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Review

A Planetary Health Perspective on Agroforestry in Sub-Saharan Africa

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Human activities change the structure and function of the environment with cascading impacts on human health, a concept known as "planetary health." Agroforestry—the management of trees with crops and livestock—alters microclimates, hydrology, biogeochemistry, and biodiversity. Besides the nutritional benefits of increased fruit consumption, however, the ways agroforestry affects human health are rarely articulated. This review makes that link. We analyze the pathways through which tree-based farm and landscape change affect food and nutrition security, the spread of infectious disease, the prevalence of non-communicable diseases, and human migration in Sub-Saharan Africa. The available evidence suggests that, despite some increased risks of infectious disease, agroforestry is likely to improve a diverse range of pressing health concerns. We therefore examine the factors determining agroforestry use and identify three drivers of social and environmental change that will determine the future uptake of agroforestry in the region.

Planetary Change, Health, and Agroforestry

Human activities have radically altered the environment. Carbon dioxide and other greenhouse gases emitted into the atmosphere from energy production, agriculture, transportation, and other sources increase ambient temperatures, shift the quantity and timing of precipitation, and affect the frequency of extreme weather events.[1] More species are threatened with extinction from human activities than ever before.[2] Extensive areas of land have been transformed, with croplands now covering one-third of Earth's surface.[3] In higher-income countries, the use of fertilizers overwhelms local and global biogeochemical cycles, while in other areas, especially Sub-Saharan Africa, insufficient nutrient inputs lead to degraded soil and water resources.[4] These trends, among many others, point toward a planetary crisis whereby human activity threatens Earth's life-support systems.[5]

Changes to the functioning of the natural world have profound impacts on human health.[6,7] Climate change may reduce the amount of food available by disrupting crop and livestock growth, development, and important phenological events, as well as in other ways.[8] Furthermore, increased carbon dioxide levels in the air can reduce the nutritional value of foods by lowering the amount of zinc and iron they contain.[9,10] Land-use change drives the emergence and transmission of infectious diseases by altering the ecology of pathogens, hosts, and vectors.[11] Clearing land and burning biomass contributes to widespread air pollution, morbidity, and mortality.[12] Meanwhile, reactive nitrogen discharged into the air and water from fertilizers and fuel is associated with cancer, respiratory illnesses, and other health risks.[13] These examples provide just a fraction of the emerging evidence of how human activities change the capacity of the planet's natural systems to support human health, a concept known as "planetary health."[14]

Humans have significantly modified the landscapes of Sub-Saharan Africa in efforts to improve welfare. This started in the savannahs, where grasslands were burned annually to minimize bush encroachment and improve hunting success.[15] Forests were then cut down for shelter, fuelwood, and access to fertile soils.[16,17] Recently, the emergence of megacities has resulted in unprecedented flows of natural resources, including water and wood, from rural to urban areas.[18] Exploitation of the natural environment has supported dramatic population growth, as well as improvements in life expectancy and reductions in poverty for some. Even today, the majority of livelihoods in Sub-Saharan Africa are directly derived from natural resources, particularly from no- or low-input agriculture and pastoralism.[19] This continued direct reliance on natural resources makes Africans' health especially sensitive to environmental change, including

Table 1. Areal Extent of Tree Cover on Agricultural Lands and Population Living in Landscapes with Tree Cover in Sub-Saharan Africa

	2000				2010	
Tree Cover (%)	km^2	% of Total Agricultural Land	Population (Millions)	% of Persons Who Live in Agricultural Areas	km^2	% of Total Agricultural Land
>10	1,089,278	27.5	67.6	37	1,137,864	28.7
>20	528,602	13.3	28.2	16	582,064	14.7
>30	345,302	8.7	13.0	7	353,961	8.9

Population estimates were not calculated for 2010. Source: Zomer et al.[26]

climate change.[20] However, that may also increase the efficacy and reduce the lag time of nature-based solutions to health challenges.

Agroforestry—the integration and management of trees and woody shrubs with crops and livestock—is a frequently suggested solution to intertwined food-, climate-, energy-, land-, and water-related challenges in Sub-Saharan Africa. Seventy-one percent of African countries have committed to using agroforestry for climate change adaptation and/or mitigation in the Nationally Determined Contributions—blueprints for climate action—they submitted to the United Nations Framework Convention on Climate Change.[21] More than half the countries on the continent (28 out of 54) have pledged to ecologically restore a total of 1,130,000 km^2 of land, and much of this restoration will rely on tree planting. Countries such as Kenya and Ethiopia have taken steps to conserve and restore landscapes with trees to preserve vital watershed functions. Development paradigms including "nature-based solutions," "climate-smart agriculture," "agroecology," "sustainable intensification," and "ecosystem-based adaptation" all promote agroforestry.[22–25] With politics and practice aligning, agroforestry is likely to be a driver of environmental change in Sub-Saharan Africa in the future.

Agroforestry is not only tomorrow's solution: trees already are widely scattered on farms and ranches, and in other managed landscapes. Zomer et al.[26] mapped the extent of trees on farms using satellite imagery and geo-datasets and found that nearly 30% of the agricultural land in Sub-Saharan Africa had at least 10% tree cover (registering at about this level in both 2000 and 2010), with nearly 40% of the population that lives in agricultural lands based in such areas (Table 1). It is therefore clear that agroforestry is a major current land use in Sub-Saharan African landscapes. In fact, the aforementioned may significantly underestimate the current extent of agroforestry on the subcontinent due to technical limitations in using satellite imagery to identify low-density tree cover common in agroforestry systems[27] and because agroforestry occurs in areas not officially defined as cropland.[21] For example, silvopastoral systems that integrate livestock and trees take place on grazing lands, and shade-grown commodity agroforestry systems (e.g., coffee and cocoa) often meet the formal definition of forests, and therefore may not be captured.[28]

Despite the pervasive presence of agroforestry in Sub-Saharan Africa, the diverse impacts of tree-based environmental change on human health are rarely articulated. This is even though it is widely known that agriculture has significant implications for the spread of infectious disease, the prevalence of non-communicable diseases, human nutrition, and migration of human populations.

In this review, we target this space by examining how changes in the environment due to agroforestry may influence human health. We have considered relevant peer-reviewed literature, starting with the current authors' experience in the various subjects covered, and complemented by Google Scholar searches. Although not a formal systematic review, we have made efforts to include studies illustrating both positive and negative impacts of agroforestry on the environment and health to provide a balanced assessment. When available, we used recent meta-analyses to frame the discussion. In brief, we found that the evidence suggests that, despite some disease risks, agroforestry can positively affect human health outcomes across a broad range of concerns (Figure 1). Here, we first detail the evidence of the many links between agroforestry and health. Then, given the benefits of agroforestry and the current interest in promoting it, we discuss the social determinants of agroforestry use in Sub-Saharan Africa and three key drivers that will influence the capacity to improve planetary health with agroforestry going forward.

