Climate Change Mitigation through
Organic Carbon Strategies

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Initiative Overview

Precision Development (PxD) and the Institute for Governance & Sustainable Development (IGSD) are partnering on a unique initiative to collaboratively identify opportunities for innovation in climate change mitigation, particularly for the greenhouse gases most problematic in agricultural production, methane and nitrous oxide, as well as carbon dioxide. We are specifically focused on innovations with pertinence to the world's smallholder farmers, who farm most of the world's approximately 570 million farms.[1] The Food and Agriculture Organization of the United Nations defines these smallholder farmers as "small-scale farmers, pastoralists, forest keepers, fishers who manage areas varying from less than one hectare to 10 hectares…(and) are characterized by family-focused motives such as favouring the stability of the farm household system, using mainly family labour for production and using part of the produce for family consumption."[2] The majority of farms in the Global South[3], a term used to denote the regions of Asia, Latin America, Africa, and Oceania, are small and it is within this broad geography and smallholder farming context that we focus our climate change mitigation initiative.

This initiative includes four analytical pieces on the following opportunities for climate change mitigation by smallholder famers:

- carbon dioxide sequestration through enhanced rock weathering,
- carbon dioxide sequestration through conserving (keeping what is already present) or increasing (i.e., sequestering) the organic carbon storage in soils and plant biomass,
- nitrous oxide mitigation through precision nutrient management, and
- methane mitigation in dairy through improved livestock feeding practices.

In our initiative we are guided by the following principles:

Consider the tradeoffs: We aim to determine smallholder farmers' private returns from the adoption of new technologies or agricultural practices, as well as the societal return of such adoption as measured by gauging the impact of these innovations on our main outcome of interest in climate change mitigation, namely, reducing greenhouse gas (GHG) emissions.

Farmer welfare first: Smallholder farmers cannot be expected to pay the price for climate change mitigation. Climate change-related advisory should support livelihoods, especially as sustained adoption cannot occur without realized benefits for farmers. If it is difficult to understand *a priori* how a specific agricultural practice or technology might impact yields or income, we commit to exploring ways to compensate early adopters as payment for promoting the broader social benefit.

Replicate and scale: We aim to deliver impact at scale. We are particularly interested in low-cost climate change mitigation innovations with strong adoption potential, that can be customized to local contexts, and scaled throughout other regions with similar constraints or needs.

Our goal is to identify opportunities in agriculture with potential benefits for smallholder farmers, either directly or through compensation mechanisms for their environmental services, as well as for GHG mitigation. In identifying these opportunities, we will outline the evidence for impact on farmers' outcomes and on GHG-mitigation outcomes, as well as address challenges in building that evidence, particularly in outcome measurement methods. We will also address practical next steps to build a pathway to scale for the identified opportunities.

About Precision Development (PxD)

Precision Development (PxD) is a global non-profit organization that harnesses technology, data science, and behavioral economics to build digital services that empower people to change their own lives. We build low-cost information systems at scale to share knowledge with the world's poorest and most disadvantaged people. Our pioneering model of digital development is implemented in collaboration with partner organizations to maximize scale. We continuously experiment, iterate, and gather evidence on our impact to improve service delivery and demonstrate our value. Most of PxD's services deliver customized digital agricultural advisory to smallholder farmers, with more than 6 million users using these services in 2022. Given the many constraints facing these farmers, PxD is investigating the application of our platforms and core competencies to deliver advisory in new informational fields, including climate change adaptation and mitigation, as the effects of global warming ripple through the agriculture sector.

About the Institute for Governance & Sustainable Development (IGSD)

The Institute for Governance & Sustainable Development (IGSD) promotes just and sustainable societies, specifically through building resilience by accelerating fast climate change mitigation actions to slow near-term warming and self-reinforcing climate feedbacks, avoid catastrophic climate and societal tipping points, and limit global temperature increase to 1.5°C—or at least keep this temperature guardrail in sight. IGSD's latest research shows that decarbonization alone is insufficient to slow near-term warming to keep us below 1.5°C or even the more dangerous 2°C guardrail, and that the fastest and most effective strategy is to combine the marathon to zero out carbon dioxide (CO_2) emissions by decarbonizing the energy system with the sprint to rapidly cut non-CO_2 super climate pollutants, and to protect carbon sinks. The super climate pollutants include four short-lived climate pollutants (SLCPs)—methane (CH_4), hydrofluorocarbons (HFCs), black carbon soot, and tropospheric ozone (O_3)—as well as the longer-lived nitrous oxide (N_2O).

