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Agroforestry: Enhancing the Prospects for Ameliorating Climate Change

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Abstract

There is increasing recognition that achieving the objectives of the Paris Agreement will require both extremely robust decarbonization policies and large-scale deployment of approaches that removal carbon from the atmosphere, usually referred to as carbon dioxide removal (CDR). One of the most widely discussed CDR options is tree-planting initiatives, such as the One Trillion Trees Initiative. However, tree-planting at this scale poses serious risks on a number of different axes, including biodiversity, social justice and threats to critical resources such as water. This article argues that substantial expansion of agroforestry systems, involving the introduction or mixture of trees or other woody perennials with agricultural crops, pastures and/or livestock, may effectuate substantial amounts of atmospheric carbon dioxide, while avoiding many of the threats of large-scale afforestation and reforestation projects in other areas, as well as yielding substantial co-benefits for farmers, especially in developing countries. However, expansion of agroforestry operations faces a number of challenges that must be addressed through a combination of market incentives, training, and the legal landscape in terms of land tenure.

Introduction

In recent years, there has been increasing recognition that meeting the temperature targets of the Paris Agreement (United Nations Framework on Climate Change [1]. will require both aggressive decarbonization strategies and large-scale deployment of so-called carbon dioxide removal approaches, sometimes also referred to as "negative emissions technologies" [2]. Carbon dioxide removal options seek to remove and sequester carbon dioxide from the atmosphere, either by enhancing natural sinks for carbon, or deploying chemical engineering to remove carbon dioxide from the atmosphere [3]. This, in turn, can increase the amount of long-wave radiation emitted by Earth back to space, reducing radiative forcing, thus, exerting a cooling effect [4].

The Intergovernmental Panel on Climate Change's Fifth Assessment Report included 204 scenarios in which integrated assessment models held atmospheric temperature increases to less than 2 °C above pre-industrial averages by 2100. Of those 204 scenarios,184 contemplated large-scale deployment of carbon dioxide removal approaches [5]. Across all these scenarios, the median commitment to the use of carbon dioxide removal in the latter half of this century is 12 gigatons of removal annually, equivalent to a quarter of current anthropogenic emissions [5]. Moreover, even with extremely stringent initiatives to strengthen greenhouse gas reductions, all scenarios that hold temperatures to 1.5 °C by the end of the century contemplate large-scale use of carbon removal options, at levels of somewhere between 640-960 GtCO2 [6].

One of the most widely discussed carbon dioxide removal options is afforestation and reforestation initiatives [7], as trees remove carbon dioxide from the atmosphere, resulting in a net accumulation of carbon in living biomass [8] and potential increases

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in soil organic carbon [9-11]. Indeed, some studies in recent years have concluded that large-scale tree-planting programs could effectuate sequestration of as much as a quarter of the current atmospheric carbon pool [12] potentially comprising a very large share [13,14] of the 400-1000 gigatons of carbon dioxide that needs to be removed over the course of this century to help meet the Paris Agreement's temperature targets [15].

In 2011, the Bonn Challenge was launched by the German government and the International Union for the Conservation of Nature, seeking to restore 350 million hectares of degraded and deforested land by 2030 [16,17]. In 2020, the World Economic Forum launched an even more ambitious initiative, 1T.org, which seeks to restore and grow one trillion trees by 2030 by mobilizing the private sector and engendering regional multi-stakeholder partnerships. Even Republican politicians in the United States, including former President Trump, have touted the benefits of the trillion-tree initiative.

However, poorly formulated massive afforestation/reforestation initiatives could also potentially displace and undermine natural ecosystems, as well as undercut sustainable livelihoods. For example, almost half of the pledged areas under the Bonn Challenge are slated to be plantations, often planted with commercially valuable trees [18-20]. In many cases, plantations are displacing native forest stands [18,21]. Because native forests can store more than forty times as much carbon as plantations in the longer term [19], this could result in a net increase in carbon emissions over the course of this century and beyond [19]. Plantations that supplant natural forests are also usually characterized by much lower fauna and flora speciation [22-24]. Moreover, fast-growing plantation species require significant nutrient inputs that can damage ecosystems [25]. Plantation species also often require higher water inputs that can alter hydrological regimes [25], including seriously diminishing stream flows in some regions [26].