Agroforestry-Driven Environmental Change

Agroforestry is the purposeful integration and management of trees on farms and in wider landscapes, either through retaining existing trees, planting indigenous or exotic trees, or allowing trees to naturally regenerate. In Sub-Saharan Africa, land managers practice agroforestry in nearly all climatic zones and farming systems, from arid to humid and from extensive livestock to intensive crop-management systems (Figure 2). In all cases, trees modify the biophysical structure of land, directly affecting the environment at multiple scales, from processes occurring at the micron scale immediately beneath the tree (e.g., soil aggregation) to those at the global scale in the atmosphere (e.g., climate change). Knowledge of how agroforestry affects climate, hydrology, nutrient cycles, and biodiversity is a prerequisite to understanding agroforestry-mediated connections between environmental change and human health.

Climate

Agroforestry regulates field-scale microclimate including air temperature, solar radiation, and wind speed. Changes result from the physiological habit of trees: the shade effect and the cooling effects of water vapor due to increased evapotranspiration. Change in temperature can be significant. Midday temperatures are reduced by up to 6°C under a canopy of *Faidherbia albida* (faidherbia) trees in Ethiopia compared with open fields,[29] and trees also reduce temperature at field level in Ghanaian cocoa agroforests.[30] Furthermore, the presence of trees buffers temperature fluctuations, helping to maintain

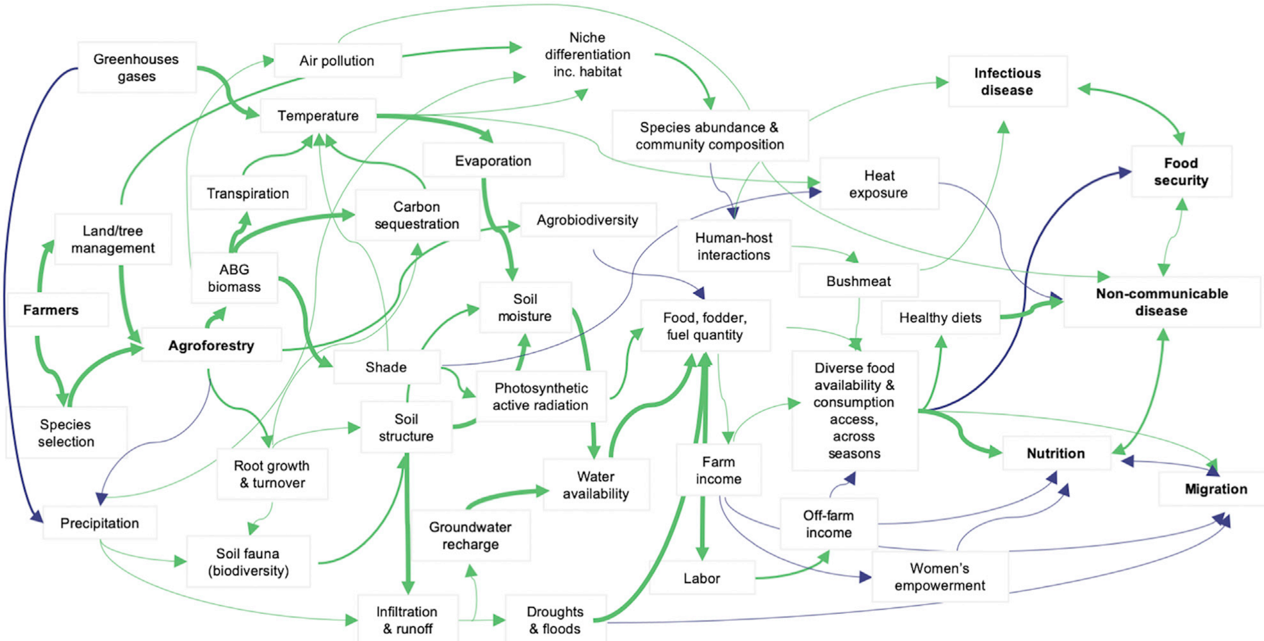

Figure 1. Pathways and Qualitative Evaluation of the Evidence by which Agroforestry May Affect Human Health though Mediating Changes of Climate, Hydrology, Biogeochemistry, and Biodiversity

Line thickness represents the amount of evidence available; three weights are used. Line color indicates the agreement in the available evidence, where green suggests general agreement and purple suggests some disagreement.

more optimal growing conditions for associated crops and livestock.[31] Trees, however, do not always change microclimates in beneficial ways. Shade can reduce, sometimes significantly, the photosynthetic active radiation reaching crops. For example, in semi-arid areas of Burkina Faso, unpruned trees reduced photosynthetic active radiation by more than 50% compared with open fields, suppressing crop yield.[32] The impacts of agroforestry trees on climate at larger scales are positive and similar to those of forests; trees reduce temperatures and help mitigate climate change.[33–37]

Water

Trees modify soil structure directly through root growth, reducing soil compaction and increasing water retention and infiltration. Trees reduce water evaporation from soil by lowering ambient temperatures, which also reduces transpiration of associated crops.[38] This is one of the reasons that farms in agroforestry systems often have greater moisture content than farms without trees.[39] Conversely, trees can compete with crops for water, depleting soil water close to them. Small-scale impacts of trees on soil-moisture dynamics are amplified with high tree density and fast-growing species. Under these situations, trees increase transpiration and can draw down water tables. When trees are absent, water runs off the land more quickly. In Ethiopia, for instance, agroforestry increased infiltration and reduced catchment runoff by up to 81%.[40] Thus, intermediate tree cover may be most appropriate for balancing water demand and increasing groundwater recharge.[41] Trees (and forests) also link local to regional and global water cycles through recycling of rainfall. Precipitation, especially inland precipitation, is mediated by the hydraulic pump of evapotranspiration and tree volatile compounds.[42] At least 40% of rainfall originates from evapotranspiration globally. This means that trees connect different locations, with land use in one location altering rainfall in another.[37]