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Terminology

Agroforestry – Agroforestry is a land-use system that integrates trees and shrubs with crops and livestock and can act as a sustainable agricultural intensification practice as well as address global land degradation challenges.[4] Agroforestry can also be used as an extensification strategy, for example the expansion of oil palm agroforestry systems compared to monoculture systems.[5]

Biochar – Biochar is created through pyrolysis when biomass, such as crop residues, manure, or other plant residues, is burned at high temperatures in a low oxygen environment. Biochar has a significantly more stable carbon structure than its biomass feedstock, and some studies find that when biochar is added to soils as an amendment, it can lengthen soil carbon storage.[6] This result is variable, however, as biochar's carbon sequestration effects depend heavily on the types of input materials, the characteristics of the soil it is added to, as well as surrounding climatic conditions.

Carbon Sequestration/Carbon Dioxide Removal (CDR)/Carbon Drawdown – Carbon sequestration "is the process of capturing, securing and storing carbon dioxide (CO_2) from the atmosphere." Many terms are used interchangeably to refer to this process, including carbon dioxide removal, carbon removal, and carbon drawdown. All refer to the process of capturing CO_2 from the atmosphere and "locking it away for decades or centuries in plants, soils, oceans, rocks, saline aquifers, depleted oil wells, or long-lived products like cement," which is key for climate change mitigation.[7]

Conservation agriculture – Conservation agriculture (CA) is typically defined by three principles: 1) minimum mechanical soil disturbance (no- or reduced-tillage); 2) permanent soil organic cover of at least 30% of the farm plot covered with crop residues and/or crops; and 3) diversifying plant species in cropping systems.[8] Although there are many agricultural practices which lead to SOC sequestration, most discussions of carbon storage on agricultural land refer to CA principles[9] as there is strong evidence they can increase the return of biomass to agricultural systems, which we detail in Section 3 of this paper. Conservation agriculture, agroecology,[10] climate-smart agriculture (CSA),[11] and regenerative agriculture (RA)[12] are often used interchangeably in the literature to describe approaches in agriculture to combat climate change, including SOC sequestration. This overlap is due to their many shared concepts as well as differing definitions of each term within the field itself.[13] What these terms all share is a focus on agricultural sustainability, both for positive environmental outcomes as well as for human welfare, including those of farmers.

Global Warming Potential – Global Warming Potential (GWP) allows comparison of the potency of warming impact of different gases relative to carbon dioxide over a given period of time. The GWP for a given gas is defined as how much energy "1 ton of the gas will absorb over a given period of time, relative to 1 ton of carbon dioxide."[14] Higher GWP means that an emission of that gas has a larger warming impact on the Earth compared with CO_2 over that time period.[15] Time periods of 100 years are commonly used to capture longer-term warming impact, while a 20-year time period better captures warming impact in the near term.[16] Carbon dioxide's GWP is 1 by definition regardless of the time period used.[17]

Greenhouse Gas Mitigation – The Intergovernmental Panel on Climate Change (IPCC) defines GHG mitigation as "A human intervention to reduce emissions or enhance the *sinks* of *greenhouse gases.*"[18]

GtC – GtC, or gigatonnes of carbon, is a common unit to refer to the immense amount of carbon discussed in climate change literature. There are 10^9 tonnes of carbon in 1 GtC.

Nature-based solutions (NbS) – The most commonly accepted definition of nature-based solutions (NbS) to climate change is put forward by the International Union for Conservation of Nature (IUCN), which defines NbS as "actions to protect, sustainably manage, and restore natural and modified ecosystems that address societal challenges effectively and adaptively, simultaneously benefiting people and nature."[19] The NbS term can be contentious as it is often difficult to clarify conceptually and is overapplied. Nevertheless, it is a common term in the field and many of the carbon sequestration strategies most relevant for the smallholder farmer context, like agricultural practices aimed at building soil organic carbon,[20] are considered to fall into this category as they emphasize the strong linkages between land and the indigenous peoples and local communities (IPLC) working that land. This close connection between farmers sequestering carbon and the potential human health and socioeconomic benefits of doing so, i.e., the opportunity for improved agricultural productivity, is a key aspect of NbS, which stresses an equitable distribution of benefits for both environment and human welfare.[21]

On-farm vs. on-station agronomic trials – On-farm agronomic trials refer to agronomic research performed on farmers' plots using farmer management practices, but with varying degrees of researcher oversight depending on the exact study. In some studies researchers may make many of the farm management decisions during the trial, even though the farmers are implementing those management decisions.[22] On-station agronomic trials refer to agronomic research on plots designated for research purposes and completely under researcher control.

