–65. https://doi.org/10.1016/j.foodpol.2019.02.003.

25. Wells, G.J., Ryan, C.M., Das, A., Attiwilli, S., Poudyal, M., Lele, S., Schreckenberg, K., Robinson, B.E., Keane, A., Homewood, K.M., et al. (2023). Hundreds of millions of people in the tropics need both wild harvests and other forms of economic development for their well-being. One Earth *7*, 311–324. https://doi.org/10.1016/j.oneear.2023.12.001.

26. Angelsen, A., Jagger, P., Babigumira, R., Belcher, B., Hogarth, N.J., Bauch, S., Börner, J., Smith-Hall, C., and Wunder, S. (2014). Environmental Income and Rural Livelihoods: A Global-Comparative Analysis. World Dev. *64*, S12–S28. https://doi.org/10.1016/j.worlddev.2014.03.006.

27. Wan, M., Colfer, C.J.P., and Powell, B. (2011). Forests, women and health: opportunities and challenges for conservation. int. forest. rev. *13*, 369–387. https://doi.org/10.1505/146554811798293854.

28. Reed, J., Van Vianen, J., Foli, S., Clendenning, J., Yang, K., MacDonald, M., Petrokofsky, G., Padoch, C., and Sunderland, T. (2017). Trees for life: The ecosystem service contribution of trees to food production and livelihoods in the tropics. For. Policy Econ. *84*, 62–71. https://doi.org/10.1016/j.forpol.2017.01.012.

29. Karlson, M., Bolin, D., Bazié, H.R., Ouedraogo, A.S., Soro, B., Sanou, J., Bayala, J., and Ostwald, M. (2023). Exploring the landscape scale influences of tree cover on crop yield in an agroforestry parkland using satellite data and spatial statistics. J. Arid Environ. *218*, 105051. https://doi.org/10.1016/j.jaridenv.2023.105051.

30. Baudron, F., Duriaux Chavarría, J.-Y., Remans, R., Yang, K., and Sunderland, T. (2017). Indirect contributions of forests to dietary diversity in Southern Ethiopia. Ecol. Soc. *22*, art28. https://doi.org/10.5751/ES-09267-220228.

31. FAO (2015). Livelihood diversification and vulnerability to poverty in rural Malawi.

32. Global Forest Watch (2023). Malawi Deforestation Rates & Statistics. https://www.globalforestwatch.org/dashboards/country/MWI.

33. Bone, R.A., Parks, K.E., Hudson, M.D., Tsirinzeni, M., and Willcock, S. (2017). Deforestation since independence: a quantitative assessment of four decades of land-cover change in Malawi. J. For. Sci. *79*, 269–275. https://doi.org/10.2989/20702620.2016.1233777.

34. Zomer, R.J., Trabucco, A., Coe, R., Place, F., van Noordwijk, M., and Xu J, C. (2024). Trees on farms: an update and reanalysis of agroforestry's global extent and socio-ecological characteristics. Working Paper 179. Bogor, Indonesia: World Agroforestry Centre (ICRAF) Southeast Asia Regional Program. https://doi.org/10.5716/WP14064.PDF.

35. Brandt, M., Tucker, C.J., Kariryaa, A., Rasmussen, K., Abel, C., Small, J., Chave, J., Rasmussen, L.V., Hiernaux, P., Diouf, A.A., et al. (2020). An unexpectedly large count of trees in the West African Sahara and Sahel. Nature *587*, 78–82. https://doi.org/10.1038/s41586-020-2824-5.

36. Vansant, E.C., Mausch, K., Ickowitz, A., McMullin, S., Karanja, A., and Rasmussen, L.V. (2022). What are the links between tree-based farming and dietary quality for rural households? A review of emerging evidence in low- and middle-income countries. People Nat *4*, 296–311. https://doi.org/10.1002/pan3.10306.

37. Milheiras, S.G., Sallu, S.M., Marshall, A.R., Shirima, D.D., Kioko, E.N., Loveridge, R., Moore, E., Olivier, P., Teh, Y.A., Rushton, S., and Pfeifer, M. (2022). A Framework to Assess Forest-Agricultural Landscape Management for Socioecological Well-Being Outcomes. Front. For. Glob. Change *5*.

38. Fernandez, M., and Méndez, V.E. (2019). Subsistence under the canopy: Agrobiodiversity's contributions to food and nutrition security amongst coffee communities in Chiapas, Mexico. Agroecol. Sustain. Food Syst. *43*, 579–601. https://doi.org/10.1080/21683565.2018.1530326.