Nutrient Cycling

Trees influence the cycling of nutrients in agricultural fields, farms, and surrounding landscapes both directly and indirectly. They mine deep soil layers for nitrogen, phosphorus, and other critical nutrients, making these available to crops through the decomposition of their dropped biomass and root turnover.[43] Leguminous trees and shrubs form symbiotic relationships with bacteria to fix atmospheric nitrogen and accumulate it in soils and biomass.[44,45] This provides a natural fertilizer to crops and protein-rich fodder for animals.[46,47] These processes all have the effect of increasing nutrient inputs and organic materials into agricultural systems, through litter, biomass, and root decomposition. Such inputs have been considered crucial in increasing land-use efficiency, particularly in Sub-Saharan Africa, where farmers often cannot source and/or afford commercial fertilizers, and base-nutrient levels in soils are often low. However, tree-based systems also present some challenges for nutrient management. Increased nutrient inputs do not always end up in the target crop or livestock and may leach into groundwater or be lost to the atmosphere.[44,48] Increases in soil moisture and carbon content, and concomitant increases in soil biodiversity, can increase rates of nutrient cycling; although generally positive, this also results in higher emission rates of carbon dioxide through soil respiration. Lastly, harvesting of tree products from farms, especially of young woody material from dense plantings, can export large amounts of nutrients, leading to nutrient depletion.[49]

Figure 2. Select Examples and Environmental Impacts of Agroforestry in Sub-Saharan Africa
Agroforestry trees may be planted new, regenerated from seed reserves dormant in soils, or maintained after land-use change. Because land managers have countless options of tree species and management actions (e.g., pruning, spacing, and timing), there are literally thousands of permutations of agroforestry across the continent, with each changing the structure and function of the natural world. Photos: World Agroforestry.

Biodiversity

The addition of trees to agricultural landscapes results in diversification of microclimates both above and below ground, as well as diversified strata and, potentially, vegetation phenology. Thus, agroforestry can create new ecological niches for both beneficial and detrimental species. Generally, agroforestry systems support higher biodiversity of birds, insects, and small rodents compared with monoculture systems;[50–52] however, increases in biodiversity are not always associated with increases in functional diversity or conservation of rare and/or endemic species.[53] Effects on biodiversity are borne out with microorganisms too, in that adding trees to systems increases the diversity and function of soil biota.[54] The effect of trees on associated biodiversity appears to be determined by tree species, arrangement, and management intensity.

In summary, agroforestry affects the environment by intercepting sunlight, lowering ambient temperatures, reducing crop evapotranspiration, increasing water use in some cases, improving soil water-holding capacity and water infiltration, and enhancing carbon storage and biodiversity, among other mechanisms. A synthesis of studies conducted in Africa (mostly addressing field-scale effects) suggested that, in about 60% of cases where the agroforestry-environment relationship was investigated, trees improved the delivery of ecosystem services (Table 2). Although most of the studies showed largely positive impacts, the considerable number of studies that showed negative or non-significant effects of agroforestry suggests the possibility of diverse, often site-specific, and unintended outcomes when managing land with trees.

Food and Nutrition Security

There were 237 million food-insecure people in Sub-Saharan Africa in 2017.[55] The level of severe food insecurity that year was 9% higher than 3 years earlier. Malnutrition, including undernutrition, micronutrient deficiency, and overnutrition, affects around 20% of people in Africa and is a major risk factor for both infectious and non-communicable disease.[56,57] We relate three ways by which agroforestry influences food and nutrition security.

Availability

Environmental changes driven by agroforestry modify the production conditions for crops and livestock grown in their vicinity. Evidence suggests that this process largely increases food

Table 2. Impact of Agroforestry on Ecosystem Services in Africa

	No. of Studies[a]	Significant Effect (%)		Non-significant
		Positive (+)	Negative (−)	
Microclimate	18	61	39	–
Nutrient cycling	128	59	8	33
Water dynamics	69	51	35	14
Soil fertility	156	59	3	38
Biodiversity	25	56	16	28

Adapted from Kuyah et al.[58]
[a]Total n = 207 studies.

availability. A systematic review of 207 case studies in Sub-Saharan Africa found that trees increased crop or livestock product yields in 68% of studies, while yields were reportedly suppressed in only 18% of cases (the rest of the studies saw no obvious effect).[58] Benefits of trees were realized in every climatic zone. The precise mechanism by which yields increased or decreased depended on the agroecological context and agroforestry technology used. For example, improved fallows using short rotation and fast-growing woody legumes increased subsequent maize yields, in large part due to increased soil nitrogen. Intercropping positively affected yields, but only in circumstances where trees were heavily managed; otherwise yields went down.[32,46] These results suggest that while there is a risk of decreasing food availability due to competition for resources, concerns may be mitigated through good management and appropriate selection of species.

Where trees on farms and/or trees in wider landscapes increase the production and availability of, for example, micronutrient-rich fruits, leafy vegetables and other foods such as nuts, agroforestry can have a significant effect in reducing malnutrition. Fruit consumption, regardless of type, has been associated with significant reductions in undernutrition (nearly 2%).[59] Average consumption of fruits, leafy vegetables, and nuts on the subcontinent is well below 50% of the World Health Organization's recommendations.[60] With more than 70% of fruit produced for human consumption globally harvested from trees, agroforestry represents a key opportunity to raise the level.[61] Indeed, intermediate levels of tree cover, such as those provided by agroforestry, are positively associated with fruit and vegetable consumption in Africa,[62] further supporting the utility of agroforestry for improved nutrition.[63,64] Many indigenous species, in particular, have the potential to provide needed micronutrients (Figure 3). They often contain higher levels of important minerals and vitamins than mainstream exotic fruits. For example, vitamin C concentrations in the edible portions of the fruit of the indigenous species *Adansonia digitata* (baobab), *Sclerocarya birrea* (marula), and *Sorindeia madagascariensis* (mtikiza) are all at least twice as high as for the standard (exotic) orange that is regarded as the reference source.[65] Thus, agroforestry products and the diversity of locally available African tree foods found in landscapes have great potential to fill nutrition gaps and contribute to nutrient adequacy in poor rural communities, and they represent an underexploited opportunity to improve nutrition.[63,64,66]

Agroforestry directly influences the availability of food through mechanisms other than supporting crop production and the direct consumption of tree foods. For example, leguminous fodder shrubs are a commonly used agroforestry component in mixed crop-livestock systems, where they provide a protein-rich diet supplement for cattle and goats, increasing the production of milk and meat. *Calliandra calothyrsus* (calliandra) leaves fed to dairy cows provide amounts of digestible protein similar to processed feeds, and increase milk production.[67] Increased production can fuel local consumption of animal-source foods, a critical nutrition intervention to combat both child stunting and wasting. Indeed, intake of animal-source foods has an even more significant effect on reducing stunting than fruit consumption, though only slightly, and its effect is most pronounced for children aged 18–24 months.[59]