Pyrolysis – Pyrolysis is the heating of biomass to between 300°C and 700°C in low oxygen conditions to produce biochar.[23]

Soil Organic Carbon (SOC) Sequestration – SOC sequestration refers to carbon sequestration through increasing stocks of soil organic carbon by enhancing above- and below-ground plant biomass.[24] Agricultural practices like reduced tillage and cover cropping foster the SOC sequestration process for carbon drawdown on agricultural land.

1. Executive Summary

Human activities are the main driver of carbon dioxide (CO_2) emissions, primarily through the use of fossil fuels for energy, industry, and transportation, while land use and land use change (LULUC) are responsible for about a third of cumulative CO_2 emissions from 1850 to 2019.[25] To contextualize these anthropogenic emissions, it is helpful to look at the concentration of atmospheric CO_2 over time. In 2021, atmospheric CO_2 was around 414 parts per million (ppm) compared with less than 320 ppm in 1960 and less than 280 ppm in 1750 (pre-industrial era).[26] This means not only has the amount of CO_2 in our atmosphere increased by almost 50% since the industrial revolution, but its growth rate has also accelerated in recent decades. Over half of cumulative CO_2 emissions from fossil fuel use and cement production since 1850 has occurred since 1990.[27] The Global Carbon Budget estimates that annual emissions in 2021 were 9.9 GtC yr^{-1}, around the same as in 2019 or pre-pandemic.[28]

The agriculture and food system sector is a significant emitter of greenhouse gases (GHGs), primarily methane – associated with livestock and rice production – and nitrous oxide – most directly associated with nitrogen fertilizers, animal manure, and biological nitrogen fixation. While direct carbon dioxide emissions from agriculture is relatively low,[29] particularly in Global South geographies where the sector is less mechanized,[30] agriculture and food systems are indirectly responsible for CO_2 emissions from LULUC, which represent about a third of total agriculture and forestry emissions and 6–13% of total anthropogenic CO_2 emissions.[31]

There is, however, potential for agriculture to contribute to climate change mitigation. By leveraging the natural role of plants and soils in the cycling of organic carbon, agricultural land can act as a carbon sink through interventions for carbon sequestration like conservation agriculture. Studies estimate a technical potential of soils in global cropland and pasture land to store 2–5 Gt CO_2 per year.[32] The Intergovernmental Panel on Climate Change's most recent report (Working Group III Assessment Report 6) on climate change mitigation also highlighted the importance of interventions in agriculture, forestry, and other land use (AFOLU) sectors for GHG mitigation, primarily through the reduction of deforestation, but also through "carbon management in croplands and grasslands, agroforestry and biochar."[33]

Strategies for enhancing carbon sequestration in agricultural systems include the above-mentioned conservation agriculture (CA), agroforestry, and biochar amendments. The amount of carbon it is possible to sequester from these strategies are dependent on multiple factors, including soil properties and temperature, and are extremely context-specific.[34] It is difficult to generalize from one agriculture focused carbon sequestration project to another as the amount of carbon stored, as well as the most relevant types of agricultural practices for carbon sequestration, will depend on each project's specific characteristics. It is also important to keep in mind these strategies provide impermanent carbon sequestration; if a management regime like conservation agriculture stops, carbon sequestration stops as well and, in some contexts, there may even be a reversal of carbon stocks in the land.[35] Determining how much and for how long carbon is stored by land-based climate change mitigation strategies is therefore still a matter of scientific inquiry, as the evidence for the reduction of greenhouse gas emissions remains inconclusive, especially in smallholder farmer contexts in the Global South where there is a substantial evidence gap in existing research.

Beyond the technical mitigation potential, there are also unique scaling challenges associated with land-based climate change mitigation strategies in smallholder farming contexts. Supporting behavior change for smallholder farmers in low- to middle-income countries (LMIC) requires approaches appropriately prioritized and targeted for these farmers, as well as as well as approaches embedded within sustainable value chains functioning at the right scale. This kind of change will require much more than promotion of specific pieces of technology, i.e., change will require sustainable agricultural practices like CA. Success will require, as stated by Seghieri et al. (2021) in an academic report on the state of agroforestry:

> *“transformations in policies and budgets that are long term and powerful enough to be able to catalyze deep transformations within power relations and land tenure rights that are currently big barriers to widespread adoptions.”*[36]

Opportunities for climate change mitigation in smallholder farmer contexts can thus only be leveraged when farmers’ many intersecting challenges are taken into account. For example, it can be extremely costly for farmers to implement technologies that increase carbon sequestration.[37] And while these technologies can directly benefit livelihoods in the long run through improved environmental and soil health benefits, they may erode crop yields and profits in the short term.[38] The resulting indirect land use changes from such productivity hits can undermine the value of any carbon sequestration obtained. Addressing barriers to sustained adoption of sustainable agricultural practices, like the potentially negative impacts on crop productivity, is thus essential for successful behavior change as well as climate change mitigation goals.