Large-scale tree-planting initiatives such as the Bonn Declaration are also targeting areas that are misclassified as degraded or deforested, including large swathes of savannas, grasslands and shrublands in the Global South [27]. Some of the most prominent mappings for such initiatives include high conservation areas, including Kruger National Forest and the Serengeti Plains in Africa [28].

This strategy is misguided on several grounds. First, such a strategy threatens to undermine both ecosystems and local populations. Savannas and grasslands are huge storehouses of biodiversity in neotropical regions [29], including iconic species in Africa such as elephants [30]. Afforestation can undermine biodiversity in such regions by replacing diverse-community biotic communities with lower-diversity forests [31]. Additionally, reduction of stream flows associated with afforestation in savanna ecosystems in Africa may also severely limit water supplies for local communities in Africa during dry seasons [32].

From the perspective of climate policy, large-scale afforestation in inappropriate regimes may also prove ineffective, or even counterproductive. Grasslands may store almost as much carbon, or in some cases more, than the trees that may replace them in afforestation programs [33]. Also, savannas and grasslands are more prone to drought and fire risk, both of which will be exacerbated by climate change. This could denude the prospects for long-term carbon storage [34]. Thus, ultimately, afforestation in areas where trees do not naturally thrive may reduce global resilience to climate change [34,35].

Indeed, it's hard not to view current tree-planting initiatives as "a great example of what happens when bad science hooks up with do-gooderism and they sleep together in a bed of political expediency" [36]. However, as one recent study concluded, carefully formulated and implemented forest mitigation projects can both help achieve climate objectives, as well as yield co-benefits, including bolstering the well-being of communities and contributing to ecosystem resilience. This article will advance the argument that agroforestry is one such approach, potentially both furthering climate goals while protecting and fostering ecosystems and livelihoods. This article will also outline a path for expanding the scope of this practice substantially beyond its current global outreach. In this pursuit, I will:

- Set forth a definition of agroforestry and assess its current scope of adoption and potential expansion;
- Assess the current and future benefits of agroforestry from the perspective of carbon sequestration;
- Discuss potential co-benefits of agroforestry approaches;
- Outline potential constraints and challenges to expanding the scope of agroforestry operations, as well as recommendations to address these issues.

Overview of Agroforestry and its Role in Climate Policymaking

Definitions and scope

In a broad sense, agroforestry is defined as "the land-use system that involves the deliberate retention, introduction or mixture of trees or other woody perennials with agricultural crops, pastures and/or livestock to exploit the ecological interactions of the difference components" [37,38]. Agroforestry falls into three broad categories:

- Agrosiviculture, integrating annual crops and trees;
- Silvopastoral, integrating livestock and trees; and

- Agrosilvopastoral, integrating annual crops, livestock, and trees [39]. Agricultural areas with more than 10% tree cover are classified as agroforests [40].

Home gardening, an agroforestry practice involving the management of trees, shrubs, crops and livestock within compounds of individual houses [41] was associated with fishing communities in Southeast Asia in the period of 13,000-9000 BC [42]. However, agroforestry has only been incorporated into contemporary science-based land-use systems within the past three decades [42].

Major categories of agroforestry include the following:

- Home gardening: see above.
- Parklands: landscapes in which mature trees occur scattered in cultivated or recently fallowed fields ... included in the very general category of 'multipurpose trees on farmlands'".
- Shaded Perennial Systems: "managed, vertically stratified plant associations involving shade-tolerant and/or shade-adapted crops under tall growing trees" [43].
- Shelterbelts: "linear arrays of trees and shrubs planted to create a range of benefits . . . Shelterbelts are called by different names (windbreaks, hedgerows, fence rows), depending upon their use, region, or preference of the individual" [44].
- Silvopasture: "the intensive management and growing of perennial grasses or grass-legume mixes in a forest stand for livestock pasture".
- Rotational woodlots: "growing of trees and crops on farms in three inter-related phases: 1) an initial tree establishment phase in which trees are intercropped with crops, 2) a tree fallow phase, and 3) a cropping phase after harvest of trees" [45].
- Windbreaks: "strips of trees and/or shrubs planted and maintained to alter wind flow and microclimate, thereby protecting a specific area. They are often planted and managed as part of a crop and/or livestock operation".