Access

Another way agroforestry influences food and nutrition security is by overcoming economic and cultural barriers to sourcing nutritious foods. That is, agroforestry contributes to increased access to food. The suite of agroforestry technologies available can produce a range of products including fruits, fuelwood, and fodder that are sold into local, regional, and international markets.[68] Coffee and cocoa are perhaps the best-known examples of cash crops often, though not always, grown in agroforestry systems by Sub-Saharan African smallholders. Their production contributes significantly to rural livelihoods and national economies. In Ghana, for example, cocoa is grown by 800,000 smallholder farmers and contributes 16% of gross domestic product.[69] Trees are important at the household level too, where benefits make up a significant fraction of household incomes in multiple countries.[70] Across Ethiopia, Malawi, Nigeria, Tanzania, and Uganda, tree products provide 6% of total annual income for all rural households and 17% for households that specifically cultivate trees.[71] Less well-known African tree crops, such as *Vitellaria paradoxa* (shea) nuts—used in food and cosmetics globally and collected in parklands agroforestry systems—contribute 12% to household incomes (in terms of all produced outputs, including for subsistence use) for poorer households in Burkina Faso in places where other economic activities are limited.[72] Although linkages between incomes and diets are complex, incomes are sometimes spent to diversify diets through the purchase of fruits and other healthy foods in Africa, as well as other goods that positively affect household food and nutrition security.[73]

Often the impact of increased incomes and economic exchange on food and nutrition security depends on gender roles and norms. Households do not work as a single production and consumption unit with a single set of needs, resources, benefits, and goals.[74] Instead, members of the same household can have different livelihood strategies and benefit differently from household income streams and assets, depending on their positions within the household and their bargaining power.[75] Preferences and decisions regarding which tree species are planted in what locations are heavily influenced by gender-determined interests, needs, and constraints. In both eastern and western Africa, male motivations to plant and care for trees in farms are largely conditioned by obvious commercial opportunities.[76,77] Although women's motivations are also driven by prospects of income generation, they give higher value to the use of tree products as foods for family use.[78,79] Traditionally, however, women have limited rights to tree products, with their access mostly restricted to those products normally considered to have only little or no commercial value. For example, women in Sub-Saharan

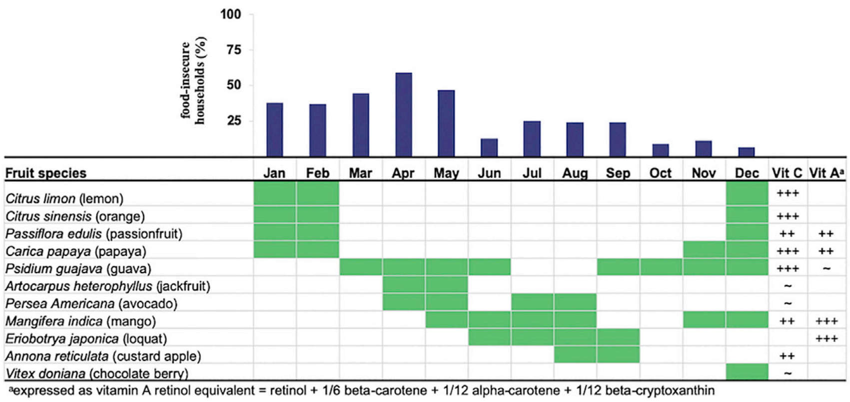

Figure 3. Fruit Tree Portfolio for Machakos, Eastern Kenya

Ten fruit tree species with moderate to high vitamin A and/or vitamin C contents (plus avocado, which provides high levels of vitamin E and antioxidants, is available during peak food-insecure months, and is a preferred fruit tree species of farmers) and their months of harvest, indicated by green-shaded boxes in a calendar. Availabilities are mapped against months of food insecurity of the surveyed households (HHs) (nHH = 304). Note the overlap of months showing high food insecurity and available fruit. Ratings of vitamin A and vitamin C contents are given as +++ (high source); ++ (source); ~ (present, but low); blank, white (no source).

Africa participate in indigenous fruit enterprises at rates much greater than for exotic fruit enterprises, the former being socially and culturally considered a domain for women and children.[80] Efforts to develop value chains or enterprises that focus on tree products traditionally managed by women can help empower them. Such enterprises allow women to pool labor, assets, and other resources to help overcome gender-related challenges.[81] That empowerment often translates to positive food security and nutrition outcomes.[82]

Stability

The factors discussed above improve the production of, access to, and diversity of foodstuffs. Availability of food, however, may be limited by a number of other factors, including seasonality.[83] Long dry periods in many locations on the continent, as well as increased instability in weather patterns caused by climate change, mean that the seasonality of food availability is of increasing concern. Agroforestry addresses seasonality in at least two ways. First, gaps in availability can be closed by planning and planting a diversity of trees with different harvest phenologies that address month-on-month fruit availability and micronutrient gaps in local households' diets (Figure 3). Furthermore, diversification is expected to promote greater resilience in food systems through spreading the risk of crop failure.[84] Second, the deep and extensive root systems of trees make them more drought tolerant than annual crops, meaning they can provide food for humans and livestock in dry periods when other sources are not available. Tree foods thus have the potential to complement and diversify predominantly staple-based diets in ways that meet food and nutrition needs of rural households throughout the year.

Infectious Disease

Agroforestry, by delivering higher staple crop yields and micronutrients, and by generating income and supporting women's empowerment, among other mechanisms, can have positive effects on food and nutrition security. However, agroforestry also may present some risks to health. Changes in land use and land cover may increase or decrease risks of infectious disease outbreaks by influencing the distribution of disease pathogens, vectors, or hosts.[11] Although human disease ecology and epidemiology rarely explicitly consider agroforestry systems, environments and conditions where disease emergence and transmission typically occur—at forest edges or under mixed cropping systems[85]—are agroforestry. Understanding how human influence on land use affects (and can mitigate) infectious disease is of paramount importance in Sub-Saharan Africa because it is the only region globally where deaths from infectious disease still exceed those from non-communicable diseases.[86] We focus on four pathways through which agroforestry may affect disease emergence and transmission.