39. Euler, M., Krishna, V., Schwarze, S., Siregar, H., and Qaim, M. (2017). Oil Palm Adoption, Household Welfare, and Nutrition Among Smallholder Farmers in Indonesia. World Dev. *93*, 219–235. https://doi.org/10.1016/j.worlddev.2016.12.019.

40. Jemal, O.M., Callo-Concha, D., and van Noordwijk, M. (2022). Does income imply food security in coffee growing communities? A case study in Yayu, Southwestern Ethiopia. Front. Sustain. Food Syst. *6*.

41. Luo, Y., Min, S., and Bai, J. (2021). The role of rubber farming in household dietary diversity in the upper Mekong region, Southwest China. Food Energy Secur. *10*. https://doi.org/10.1002/fes3.285.

42. Vansant, E., den Braber, B., Hall, C., Kamoto, J., Reiner, F., Oldekop, J., and Rasmussen, L.V. (2024). Food-sourcing from on-farm trees mediates positive relationships between tree cover and dietary quality in Malawi. Nat. Food *5*, 661–666. https://doi.org/10.1038/s43016-024-01028-4.

43. Chiputwa, B., Ihli, H.J., Wainaina, P., and Gassner, A. (2020). Chapter 12 - Accounting for the invisible value of trees on farms through valuation of ecosystem services. In The Role of Ecosystem Services in Sustainable Food Systems, L. Rusinamhodzi, ed. (Academic Press), pp. 229–261. https://doi.org/10.1016/B978-0-12-816436-5.00012-3.

44. Headey, D., and Masters, W.A. (2019). Agriculture for nutrition: direct and indirect effects. Agric. Improv. Nutr. Seizing Momentum, 16–26. https://doi.org/10.1079/9781786399311.0016.

45. Kehlenbeck, K., Asaah, E., and Jamnadass, R. (2013). Diversity of indigenous fruit trees and their contribution to nutrition and livelihoods in sub-Saharan Africa: examples from Kenya and Cameroon. In Diversifying food and diets: using agricultural biodiversity to improve nutrition and health Issues in agricultural biodiversity (Earthscan from Routledge), pp. 257–269.

46. Akinnifesi, F.K., Sileshi, G., Ajayi, O.C., Chirwa, P.W., Mng'omba, S., Chakeredza, S., and Nyoka, B.I. (2008). Domestication and conservation of indigenous Miombo fruit trees for improving rural livelihoods in southern Africa. Biodiversity *9*, 72–74. https://doi.org/10.1080/14888386.2008.9712888.

47. Jamnadass, R.H., Dawson, I.K., Franzel, S., Leakey, R.R.B., Mithöfer, D., Akinnifesi, F.K., and Tchoundjeu, Z. (2011). Improving livelihoods and nutrition in sub-Saharan Africa through the promotion of indigenous and exotic fruit production in smallholders' agroforestry systems: a review. int. forest. rev. *13*, 338–354. https://doi.org/10.1505/146554811798293836.

48. Ndoli, A., Baudron, F., Schut, A.G., Mukuralinda, A., and Giller, K.E. (2017). Disentangling the positive and negative effects of trees on maize performance in smallholdings of Northern Rwanda. Field Crops Res. *213*, 1–11. https://doi.org/10.1016/j.fcr.2017.07.020.

49. Sida, T.S., Baudron, F., Hadgu, K., Derero, A., and Giller, K.E. (2018). Crop vs. tree: Can agronomic management reduce trade-offs in tree-crop

interactions? Agric. Ecosyst. Environ. *260*, 36–46. https://doi.org/10.1016/j.agee.2018.03.011.