Agroforestry is currently carried out in temperate, sub-tropical and tropical zones [46], with over 1.2 billion people dependent upon such systems [47]. Agroforestry accounts for 46% of total agricultural area, encompassing approximately one billion hectares globally [40,48]. South America has the largest area under agroforestry operations, followed by sub-Saharan Africa [49].

Carbon sequestration and agroforestry: current and potential

Agroforestry practices effectuate carbon sequestration through uptake of carbon dioxide in the photosynthetic process, and transfer of fixed carbon into secure storage repositories, including vegetation, detritus and soil pools [50]. Agroforestry can substantially enhance biomass carbon stocks, with the biomass of trees consisting of 46-51% carbon [51,52]. Moreover, it can bolster soil carbon sequestration through enhancement of fine root production, rhizo-deposition, and litter fall [53,54]. Carbon can be stored in agroforestry systems for centuries through organic decomposition and absorption by plants [55]. Agroforestry can even rival monocultural plantations or secondary forests in terms of long-term carbon storage, while as outlined below, yielding substantial co-benefits [56,57].

Carbon sequestration rates in agroforestry systems vary widely, based on factors such as different practices, species, management protocols, densities of trees, and differences in climate, soil properties and land-use history [51]. However, a recent analysis concluded that, on average, agroforestry practices sequester 7.2 ± 2.8 t C ha-1y-1 [51]. Overall, recent estimates are that agroforestry systems are storing more than 34-36 gigatons of carbon globally [47,58]. In Africa, agroforestry constitutes the third largest sink for carbon, after primary forests and long-term fallows [46].

While agroforestry is already practiced extensively, there are prospects for substantial expansion, potentially contributing to the exigencies of carbon removal in a way that avoids environmental risks and social inequities. Indeed, agroforestry has been recognized by the Intergovernmental Panel on Climate Change as having the greatest potential of all land-use options for effectuating net changes in sequestration of carbon [59,60].

The IPCC has estimated that there is 630 million hectares of unproductive agricultural land globally, with 20% that could feasibly be converted to agroforestry [60]. This includes degraded forest land, low-productivity cropland, and land laid bare after stem harvest [61]. Kim et al. recently concluded that this level of conversion could sequester approximately 3.4 GtCO2eq annually [51], or approximately a quarter of the carbon dioxide removal that may be necessary in the latter half of this century to help meet the Paris Agreement's temperature targets [3,5,62]. Moreover, this may be an underestimation of the impact of this potential initiative. Several recent studies have concluded that agroforestry could result in much higher carbon sequestration rates than projected by the IPCC [14,51]. Also, agroforestry systems may decrease pressure on natural forests, potentially offsetting 5-20 hectares of deforestation per hectare of agroforestry stands, and thus avoiding releases of carbon [63,64].

Co-Benefits of agroforestry

Agroforestry has been characterized as a means of operationalizing principles of agroecology by potentially adapting ecological concepts and principles to agroecosystem design [65]. It has been touted as a holistic approach that can both further climate goals as well as other important objectives, such as enhanced food security and the fostering of biodiversity conservation and ecosystem services [65,66]. As such, agroforestry approaches can prove to be a better climate mitigation option than many other terrestrial or ocean-based options [38].

Agroforestry system co-benefits include the following:

Agroforestry enhances food security: Agroforestry can enhance nitrogen cycling compared to conventional agricultural systems. This reduces the loss of nitrogen, and increases its transfer rate, which can help restore the fertility of soils. In regions such as Africa, where declines in soil fertility threaten yields and sustainability, agroforestry systems can improve soil fertility by increasing soil organic matter, facilitating tighter nutrient cycling, and improving soil structural properties [67,68]. Overall, agroforestry can effectuate a doubling or even tripling of yields. Moreover, the range of foods produced in many agroforestry systems, including fruits, vegetables, and nuts, can enhance the nutritional quality of diets [69]. Finally, the sale of products related to agroforestry operations can provide cash for food purchases [70].