Species Abundance

Trees regulate disease organisms by creating or reducing ecological niches. Structural changes to land use, either when land becomes more complex (e.g., monoculture to intercropping) or simplified (e.g., closed forest to intermediate tree cover), affect ambient temperature, humidity, wind speed, nutrient availability, solar radiation, and physical structures such as soil undulations. Creation of novel niches in turn influences the growth, reproduction, and fitness of various disease vectors, hosts, and parasites.[87]

It is therefore logical that agroforestry may alter the population dynamics of human disease vectors.[88] For example, agricultural development in Sub-Saharan Africa has been associated with changes in densities, life cycles, and human biting rates of *Anopheles* mosquitoes, the vector of malaria. Productivity of *Anopheles gambiae* was significantly higher in western Kenyan farmland with an average of 15% tree cover (i.e., agroforestry) than in associated natural forest or wetland habitats.[89] *A. gambiae* appears to use specific physical structures such as tree holes for breeding.[90] Microclimate and habitat modification by agroforestry thus increases mosquito prevalence and the risk of transmission to humans.[91] This relationship is also borne out by tree crops in Uganda being positively associated with local incidences of malaria.[92] However, these changes have not always been linked to increases in human malaria risks.[93,94]

Concerns about the consequences of agroforestry development on infectious diseases are not limited to malaria. Woodland patches used for grazing livestock were identified as the main habitats for tsetse flies, driving human trypanosomiasis risks in Zimbabwe.[95] Nutrient enrichment of fresh water, which may occur when using leguminous tree species in agroforestry systems,[48] may promote increases in the abundance of human pathogens. For example, snail populations, which are a vector for schistosomiasis, increase in response to nitrogen and phosphorus in the environment.[96]

Biodiversity Loss

Increasing or decreasing tree cover can change community dynamics and tip balances in interspecific competitions. Where diseases can be transmitted by multiple vectors (e.g., different species of mosquito for malaria), or where hosts are engaged in complex food webs, changes in tree cover and consequently biodiversity can favor or suppress transmission based on resulting changes to ecological community structure.[97] The effect will depend on the sequence whereby species emerge or are lost as species richness changes, because different disease vectors are not equally efficient at transmitting pathogens.[98] Some evidence indicates that biodiversity loss increases pathogen transmission.[87] This suggests that the species most likely to spread pathogens persist as biodiversity declines. In areas where agroforestry represents a simplification of the landscape, e.g., from tropical forests to plantations or even complex agroforests, one might thus expect potentially greater incidence of disease transmission (see also previous paragraph). However, recent evidence also shows a contradictory relationship: increasing biodiversity, through forestation, is associated with increased disease burden.[99] The impact of altering biodiversity on infectious disease, therefore, seems to depend on the ecology of disease and location. Further study is needed to better elucidate these associations for important diseases on the subcontinent.

Spillover

Facilitating increased transmission of pathogens from reservoir animal populations living in natural habitats is a third mechanism by which agroforestry may contribute to infectious disease emergence and persistence. Agroforestry, especially along the forest margins, changes the ecology of hosts and pathogens by altering species abundance and distribution and the connectivity of landscapes. The habitat fragmentation involved typically increases human exposure to pathogens by increasing spatial overlap of populations, either directly through activities such as bushmeat consumption or via transmission through livestock. Forest loss and habitat fragmentation mechanisms have been linked to the spread of both Marburg and Ebola viruses in Sub-Saharan Africa.[100] Recent spatial analysis of outbreaks of Ebola virus in West and Central Africa, for example, suggests that spillover is more likely to occur in areas affected by forest fragmentation,[101] some of which could be agroforestry parcels.

The precise mechanism by which agroforestry contributes to spillover is uncertain. For example, transmission may occur due to activities within agroforestry at the forest margin, or agroforestry patches may simply act as gateways to deeper forest areas. Regardless, complex relationships could emerge. For example, we speculate that agroforestry could lead to increased interaction with bats, an important host for a number of diseases. Previous studies have identified deforestation and agricultural practices as risk factors for exposure to bat-borne henipaviruses in Africa.[102] In Malaysia, the emergence of Nipah virus was traced to industrial pig farms in close proximity to mango tree farms used as a fruit source by wild bats.[103] Date palm agroforestry systems have subsequently become the main driver of Nipah virus epidemics across Bangladesh.[104] These examples from elsewhere provide an indication of potential disease risks due to agroforestry in Sub-Saharan Africa.

Human Behavior

Agroforestry and changes in agricultural practices are intricately linked with changes in the movement, distribution, and behavior of people.[105] While long-range migration has been linked to the spread of malaria and other infectious diseases, changes in finer-scale mobility may be linked to occupational or forest activities. For example, importation of immunologically naive individuals as workers in a newly developed tea plantation in the Kenyan highlands led to a re-emergence of malaria within the region.[106] Occupational activities associated with planting and farming fruit trees are associated with increased risks of exposure to bat-borne henipaviruses in Ghana; these populations also reported high rates of hunting and eating bats, further increasing opportunities for zoonotic transmission.[95] Development of roads to transport agricultural products increases proximity and access to wildlife habitats and has been associated with increased bushmeat consumption.[107,108] Conversely, increases in socioeconomic status due to agroforestry can lead to improvements in housing quality, infrastructure, and access to healthcare, factors associated with decreased risk of malaria in Africa.[109]

Non-communicable Disease

The prevalence of non-communicable diseases such as cardiovascular disease, cancer, chronic respiratory diseases, hypertension, diabetes, and mental illness is increasing rapidly in Sub-Saharan African nations, often at a greater rate than that in higher-income countries.[86,110] This trend will continue as increasing longevity changes the demographic profile of the population and as changes in lifestyle associated with economic development and urbanization, including reduced activity, dietary change, and tobacco and alcohol use, take place.[111,112] These factors threaten the development of the continent because non-communicable disease places significant economic burdens on households and economies through treatment costs, decreased productivity, and reduced labor supply.[113] These effects are disproportionately felt by the least well off and link non-communicable disease to poverty. Agroforestry may help mitigate the threat posed by the rise in incidence of many non-communicable diseases in Sub-Saharan Africa by directly reducing exposure. We highlight a few probable but little-studied pathways that may affect large segments of the population, including healthy diets, heat exposure, air pollution, and sources of medicines. We suspect there are also likely important effects of agroforestry on mental health, given evidence linking green space and forests to health in urban and rural environments in other locations,[114,115] although data to draw out those connections are not yet available.