One emerging pathway to make climate change mitigation an attractive opportunity for farmers is the voluntary carbon credit market, which experienced annual growth of 48% in 2021.[39] In that same year, the total value of the voluntary carbon market exceeded more than $1 billion USD.[40] Enabling farmers to tap into this financing mechanism could funnel the type of funds needed for system-wide change into the smallholder farming context. The voluntary carbon market will only continue to grow as corporations adopt net zero pledges[41] e.g., Netflix as well as Microsoft, in line with the Paris Agreement’s goal of limiting global warming to a *preferred* 1.5 ºC, creating large demand for carbon offsets. Although there is potential for the voluntary carbon credit market to provide climate change financing where it is needed most, significant work remains for the market to develop robust infrastructure to ensure climate outcomes are actually met, i.e., measurement, reporting, and verification (MRV) systems, as well as more transparency and standardization of project protocols and prices. The ability of the voluntary carbon market to help the agriculture sector address climate change thus ultimately depends on the quality of its projects, which requires a through and nuanced view of the scientific processes at play, as well as of the unique circumstances smallholder farmers face.

2. Carbon Sequestration Opportunities for Smallholder Farmers

Practices such as conservation agriculture, agroforestry, and biochar amendments can result in a net sequestration of CO_2 through soils and plants, i.e., the increase in carbon stocks exceeds the carbon stock losses from microbial decay processes, fire, etc. However, the net amount of carbon stored depends on various environmental factors, like soil texture, climate, and humidity, as well as land and agronomic management. In very simple terms, biomass returns to a system must either increase (e.g., with residue recycling, yield intensification) or decay processes must be reduced (e.g., no till for SOC, increasing recalcitrant woody biomass with trees or perennials).[42]

This paper investigates three land-based climate change mitigation strategies which increase biomass returns and can be appropriate for the smallholder farmer context:

- Soil organic carbon sequestration in cropland and pasture lands through **conservation agriculture practices**: Conservation agriculture (CA) is typically defined by three principles: 1) minimum mechanical soil disturbance (no or reduced tillage); 2) permanent soil organic cover (at least 30% of the farm plot covered with crop residues and/or cover crops; and 3) diversifying plant species in cropping systems.[43]

- Soil organic carbon sequestration and organic carbon sequestration in above-ground biomass through **agroforestry**: Agroforestry is a land-use system that integrates trees and shrubs with crops and livestock.[44] Often defined as more than 10% cover of woody perennials such as trees and shrubs on a farm plot, agroforestry is practiced around the world on approximately 43% of all agricultural land.[45]

- Organic carbon sequestration through **biochar amendments to soils**: Created by high temperature pyrolysis (heating biomass to between 300°C and 700°C in low oxygen conditions),[46] biochar can be made from a variety of materials, including crop residues, manure, aquatic weeds, and forest residues or wood waste.[47]

The main principle for carbon sequestration on agricultural land is to retain as much carbon in the soil-plant system as biophysically feasible and economically desirable. It is important to note, however, the amount of organic carbon in soils and above-ground biomass is a result of many interacting land management and environmental factors. Increasing carbon sequestration capacities is affected by tillage methods, return of crop residues, erosion management, soil fertility, water management, and farming systems management (such as crop rotations), amongst others.[48] While conservation agriculture, agroforestry, and biochar represent three possible solutions, they exist in a complex system where other mechanisms and other factors will affect SOC sequestration and climate change mitigation.

As for impacts on farmer outcomes, practices which facilitate carbon sequestration on agricultural land can have significant soil health co-benefits which help restore degraded soils in smallholder farmer geographies. For example, in Sub-Saharan Africa (SSA) where the majority of arable land is considered degraded and can be unresponsive to additional nutrient applications like nitrogen or phosphorus, practices like intercropping, crop rotations with legumes, and residue returns are recommended ways to restore soil fertility.[49] It is important to keep in mind, however, the soil health co-benefits and associated productivity increases of agricultural practices associated with carbon sequestration mostly accrue over the long term, and immediate effects on yield are variable and can be negative.[50] Hence, there is a potential role for climate finance to play in making financial gains from these practices pertinent in the short term to farmers, which will increase the likelihood of the initial adoption and continued use of these practices.