As Waldron observes, however, long-term food security in developing countries is dependent on not only increases in crop yields, but also resilience in the face of climate change [71]. Climate change has already emerged as a major threat to food security and is likely to have a profoundly negative impact on food production in the decades to come [72].

Agroforestry systems can help farmers adapt to climate change in a number of ways. Tree canopies can moderate climate extremes in terms of rainfall and temperature by creating a more propitious microclimate for crop production [63,73,74]. For example, tree-based systems are characterized by higher evapo-transpiration rates than row crops or pastures, which can facilitate superior aeration of soils [75]. Agroforestry systems can also increase soil porosity and reduce runoff, which can be critical during low rainfall years [75]. Moreover, agroforestry practices can also cushion farmers from financial shocks associated with crop losses related to flooding or drought by providing diversified sources of income [76,77].

Overall, the IPCC's 2019 report on climate change and land concluded that the combination of rapidly degrading agricultural lands and climate change could reduce food production by 10% by 2050 [78]. It concluded that agroforestry could benefit more than 1.3 billion people by enhancing food security [78].

Agroforestry enhances protection of biodiversity: Agroforestry systems can create "fauna refuges" even in habitats facing rapid Degradation [79]. They can also provide corridors to facilitate the movement of animals and dispersal of plant propagules in fragmented forest environments [79,80], as well as a buffer to prevent deforestation and conversion of forestlands to other uses [81]. Agroforestry can comprise as little as 5% of agriculture land, yet account for 50% of biodiversity, both enhancing habitat for an array of species, as well as benefiting crop production by supporting birds and insects that feed on crop pests [81], and contribute to seed dispersal and pollination [82,83]. Finally, agroforestry can reduce deforestation in regions being cleared for crop production [84] by increasing yields, helping to preserve biodiversity [85].

Agroforestry could help to facilitate sustainable bioenergy with carbon capture and storage: Bioenergy with Carbon Capture and Storage (BECCS) is currently recognized as the other primary carbon removal option alongside afforestation/reforestation [86], with some analysts identifying it as the "linchpin" of negative emissions approaches [87,88]. While BECCS constitutes an array of technologies in different sectors, all approaches entail absorption of carbon dioxide by plant biomass, which is then burned or gasified, with capture of the carbon dioxide through industrial processes, preventing its return to the atmosphere [87].

However, there are major concerns that large-scale deployment of BECCS could require diversion of huge swathes of land currently used to grow food crops to grow dedicated energy crops [78,89], potentially resulting in huge increases in food prices for the world's most vulnerable populations [90]. Moreover, the demand for bio-feedstocks could result in the clearing of vast areas of native forests and grasslands [91].

Agroforestry systems are well suited for provision of feedstocks for biopower and biofuels [92,93]. Use of first-generation bio-feedstocks may prove to be unsustainable and result in marginal or even negative outcomes in terms of reducing greenhouse gas emissions. However, incorporating the production of bio-feedstocks into agroforestry systems can yield positive carbon footprints [39,94].

Moving Forward: Constraints, Challenges and Recommendations

Despite the compelling climate benefits that an expansion of agroforestry could facilitate, there are some serious barriers that must be addressed. In this last section, I will discuss some of these challenges and constraints, and proffer a number of recommendations.

Capital/Credit constraints

Some of the areas with the highest potential for carbon sequestration are occupied by smallholder farmers in developing countries. Unfortunately, many such farmers may be unable, or unwilling, to invest in operations that require forgoing immediate revenue from valuable cash crops [63,67,95,96], and which may not produce additional revenue for 1-3 years [97]. Moreover, many poor food-insecure farmers are less likely to embrace agroforestry due to immediate food needs [98]. Indeed, in some regions in recent years, farmers have been converting agroforestry areas into monoculture croplands in pursuit of short-term income [83,99].