Healthy Diets

There is a clear link between low fruit and vegetable consumption and increased risks of obesity, cardiovascular diseases, cancer, and diabetes.[116] Despite this evidence, trends in most countries in Sub-Saharan Africa are toward a nutrition transition away from healthier options to foods with higher sugar, fat, and caloric content, partly driven by changes in food supply and the sometimes higher cost of healthier options.[117] Agroforestry, especially the growing of fruit trees, may result in cost-effective interventions against diet-related disease by ensuring sustainable access and availability of fruits and nuts (discussed in detail in Food and Nutrition Security). The link between nuts and sustainable diets recently received significant attention. The landmark 2019 EAT-Lancet Commission report recommended a significant increase in nut consumption to achieve a planetary diet.[118] Nuts are nutrient dense and can provide important

Box 1. Importance of Indigenous Fruits for Income, Nutrition, and Medicinal Purposes in Southern Africa

Consumption of fruits plays a significant role in prevention and delay in the onset of chronic degenerative diseases such as hypertension, cancer, and cardiovascular diseases. In southern Africa, indigenous fruits contribute on average about 42% of the natural food basket of rural households.[125] During the lean period of low food stock, indigenous fruits can reduce the probability of falling below the income threshold by 30% and fill food gaps with nutritious products.[126,127] Besides provision of fruits, indigenous trees provide medicines. Global trade in medicinal plants is a significant business. From 70% to 80% of the population in developing countries depends on traditional medicine, mainly medicinal plants, for primary health care,[128] partly due to the high cost of modern pharmaceuticals and health care, and partly because traditional medicines are a cultural preference.

The Miombo ecoregion, dominated by trees belonging to the family Caesalpiniaceae, and covering an area of over 3.6 million km^2 across 11 countries of southern Africa, has more than 80 known species of edible indigenous fruits.[129] More than 10% of the tree species found in the ecoregion have medicinal and pesticidal properties. There is increasing evidence that climate change is likely to alter the distribution of some indigenous fruit and medicinal trees in the region, for example baobab,[130] *Colophospermum mopane* (mopane), and *Aloidendron dichotomum* (quiver tree).[131] Impact on fruit and medicine production of these critical genetic resources through increased tree mortality as a result of heat stress, drought stress, and pest outbreaks is likely.[132]

unsaturated fatty acids, fiber, minerals, vitamins (vitamin E), and antioxidants; nuts such as *Anacardium occidentale* (cashew) also contain high amounts of protein. Nut-based agroforestry, such as coconut-cashew systems in Kenya and mixed crop-macadamia systems in Malawi, may increasingly be a source to meet demand.

Heat Exposure

Heat exposure is a significant health hazard. In hot and humid conditions, physiological mechanisms are sometimes inadequate to keep the body temperature below harmful levels. Heat stress and exposure in excess of physiological tolerance is a risk factor for ill health and mortality from cardiovascular and respiratory illness, heatstroke, heat exhaustion, organ failure including kidney damage, heat-related injuries, cognitive decline, and mood changes.[119,120] Outdoor agricultural workers in Sub-Saharan Africa are especially vulnerable due to low levels of mechanization that lead to extended hours of manual labor. One study found that wet-bulb globe temperatures on farms in Ghana peaked at 33°C–38°C; when coupled with physically demanding farm labor, heat of this magnitude can lead to serious health consequences.[121] Agroforestry may help mitigate these dangers because trees reduce ambient temperatures significantly and provide shade. With trends toward increased temperatures and reduced tree cover in some parts of Sub-Saharan Africa,[35] heat exposure could create greater health risks and increased economic impacts on rural livelihoods. Thus, the intentional integration of trees into farms may offer effective adaptation solutions for agricultural workers.

Air Pollution

Sand and dust storms cause numerous human health problems globally, especially in arid and semi-arid regions.[122] Inhalation of fine particles can cause or aggravate diseases such as asthma, bronchitis, emphysema, and silicosis (lung fibrosis). In addition, fine dust carries a range of pollutants, spores, bacteria, fungi, and potential allergens. In Sahelian countries, there is a strong correlation between dust loads from the Sahara and meningitis outbreaks. Poor visibility, sand movement, and deposition as a result of sand and dust storms also increase incidences of road accidents and aviation hazards. Climate change projections suggest that currently dusty areas of Africa are likely to become drier,[123] which will increase dust loads with potentially concomitant increases in health impacts. By providing wind barriers and stabilizing landscapes, agroforestry can offer a key strategy for preventing anthropogenic dust sources in some situations.[122] Trees and shrubs in Burkina Faso reduced wind speed by upward of 15% and sediment transport by 11%–23%.[124] Mobilization and transport of dust links this issue to other continents too, as about 50% of dust produced globally starts in Africa. Despite clear evidence of the relationship between exposure to dust and health outcomes, few studies have quantified the health impact of dust on the people of Sub-Saharan Africa or developed effective interventions to reduce exposure.

Sources of Medicine

Tree products serve key medicinal functions in Sub-Saharan Africa, where literally hundreds of known tree species are used in the pharmacopeia (Box 1). These products are a preferred source of medicine not only for rural and poor households but increasingly also for urban and wealthy people interested in "natural" products. Many of these products are currently harvested from wild trees, often in unsustainable ways. Agroforestry offers the opportunity for their cultivation, which could stabilize supply and increase the sustainability of the resources themselves.

Migration

Insofar as agroforestry affects economic opportunities and environmental conditions, it has the potential to affect migration. Migration choices, both short and long term, are often thought to be a household-level strategy to diversify risk. Evidence from Mali, Ethiopia, and Burkina Faso suggests that environmental hazards such as drought drive decisions to send migrants to urban relatives or refugee settlements.[133] Analysis of the 2014 Gallup Poll results for Sub-Saharan Africa shows that food insecurity drives both the desire and the decision to migrate.[134] Thus, agroforestry's role in food and nutrition security may affect migration. However, despite their desires, the very poor and most food insecure may not have the means to move. This suggests that while conventional wisdom suggests that economic improvement is a means to reduce rural-urban migration, the opposite may also be true. A modest increase in income such as that provided by agroforestry products, especially when they represent wild harvesting on communal lands as opposed to investment in the land itself, may provide the money required to migrate rather than the incentive to remain in place.[133,134]

Figure 4. Determinants of Agroforestry Use in Sub-Saharan Africa
A "vote-counting" meta-analysis of the factors that affect adoption and use of agroforestry (n = 23 studies). Adapted from data in Pattanayak et al.[141] Categories of factors that influence adoption include demographics, markets, resource endowments, risk, and biophysical condition (list on left). Gray-blue and green circles represent the number of times the factor was insignificant or significantly associated with adoption, respectively. Values in circles equal the percentage of positive associations of significant associations. It should be noted that vote-counting treats all studies equally: it does not provide differential weights based on an assessment of the reliability of results. Therefore, the results presented here give a general indication of the types of determinants of adoption and the relative direction of evidence.