50. Kuyah, S., Whitney, C.W., Jonsson, M., Sileshi, G.W., Öborn, I., Muthuri, C.W., and Luedeling, E. (2019). Agroforestry delivers a win-win solution for ecosystem services in sub-Saharan Africa. A meta-analysis. Agron. Sustain. Dev. *39*, 47. https://doi.org/10.1007/s13593-019-0589-8.
51. Timko, J.A., and Kozak, R.A. (2016). The influence of an improved firewood cookstove, Chitetzo mbaula , on tree species preference in Malawi. Energy Sustain. Dev. *33*, 53–60. https://doi.org/10.1016/j.esd.2016.04.002.
52. Nerfa, L., and Rhemtulla, J.M. (2019). Changes in tree species diversity, composition and aboveground biomass in areas of fuelwood harvesting in miombo woodland ecosystems of southern Malawi. For. Trees Livelihoods *28*, 176–193. https://doi.org/10.1080/14728028.2019.1621777.
53. Nandi, R., Nedumaran, S., and Ravula, P. (2021). The interplay between food market access and farm household dietary diversity in low and middle income countries: A systematic review of literature. Global Food Secur. *28*, 100484. https://doi.org/10.1016/j.gfs.2020.100484.
54. Koppmair, S., Kassie, M., and Qaim, M. (2017). Farm production, market access and dietary diversity in Malawi. Publ. Health Nutr. *20*, 325–335. https://doi.org/10.1017/S1368980016002135.
55. Matita, M., Chirwa, E.W., Johnston, D., Mazalale, J., Smith, R., and Walls, H. (2021). Does household participation in food markets increase dietary diversity? Evidence from rural Malawi. Global Food Secur. *28*, 100486. https://doi.org/10.1016/j.gfs.2020.100486.
56. Snapp, S.S., and Fisher, M. (2015). "Filling the maize basket" supports crop diversity and quality of household diet in Malawi. Food Secur. *7*, 83–96. https://doi.org/10.1007/s12571-014-0410-0.
57. World Bank (2020). Poverty & Equity Brief: Malawi.
58. Lunduka, R., Ricker-Gilbert, J., and Fisher, M. (2013). What are the farm-level impacts of Malawi's farm input subsidy program? A critical review. Agric. Econ. *44*, 563–579. https://doi.org/10.1111/agec.12074.
59. Arndt, C., Pauw, K., and Thurlow, J. (2016). The Economy-wide Impacts and Risks of Malawi's Farm Input Subsidy Program. Am. J. Agric. Econ. *98*, 962–980. https://doi.org/10.1093/ajae/aav048.
60. Walls, H., Johnston, D., Matita, M., Chirwa, E., Mazalale, J., Quaife, M., Kamwanja, T., and Smith, R. (2023). How effectively might agricultural input subsidies improve nutrition? A case study of Malawi's Farm Input Subsidy Programme (FISP). Food Secur. *15*, 21–39. https://doi.org/10.1007/s12571-022-01315-7.
61. IFPRI (2018). Agriculture, Food Security, and Nutrition in Malawi: Leveraging the Links (International Food Policy Research Institute). https://doi.org/10.2499/9780896292864.
62. Mwase, W., Sefasi, A., Njoloma, J., Nyoka, B.I., Manduwa, D., and Nyaika, J. (2015). Factors Affecting Adoption of Agroforestry and Evergreen Agriculture in Southern Africa. Environ. Nat. Resour. Res. *5*, p148. https://doi.org/10.5539/enrr.v5n2p148.
63. Amadu, F.O., Miller, D.C., and McNamara, P.E. (2020). Agroforestry as a pathway to agricultural yield impacts in climate-smart agriculture investments: Evidence from southern Malawi. Ecol. Econ. *167*, 106443. https://doi.org/10.1016/j.ecolecon.2019.106443.
64. FAO (2021). Minimum Dietary Diversity for Women (FAO).
65. Vansant, E. (2024). Replication data and code for: "Multipurpose trees on farms can improve nutrition in Malawi." Version V1 (Harvard Dataverse). https://doi.org/10.7910/DVN/OMZU3Vhttps://doi.org/10.7910/DVN/OMZU3V.
66. Harttig, U., Haubrock, J., Knüppel, S., and Boeing, H.; EFCOVAL Consortium (2011). The MSM program: web-based statistics package for estimating usual dietary intake using the Multiple Source Method. Eur. J. Clin. Nutr. *65* (*Suppl 1*), S87–S91. https://doi.org/10.1038/ejcn.2011.92.
67. World Health Organization; FAO (2004). Vitamin and Mineral Requirements in Human Nutrition (World Health Organization).
68. Alkire, S., and Santos, M.E. (2014). Measuring Acute Poverty in the Developing World: Robustness and Scope of the Multidimensional Poverty Index. World Dev. *59*, 251–274. https://doi.org/10.1016/j.worlddev.2014.01.026.
69. FAO (2018). Guidelines on Methods for Estimating Livestock Production and Productivity (FAO).