Payment for Ecosystem Services (PES) is an approach that provides financial incentives to private landowners to implement practices that generate important ecosystem services, "bridging the private interests of landowners and the public benefits of conservation" [100,101]. Compensation to landowners is premised upon "acceptance of restrictions or achievement of a condition or proxy to specified environmental outcomes" [102].

Carbon sequestration has been recognized as an ecosystem service with one of the highest potential global impacts [103]. PES programs have increased uptake of agroforestry in some areas, such as the southern region of Costa Rica, but there are clear avenues for substantially expanding such programs [104]. In this context, every effort should be made to incorporate gender inclusion into the planning and implementation process, in the interests of both fostering equity and increased participation in such schemes [105]. Efforts should also made to "bundling" environmental services associated with agroforestry to enhance payouts and increase the competitiveness of agroforestry as a conservation measure. In addition to carbon sequestration, this might include benefits associated with biodiversity protection and watershed benefits [106].

One major challenge in designing PES programs in the context of agroforestry is that the approach has neither been scientifically evaluated in national carbon accounts or in global carbon financial plans [107,108]. Moreover, the development of regional or local models for carbon sequestration is challenging given spatial and temporal heterogeneity and the need to consider a wide range of different plant species and the interaction of soil, crop and tree components. Every effort should be made to facilitate communication between field scientists and the modelling community to facilitate the generation of good process-based models [51].

One potential outlet for designing PES protocols for agroforestry is the Consultative Group on International Agricultural Research's (CGIAR) Options by Context (OxC) program. OxC helps facilitate measurement of variations in performance metrics, including ecosystem services in the context of agroforestry [109]. While OxC has been applied in a handful of countries, it could be expanded to provide critical data to stand up PES programs for agroforestry in many more countries in the future.

Of course, it is critical to identify potential sources of funding for carbon sequestration associated with agroforestry. One avenue for payments is under the United Nations Framework Convention on Climate Change/Paris Agreement's Reducing Emissions from Deforestation and Forest Degradation (REDD+) program [110,111]. REDD+ provides for "results-based finance" for developing country initiatives to reduce emissions from deforestation and forest degradation, conservation of forest stocks, sustainable management of forests, and enhancement of forest carbon stocks [1]. By increasing agricultural yields and providing a substantial source of fuel and fiber, agroforestry operations can reduce the clearance of forest lands for agricultural and energy needs [112]. Moreover, increasing farmland production of timber and fuelwood production can reduce primary drivers of forest degradation in many countries. Despite these benefits in the context of carbon sequestration, as well as many non-carbon co-benefits, agroforestry has been given short shrift in REDD+, perhaps primarily because it has never had a "clear home" within the UNFCCC, with linkages to both forestry and agriculture [63,113].

A strong argument can be made that the supporters of REDD+ should privilege agroforestry projects. As demonstrated earlier in this article, agroforestry can help to reduce deforestation and forest degradation and enhance carbon stocks, key objectives of REDD+. However, while there are concerns that REDD+ projects that focus on avoided deforestation may undermine the rights of local and indigenous communities [114,115] agroforestry programs can protect such communities by enhancing food security and reduction of environmental degradation. This counsels in favor of providing more financial support for development of agroforestry pilot programs for REDD+ to help build the capacity of foresters and local communities to avail itself of co-benefits [28]. In this context, it's important to note that many countries have not yet developed methodologies that can help REDD+ benefit local communities; this should be a priority of the UN-REDD Program, as well as organizations such as the Forest Carbon Partnership Facility [116]. Operationalization of REDD+ has been short-stepped in some cases due to a lack of access to capital. Governments should seek to facilitating farmer capital access to fund the establishment of agroforestry operations and "float" families until financial break-even is achieved [104].

Every effort should also be made to also generate localized environmental services that can generate revenue for farmers. This will maximize the potential effectiveness of these programs, as it is generally easier to structure payment for ecosystem services at this level [104]. For example, agroforestry can contribute to the removal of recalcitrant pollutants, such as nitrogen and trichloroethylene from groundwater plumes at a much lower expense than other forms of remediation [118,119].