A. Permanence of Carbon Sequestration

Strategies for enhancing carbon sequestration, like the ones we discuss – conservation agriculture, agroforestry, and biochar – require continuation of the land, water, and environment management practices known to promote sequestration.[51] If these management practices are not continued, for example returning back to tillage from no-till, not only will the carbon sequestration from those practices end, but there can also be a reversal of carbon stocks that have accumulated, by accelerating the decay process.[52] Therefore the strategies for carbon sequestration we highlight in this piece are all considered temporary. This does not mean such climate change mitigation efforts are without positive impact; rather it is important to consider these strategies as part of a larger effort for carbon dioxide removal (CDR) which works best when coupled with other efforts to reduce GHG emissions.[53]

B. Interacting Carbon and Nitrogen Cycles

The carbon and nitrogen cycles are closely intertwined, especially within soil. For example, most carbon in soil starts off in organic forms, i.e., soil organic matter (SOM) like crop residues. The microbes which convert that organic matter into more stable forms,[54] i.e., soil organic carbon, require nitrogen to do so efficiently.[55] If there is not enough available nitrogen in soils to do so, these microbes will emit more carbon dioxide into the atmosphere[56] and also co-opt plant-usable forms of nitrogen,[57] so plants will not be able to access these nitrogen reserves in the short-term. Increasing biomass production, another pathway to increase carbon stocks in agricultural systems, almost always requires increased nitrogen and water, which constitute additional farmer costs. These costs must be balanced against the economic and functional benefits of increasing carbon stocks. Simply adding large amounts of nitrogen to soils is thus an infeasible economic approach to encourage carbon storage; it can also provide more opportunities for environmental losses through nitrous oxide emissions as well as nitrate leaching.[58] One way to manage this tradeoff between carbon dioxide and nitrous oxide emissions is to manage nitrogen based on the specific context and soil characteristics of the land, which is an approach known as precision nutrient management or site-specific nutrient management (SSNM).[59] Site-specific nutrient management is a science-based approach to nutrient management based on field-specific conditions in a given cropping season and system. Developed in the 1990s with the goal of increasing yields and optimizing the resources of smallholder rice farmers in Asia, SSNM was created by the International Rice Research Institute (IRRI) and other collaborators in Asia. The SSNM approach was expanded soon thereafter to include wheat and maize systems, and now includes nutrient management guidelines for numerous crops, provided through a variety of physical and digital tools.

C. Carbon Sequestration Rates and Saturation in Soils

Soil organic carbon sequestration rates vary considerably depending on the amount of biomass returned to soil-plant systems, soil types, and climatic regions.[60] In addition, SOC sequestration may have an upper limit as soils reach their natural saturation point for organic carbon.[61] The exact saturation amount and timeline is dependent on specific soil characteristics, including the soil's current organic carbon stocks and climate.[62] For example, a meta-analysis on rice straw residue retention found that it took about 12 years for soils to reach an organic carbon saturation point.[63] Understanding the differing rates of SOC sequestration as well as carbon saturation points of soils is key to assessing the potential of SOC sequestration for persistently increasing carbon drawdown over time in different geographic locations.

D. Sustainable Intensification and Carbon Sequestration

A common argument for climate change mitigation strategies like conservation agriculture, agroforestry, and biochar is their associated agricultural productivity benefits. First, increasing crop yields, i.e., agricultural intensification, is often the most feasible and impactful pathway for increasing carbon sequestration in agricultural lands. Net primary productivity (NPP) is the amount of carbon maintained in an ecosystem as measured by changes in biomass;[64] increasing biomass accumulation, i.e. through increasing crop yields, therefore has the potential to sequester additional amounts of carbon dioxide as it increases net primary productivity. Second, as the Borlaug Hypothesis argues, intensifying agricultural production may be land "sparing" because the same amount of food can be produced using less land, thereby sparing land for nature.[65] Protecting existing carbon sinks, such as forests and peatlands, is an important climate change mitigation strategy.[66] However, the evidence behind agricultural intensification as a way to prevent land use change is mixed[67] as there are many interacting market forces which shape farmers' motivation to expand agricultural lands. It is thus uncertain if sustainable intensification leads to net climate change mitigation.