Where agroforestry helps to mitigate environment change and increase household resilience, reduced migration may occur. Random climate shocks, such as floods and drought, reduce assets and threaten livelihoods, intensifying households' vulnerability.[135] If agroforestry reduces the severity of such an event or even the perceptions of the event, such as when households in western Kenya that practice agroforestry had a reduced fear of flood and drought risk,[136] it could buffer against migration. As well as extreme events driving migration, slowly developing environmental change may also catalyze population movement. Declines in soil quality, which can occur slowly, have been linked to out-migration in Burkina Faso, Nigeria, and Uganda, but not necessarily in some parts of Kenya.[137] Conflicting results highlight the complexity of environment-migration relationships. What appears to be certain is that the availability and reliability of ecosystem services and exposure to natural hazards have the potential to affect migration.[138] Because of agroforestry's ability to affect practically all environmental conditions ranging from droughts and floods to microclimates and soil quality, as well as its potential to enhance overall household resilience, it seems that agroforestry may be an instrument for helping to curb desires and decisions to migrate.

When migration or forced displacement has occurred, agroforestry mitigates conflict and may improve mental health. Tens of millions of displaced persons rely on tree products for energy, shelter, animal fodder, nutrition, and income. Overuse of these products degrades forest and land resources around settlements and creates conflict with local populations who rely on the same resource base. These issues are particularly relevant in locations such as the Democratic Republic of Congo, where about 4.5 million people are internally displaced and nearly 700,000 have fled to neighboring Uganda and Burundi. Contrary to conventional wisdom, settlements for displaced persons are not typically short term; many often last more than 20 years, making trees and woody shrubs a reasonable and durable solution. Agroforestry trees, designed in food-energy systems, increase green space, rehabilitate land, provide vital social and resource safety nets, and create shade, all with cascading impacts on the health and wellbeing of vulnerable displaced populations and their host communities.[139] Fast-growing trees in agroforestry systems are already being used to improve soil fertility and for fuelwood in refugee settlements in Rwanda and Uganda, respectively.[140]

Agroforestry's Outlook

The available evidence largely suggests that scaling up the use of agroforestry may improve planetary health in Sub-Saharan Africa. Much has been made, however, of the challenges of turning the latent potential of agroforestry into concrete actions. One example highlighting this was a synthesis undertaken in 2003 of 23 studies on the determinants of adoption for agroforestry technologies in Sub-Saharan Africa,[141] which indicated that only access to credit, extension information, price of products, and assets widely showed positive associations with adoption (Figure 4). The majority of other possible factors had little or conflicting influence. This could be attributed to a host of demographic, institutional, and environmental factors varying by farm environment. More contemporary reviews[142] and empirical analyses[143] identify similar barriers to adoption (e.g., assets and location, as well as gender) and often report mixed evidence for factors determining the prevalence of agroforestry. Despite such context specificity, we posit that key social, demographic, and environmental trends including urbanization, climate change, and institutions will near universally affect the future of

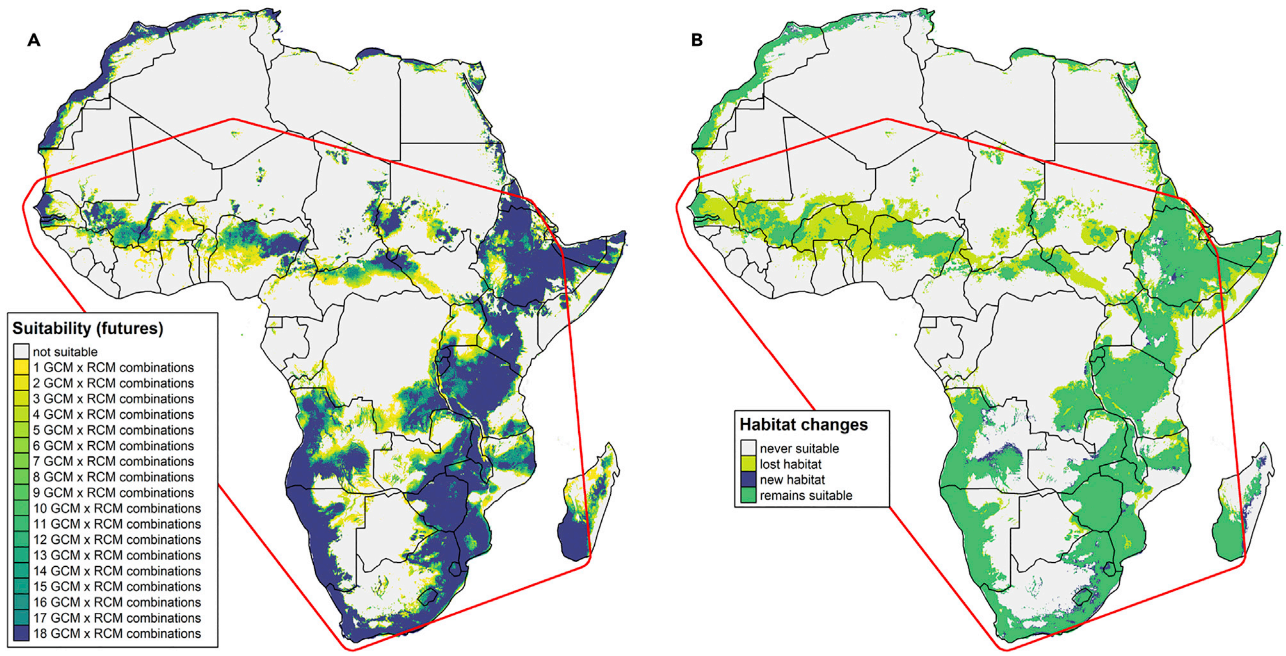

Figure 5. Climate Change Is Expected to Affect the Future Distribution of Agroforestry Tree Species in Africa

(A) Number of combinations of global and regional circulation models for which species distribution models project that *Faidherbia albida* (faidherbia) is suitable at a particular geographic position in the 2050s.

(B) Expected habitat changes for faidherbia in the 2050s compared with baseline climate.

Bioclimatic variables were sourced from AFRICLIM.[151] Mid-21st century climates correspond to the RCP4.5 scenario. Species distribution modeling was completed with ensemble algorithms in BiodiversityR using methods similar to those used for a climate change atlas for Central America.[154,155] Polygons on maps correspond to a convex hull surrounding spatially and environmentally thinned presence observations used for model calibrations.

agroforestry use across Sub-Saharan Africa. Here we describe how these mega-trends present both opportunities and challenges for the future expansion of agroforestry.

Urbanization

Arguably the most significant driver of change in Sub-Saharan Africa today is urbanization. By 2030, 50% of the population is expected to live in urban areas. The growth of megacities such as Lagos and Kinshasa, as well as villages and towns, is reshaping demographics and landscapes.