Another potential source of revenue to drive adoption of agroforestry is from the corporate sector. In recent years, hundreds of corporations have made pledges to reach either "net zero emissions" or "negative emissions" within a few decades (Institute for Carbon Removal Law and Policy (ICRLP), n.d.). Many of these corporations seek to effectuate their goals through the purchase of forest carbon offsets (ICRLP, n.d.), with forest investments projected to reach more than $800 billion by the middle of the century [120]. Corporations making such pledges, as well as the verification organizations that many of them rely on to ensure the integrity of said pledges, should be encouraged to privilege agroforestry projects given their compelling environmental and socio-economic benefits, including the potential to help further 9 of the 17 UN Sustainable Development Goals.

A final potential source of funding may be green bonds. Green bonds are instruments that facilitate the raising of capital and investments in environmentally sound and sustainable projects focused on achieving a net-zero emissions economy. The volume of green bonds has substantially increased in recent years, from $230 million in 2010 to more than $142 billion by 2017 [121]. Recently, the insurance company Swiss Re has suggested the potential establishment of a new sub-class of green bonds, which it denominated "carbon removal-type bonds" [122]. The instruments could facilitate investment in smaller carbon removal projects by an array of institutions, including insurance companies, by aggregating a pipeline of carbon removal projects of various types and sizes [122]. Governments and NGOs could assist in aggregating agroforestry projects for funding by bond instruments.

Initiatives at a landscape or community level could also help more smallholder farmers adopt agroforestry practices. One potential way to reduce and spread the costs for smallholder farmer participation in agroforestry projects, and thus to reduce risk, would be to develop projects on a community basis by creating common property regimes. Similarly, while certification programs can help provide revenue for farmers engaged in agroforestry, it may be insufficient to compensate for the production constraint of smallholders. In such cases, landscape labelling, in which certification labels aren't restricted to individual products, but rather are applied to all outputs from a particular landscape, may provide sufficient incentives for smallholder farmers [123]. This approach, emphasizing a diversity of land uses within an ecosystem, including food, commodities such as cocoa, timber, and non-timber resources can also contribute to environmental benefits, including habitats for pollinators, improved soil quality, pest control, and fostering biodiversity.

Land tenure challenges

Farmers are often chary to adopt long-term activities if they do not have secure land rights, fearing that more powerful actors might seize their lands upon improvement. This has proven to be a particularly important barrier to more widespread adoption of agroforestry, with trees often remaining the property of the state. Indeed, as the International Centre for Research in Agroforestry has concluded, "there are few agroforestry successes stories in an uncertain land tenure context". Banks are also often hesitant to extend credit to farmers in the face of insecure land tenure.

One potential solution would be to grant non-tenured land-owner's long-term contracts on state-owned land. This can provide sufficient security to justify investments in approaches such as agroforestry. This approach was adopted in Viet Nam in 2016, granting contractors twenty-year contracts for state-owned forest resources, with the possibility of extension [124]. Non-State actors have also successfully advocated for statutory land rights for smallholder farmers, such as through titling reforms, that is, grants of formal rights to land [125]. They could also help resolve conflicts within or between communities in cases of customary land tenure [125]. Of particular assistance in this context, as well as more generally, could be the GlobalEverGreening Alliance. The Alliance is a coalition of NGOs established with the goal of capturing 20 billion tons of carbon dioxide by 2050 in Africa through nature-based solutions, including agroforestry [126]. Companies may also advocate for land tenure for suppliers of products when supply chain networks have been established.

Other constraints

There are a number of additional challenges to scaling up agroforestry, especially in developing countries:

Access to seeds/seedlings: Successful agroforestry systems require the production of sufficient quantities of seeds and seedlings, and efficient distribution to farmers [67]. Unfortunately, adequate supplies of high-quality seeds are usually not available, especially in the case of smallholder farmers in Africa seeking to establish agroforestry operations [63,127]. In many cases, the upfront cost of seeds is the major constraint on uptake of agroforestry by poor farmers. However, once the trees are established, they produce seeds that farmers can collect and use for replanting and expansion of the size of their stands.

Moreover, distribution of high-quality genetic material, or germplasm, can be critical to induce adoption by farmers who wish to harvest commercially viable tree products, animal fodder and natural fertilizers [125]. Careful assessment of intra- and inter-specific diversity in provenance selection of germplasm can maximize the provision of environmental services, contributing further to the welfare of local communities [128].