Alternatives to Crop Residue, Specifically Rice Straw, Burning

Crop residue burning is a common practice by farmers throughout the world as it is low-cost, low-labor, and a quick way to clear plots for the next crop. In some regions, particularly in South Asia, there is intense pressure on farmers to act quickly between cropping seasons to maximize the ideal seasonal conditions (i.e., temperature and water availability) for crop productivity.[68] Not only does burning remove the residues of the previous crop quickly, but it kills any remaining pests in the field. Burning also returns some of the residues' nutrients back to the soil in available forms, which means farmers may see a productivity boost from the practice in the short term. However, nutrients from crop residues are also lost in the burning process, and there are negative long term consequences to soil health such as a lost opportunity to increase SOC.[69] Other harmful consequences of crop residue burning include the emission of GHGs and particulate matter.[70] Black carbon, a component of particulate matter, only stays in the atmosphere for days or weeks, but it is "the most solar energy-absorbing component of particulate matter and can absorb one million times more energy than CO_2," contributing to warming effects on the planet.[71] Black carbon also travels easily and can therefore create negative environmental consequences for sensitive areas hundreds of miles away from its origination point. For example, high concentrations of black carbon from crop burning in the Indo-Gangetic plain have been found in the Himalayan-Tibetan plateau glaciers, contributing to their melting.[72] Particulate matter also poses a serious risk to human health as particulate matter 10 microns or less (especially $PM_{2.5}$) easily travel into the lungs and the bloodstream through respiration, contributing to cardiovascular and respiratory disease and premature mortality.[73] In New Delhi, crop burning from surrounding regions contribute to a spike in $PM_{2.5}$ every winter, with consequent negative health effects.

Despite these negative consequences, crop residue burning has been an extremely difficult behavior to change.[74] This is partly due to its efficiency in dealing with crop residues and partly due to the lack of feasible alternatives for farmers. In Northwest India, where rice straw burning is widely practiced to prepare rice fields for the subsequent wheat season, the government initially banned the practice in 2015 then reversed the ban in 2021 due to farmer protests.[75] However, not only has the practice continued, but the patterns of burning are changing and burning prevalence is increasing in other parts of the country,[76] outside acknowledged hotspots in the states of Punjab and Haryana.

The existing alternatives to rice straw burning in India, which also apply to crop residue burning generally, fall into the following categories:

- *In situ* retention by keeping residues on the soil surface and sowing the next crop with specialized machinery like the Happy Seeder, which is a piece of tractor-drawn equipment used to cut and lift rice straw, sow wheat, and spread straw over fields as mulch.
- Incorporation of crop residues into soil through intensive tillage. This step can be facilitated by efforts to speed up residue decomposition, such as by applying the pusa bio decomposer, a substance developed by the Indian Council of Agricultural Research (ICAR) which speeds up rice straw decomposition when sprayed on residues.
- Collection of straw residues for alternative uses such as livestock fodder, biochar, or to sell within local markets. Collecting rice straw in combine harvested fields is facilitated by machinery like balers and reaper binders.

For farmers to adopt these alternative pathways, however, they need to be supported by a market and regulatory environment which ensures that the alternatives are attractive and as easy and cost effective to implement as burning.[77] For example, although there has been a large push by the Government of India, as well as by many non-profit organizations, to promote the use of Happy Seeder and other technologies to keep crop residues on the field, the service economy around these technologies is comparatively nascent.[78] For example, there are a limited number of Happy Seeders available to farmers within a given local market, which means competition for the ones available is high during the season between crops. Despite existing subsidies, machinery like Happy Seeders can also be prohibitively expensive for farmers and service providers, and require additional costs like diesel tractors to function. In addition, machinery like the Happy Seeder leaves room for pests like pink bollworms to fester within crop residues.[79] There are practical concerns about newer technologies like the pusa bio decomposer; reports suggest the decomposer was ineffective at quickly decomposing the straw on farmers' fields or took longer than the harvesting-planting window allowed.[80] In terms of collecting crop residues for alternative uses, whether as livestock fodder, biochar, or to sell, farmers face the cost of collecting, baling, and storing the rice straw, not to mention the indeterminate value of these alternative crop residue uses. For example, rice straw is widely known to have low nutritional value which makes it only one portion of a complete livestock diet.[81] There are also limited markets for rice straw, which vary significantly based on where a farmer may be located. For example, Punjab[82] has a few power plants which will use rice straw to create biogas, but Haryana has none.