Urban centers rely on ecosystem services from their surrounding landscapes and from within the city itself. Agroforestry may enhance and/or conserve many of these. For example, trees reduce soil erosion and remediate water pollution from agriculture. This, in turn, can increase the lifespan and efficiency of urban water supplies and hydroelectric power,[144] as well as infrastructure.[145] Increasing population densities, impervious surfaces such as roadways, and encroachment into riparian zones render urban areas more vulnerable to flooding. Agroforestry in both rural and peri-urban areas of a city water catchment can, however, enhance the storage and recharge of groundwater, thus regulating storm-water runoff and reducing the risk of severe urban flood events.[146] Food and woodfuels, which more than 70% of African households rely on as primary energy source,[147] can be supplied from agroforestry systems within and around urban areas, while creating income for rural and peri-urban farmers.[148] Trees create an urban cooling effect that can reduce extreme temperature,[149] which is especially relevant in low-income built-up areas that lack air-conditioning to regulate temperatures. Where air conditioning is used, urban cooling reduces energy consumption and the associated greenhouse gas emissions. Urban trees also filter the direct and indirect causes of non-communicable diseases and urban stressors, including UV radiation, air pollution, and noise.

However, trees and agroforestry are not entirely positive for urban centers. Trees expose people to physical hazards (such as fires), cause injury and property damage from falling branches, and increase allergy-inducing pollen. Whether the benefits outweigh the risks will depend on local conditions. However, it seems with the range of benefits possible that agroforestry warrants greater attention in planning for the sustainable development of African towns and cities in the era of rapid urbanization.

Climate Change

Trends in African climate are projected to have significant future effects on agriculture, including agroforestry.[132,150] Although global circulation models agree on significant future increases in temperatures across Africa, they are not in concordance on the magnitude or direction of changes in annual precipitation.[123,151] Available data also indicate geographic disparities in likely impacts. For example, an analysis of the longest and most detailed record of precipitation (700 stations with 70 or more years of data) shows that March-to-May precipitation during the period 1980 to 1998 was well below the mean for most of Africa, except in the eastern part.[152] Adaptation strategies will need to cope with expected (but uncertain) changes in the onset, cessation, length, and frequency of wet seasons, as well as regional differences in the changes in these patterns.

The long-lived and slow-developing nature of tree-based solutions and investments dictates planning for future climates now when implementing agroforestry programs. Methods for predicting tree vulnerability and location suitability are limited, however.[153] Kindt[154] has prepared a series of maps for 150-plus tree species' distributions in potential future climates using ensemble suitability modeling approaches. In many cases, there is a general consensus among the 18 models, with results showing dramatic reductions in suitable areas possible within the lifetime of trees being planted and managed in today's agroforestry-based interventions. For example, a comparison of baseline and predicted future habitat distribution maps for faidherbia trees suggests that an area an order of magnitude greater will be lost ($\sim$2.5 million km^2) rather than gained ($\sim$250,000 km^2; Figure 5) by 2050. Baseline-to-future comparisons for other important agroforestry tree species in Sub-Saharan Africa indicate a similar pattern, with overall more "climate losers" than "climate winners," as has also been predicted for Meso-America.[155] While agroforestry may help us adapt cropping and livestock systems to climate change and reduce atmospheric concentrations of carbon dioxide, existing evidence reinforces the imperative to match the right tree to the right location,[156] considering not only current but also likely future climate scenarios.

Institutions

Institutions—when broadly considered as social rules and norms that govern behavior—contribute to the challenges to adoption of agroforestry technologies. Institutions are influenced directly and indirectly by agriculture and environmental policies, but also by the policies and implementation approaches of other sectors (e.g., finance and land). The policy environment for agroforestry in most Sub-Saharan African countries can currently be described as conflicting, in part supporting and in part inhibiting adoption. Inhibiting regulations relate to exclusion of land and tree tenure, as well as to the commercialization of certain tree products.[157] In the Sahel, for example, women control the production, processing, and marketing of shea but it is men who inherit the trees.

Importantly, reforming and strengthening institutions does not always mean that national-level policy action is the required starting point. Working through traditional institutions, tied to social norms, can often serve a catalytic role for change. The example of Niger is informative. Here, free access to and exploitation of trees even on (otherwise) privately managed land was once accepted, diminishing the interest of farmers in regenerating trees.[158] Advocacy and awareness, however, created a shift in local by-laws and justice administration, with the population coming to more widely consider "illegitimate" tree exploitation as a form of theft. Also, in 2004, national legislation in Niger was approved that granted farmers who protected trees on their land the right to use them economically. These measures have contributed to the regeneration of trees on nearly 50,000 km^2 nationally. This and other examples demonstrate that strengthening and aligning the institutional environment is often a precondition for the use of agroforestry and is a critical lever for change.

Conclusion

Using agroforestry to improve planetary health in Sub-Saharan Africa will require further efforts to establish the evidence base and to turn this knowledge into practical and policy actions. This review of environment-agroforestry-health pathways clearly demonstrates the context specificity of outcomes, with trees likely improving environmental conditions and human health in many—but not all—situations and not across all outcomes simultaneously. The potential for tradeoffs is not surprising, given the striking number of pathways by which agroforestry appears to influence human health (Figure 1), many of which are poorly documented.

Our synthesis demonstrates that new investigations are needed to determine more precisely the situations whereby agroforestry would either promote or undermine specific aspects of planetary health on the subcontinent. Perhaps more importantly, however, the number and diversity of pathways from agroforestry to health demonstrate the need for evaluating multiple objectives at the same time. Such a research framework is largely absent from the planetary health literature. This will require new ways of working, including increased cooperation among agricultural, ecological, and health experts, as well as economists. Such partnerships have the potential to generate benefits for each entity when, for example, they permit the sharing of information through new spaces and channels (e.g., the promotion of agroforestry options through health centers and nutrition advice built on traditional agricultural extension), and the cross-fertilization of methods and datasets. Collaborations also need to bring together policymakers, practitioners, and the private sector to ensure the relevance, credibility, and legitimacy of the science. The inclusion of farmers and land managers in research and design processes is also critical, to ensure their priorities and values inform questions about tradeoffs among outcomes and constraints of operating conditions.[159]

Such a level of integration, among sectors and across scales, may sound like a tall order. But there are positive examples whereby this has already been achieved and has worked more effectively to catalyze agroforestry-based change (e.g., agroforestry policy in Rwanda and adoption in Niger). Trees have the capacity to change the environment and human lives in many ways. However, with the many complex and unconstrained linkages among trees, the environment, and human health, it is imperative that improved cooperation move efficiently toward agroforestry in support of future planetary health.

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