Partnerships of academic institutions and the private sectors in some countries, including India, have produced high-quality germplasm. This has helped increase farmer uptake of agroforestry, as has efforts by NGOs to work with communities to develop native seed sources [128]. Another option is to seek to expand Farmer

Managed Natural Regeneration (FMNR) initiatives. FMNR is an approach whereby farmers seek to protect and manage regrowth of trees in their fields, primarily by pruning shoots growing from tree stumps [129,130]. Beyond helping to address seed access issues [131], FMNR has been touted as an approach that can ameliorate low survival rates common in tree-planting. Moreover, studies have reported increases in household income, as well as crop diversity [132], which can contribute to household resilience in the face of climate change.

Access to information/expertise: Many agroforestry practices are knowledge-intensive, and specialized training is often required where extraction of trees for revenue generation is contemplated [132,133]. This has often proven to be a substantial barrier to adoption of agroforestry for smallholder farmers [125]. Moreover, training is required to ensure tree survival. For example, in the Ivory Coast, training in agroforestry operations is minimal. As a consequence, despite large-scale distribution of trees, their survival rates have been less than 2%. Also, most young tree seedlings are felled during crop weeding due to lack of training of those engaged in such operations, usually sharecroppers [134].

Uptake of agroforestry would greatly benefit from strengthening of extension services in many developing countries. Extension, which focuses on training of farmers in innovative agricultural practices, has been recognized as a critical element in the adoption of such practices [135,136]. Studies indicates that regular interfacing with extension services, including training, increases the prospects for adoption of agroforestry systems, as well as successful implementation [137], including reaching profitability [138]. Unfortunately, in recent years many developing countries have disinvested in agricultural extension services [139]. Moreover, extension services are often under-resourced and seldom focus on trees.

In recent years, Norway and other donors have invested in strengthening the Conservation Farming Unit of Zambia, which has helped the country to substantially strengthen its extension support for conservation farming. Developed countries should be encouraged to fund such programs in developing countries with high potential for agroforestry, as it can contribute to both environmental and development objectives.

Countries and NGOs providing aid should also consider funding the development of Innovation Platforms. Innovation Platforms seek to engender two-way communication between a wide array of key stakeholders, including researchers, development agents, farmers, cooperatives, input and output traders and policymakers. As such, the approach can improve the prospects for successful outcomes by engaging more of the players along the value chain that play a key role in effectuating key objectives of conservation agriculture [140].

Access to viable markets: Many successful efforts by farmers to raise production yields or diversify income sources through agroforestry have foundered due to constraints in marketing their products. This has included limited access to rural credit, a lack of expertise in developing warehouse receipt systems, and inadequate skills in selling products [141]. Moreover, there are often no established markets for sale of wood and other tree products at a reference price, permitting middlemen to exploit farmers [142]. This often results in low prices for producers, which can denude the incentives to continue agroforestry operations [143].

Programs by governments, the private sector, and NGOs to assist farmers by bolstering value chains must address all components, including livelihoods. This must include efforts by governments and others to develop marketing infrastructure that is as robust as it is for agricultural commodities, including the establishment of minimum price supports [144-151]. At the local level, the establishment of cooperatives can help poor scarce resources to improve market access.

Conclusion

There is a clear exigency in the context of climate policy-making to develop extensive carbon removal options in addition to full-throated decarbonization of the global economy. Trees can play important role in any carbon removal portfolio. However, it is critical to develop this approach in a way that both furthers climate change objectives as well as taking into consideration a broad array of social, economic, and environmental interests.

Potentially expanding the scope of agroforestry substantially could both contribute to battling climate change while affording societies, including some of the most vulnerable, the potential to avail themselves of a number of co-benefits. Successful implementation of this approach, however, will require a commitment on the part of many sectors to cooperate on many different axes, including research, finance, and regulation. Agroforestry's benefits provide a compelling rationale for incorporating this approach into national and international programs to remove carbon from the atmosphere.

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Conflict of Interest

No conflict of interest.

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