Incorporating farmers' perspectives and understanding their day-to-day financial realities is key to making these alternatives for crop residue burning feasible on the ground. Many farmers in India are well aware that rice straw burning poses environmental and human health issues, but they cannot be expected to provide environmental services while accepting hits to their livelihoods. One promising avenue to provide incentives for adoption of alternatives to crop burning is the emergence of payment for environmental services (PES) schemes. One recent study found providing farmers with upfront payments helped deter rice straw burning in India, with many choosing to bale their residues instead.[83] Identifying ways to finance and scale well-designed PES programs can change the economic realities of crop residue burning and help shift farmer behavior.

3. Conservation Agriculture

Conservation agriculture (CA) is a farming system that regenerates degraded land and prevents future degradation by minimizing mechanical soil disturbance, promoting permanent soil cover, and diversifying plant species in cropping systems.[84] Conservation agriculture also improves opportunities for carbon sequestration in agricultural land by limiting the amount of carbon that is released by soil disturbance, and by increasing soil health properties that allow for greater carbon sequestration as well as plant and soil organism biodiversity.[85] As described, CA consists of three interconnected principles that must be adjusted to the context of different production environments:

1. **Minimum mechanical soil disturbance:** Farmers use no- or low-till farming and limit soil disturbance through direct-seeding and/or fertilizer placement. Limiting mechanical soil disturbance decreases soil erosion and preserves carbon sequestered in soils.
2. **Permanent organic cover of soils:** Farmers use cover crops or leave crop residues on at least 30% of their farm plots. Using organic covers, like cover crops, over soils preserves soil moisture while decreasing weed growth, soil compaction, and the effects of extreme weather on soils, such as insufficient or excess rainfall.
3. **Crop rotation:** Farmers diversify rotations to ensure that pest and disease cycles are adequately controlled in the context of the first two principles.[86]

To minimize mechanical soil disturbance, farmers can use zero-tillage planting (or direct-drilling), which means cultivating crops without mechanical seedbed preparation.[87] In systems which need seedbed preparation (soil-compaction, small seed size) or where zero-tillage equipment is not available, farmers can opt for reduced-tillage practices like strip-tillage that minimize soil disturbance. To maintain soil cover, farmers can leave crop residues on their fields or they can plant a cover crop if the gap between harvesting and planting is long or if they have additional uses for crop residues. Cover crops improve soil fertility and soil structure, increase biodiversity (especially in monoculture environments), recycle nutrients, reduce pests and weeds, and support other livelihood strategies, including using cover crops as livestock fodder.[88] Lastly, farmers can adapt crop rotations for species diversification. Diversifying crops may have positive effects on plant production, human and livestock nutrition, pest and weed growth, nutrient balances, soil fertility, and biodiversity,[89] but these benefits cannot be generalized broadly and must be considered in the context of the needs and geography of the farm.

There is evidence that CA can mitigate climate change and improve soil health, as well as increase productivity and profitability for smallholder farmers. However, the level of added benefits to environmental and farmer outcomes depends on the specific context where CA is implemented (Table 1). In addition, cropping systems, heterogeneity in farming practices (such as water management or fertilizer use), and access to inputs also affect the climate change mitigation potential and productivity changes of CA adoption.

A. Climate Change Mitigation and Conservation Agriculture

Net climate change mitigation potential from CA depends on the interaction of several greenhouse gases (GHG), whose emissions simultaneously decrease and increase as carbon is sequestered. For example, total net flux of nitrous oxide (N_2O), carbon dioxide (CO_2), and methane (CH_4) emissions depend on biogeochemical processes in the soil related to carbon (plant biomass), nitrogen (fertilizers) additions, and environmental conditions. Emission fluxes will naturally change along the plant growing cycle and vary depending on the cropping system, environment, and agricultural inputs used, as well as other farming management practices. Another consideration is that any negative change in crop productivity, which decreases biomass and NPP, may outweigh the sequestration advantages of minimal soil disturbance by CA, so both biomass returns and decay rates must be considered. Ideally, adopting CA practices should improve carbon sequestration and lower total GWP.

Recent empirical evidence summarized in Table 1 below demonstrates mixed outcomes on the mitigation potential of CA, especially in smallholder contexts in SSA and South Asia. Under highly controlled conditions or in experimental trials, zero or reduced tillage reduces the amount of carbon losses from soil disturbance, while permanent cover crops (including crop residue retention, mulching, and green manure) increase carbon sequestration ability. In addition, energy consumption for tillage can be much lower with reduced tillage, thus decreasing emissions from combustion. However, when conditions are less controlled or other variables from on-farm trials affect results, the climate change mitigation potential of adopting CA practices remains unclear.

A recent meta-analysis (an analysis that combines results from multiple studies) on rice-wheat, maize-wheat, and rice-maize cropping systems in South Asia found mixed results on GHG emissions from both on-station and on-farm trials of CA. Using data from 9,686 paired site–year comparisons, results showed a decline in overall carbon dioxide equivalent emissions (using a 100-year GWP) as the result of reduced methane emissions when CA practices were adopted, compared with conventional agriculture, while no significant changes in nitrous oxide emissions were found.[90]

Another meta-analysis using data from 60 peer-reviewed studies assessed effects of CA (including no-tillage/reduced tillage and crop residue retention) in SSA and found an increase in soil organic carbon sequestration across practices.[91] However, while minimum tillage and crop residue retention led to improvements in total soil carbon and nitrogen, these improvements were only significant after practices were combined together[92] (although the authors suggest that these results could be skewed by a small sample size). Results from another global meta-analysis demonstrate positive effects on SOC from conservation tillage and cover crops, while also noting that SOC benefits may be negated by potential rises or fluctuations in nitrous oxide and methane emissions from adopting CA practices.[93]

The current evidence of greenhouse gas emissions reductions from CA practices therefore remains inconclusive when implemented in smallholder farmer contexts. In particular, there is a substantial evidence gap for CA’s SOC sequestration potential from on-farm trials with smallholder farmers in SSA and Asia. Many meta-analyses provide yield or SOC data from on-station and on-farm experimental trials which tend to be highly managed, but very few studies include observations of CA implementation directed by smallholder farmers (Table 1). Even in more controlled experiments, calculation methods between studies within the meta-analyses may differ, and factors such as soil or environmental differences can affect productivity and mitigation outcomes. Future research on CA practices should focus on how mitigation is affected by CA practice adoption and implementation by smallholder farmers themselves, as well as by their financial, logistical, and environmental constraints.

Table 1: Research Findings on Climate Change Mitigation Potential of Conservation Agriculture

Study	Study Information	Climate Change Mitigation Effects
Jat et al. (2020)	Meta-analysis comparing conservation treatments for rice-wheat, maize-wheat, and rice-maize cropping systems in South Asia (9,686 paired site-year conventional vs. conservation practice observations from 1,353 field experiments)	GHG emissions overall, including CO_2, decreased; CH_4 emissions decreased significantly while N_2O emissions increased in on-station studies. Zero tillage with residue retention increased water use efficiency by 12.6% and reduced GHG emissions in 100-year CO_2-equivalents by 12–33%.
Kichamu-Wachira et al. (2021)	Meta-analysis of conservation practices, green manure, zero or reduced tillage, and crop residue retention, from 60 studies in SSA (517 paired observations for crop yields, 163 paired observations for soil carbon, and 98 paired observations for soil nitrogen)	Minimum tillage and crop residue retention led to significant improvements in soil carbon and soil nitrogen, but only once practices were combined. Authors suggest these results could be affected by small sample sizes given the limited number of studies which used multiple CA methods simultaneously.
Bai et al. (2019)	Global meta-analysis of 417 studies, half of which are in North America (3,049 paired observations)	Conservation tillage and cover crops increased SOC by 5% and 6%, respectively. Authors observed stronger impacts from CA in warmer climates and in low N fertilizer input environments.
Kumara et al. (2020)	Meta-analysis of economic and environmental benefits of conservation agriculture in South Asia (670 paired observations from 147 studies representing 67 crops of South Asian countries)	CA practices increased SOC by 16.3% compared to the conventional tillage. Water consumption was lower from CA practices than conventional agriculture. CA reduced emissions of CO_2 by 4.28% and CH_4 by 25.67%, both in aerobic and anaerobic soil conditions. CA increased NO_2 and $N_2O{-}N$ by 14.45% and 5.20%, respectively.

B. Farmer Outcomes from Conservation Agriculture

Similar to the research on mitigation potential, empirical research on smallholder farmer outcomes, like yields and profits, remain inconclusive in African and South Asian geographies (Table 2). Several meta-analyses suggest that CA practices increase yields when implemented in their totality, but research finds that adopting one CA practice does not necessarily increase productivity.

For example, in a meta-analysis looking at CA in Sub-Saharan and North Africa, Kichamu-Wachara et al. (2021) conclude that minimum tillage does not affect yields as a standalone practice, but minimum tillage is associated with positive increases in yield when combined with other CA practices such as crop residue retention and rotation.[94] These results are also supported by research in another global meta-analysis, which finds a negative outcome of 9.9% on yields from zero tillage as a standalone practice.[95] Zero tillage combined with either crop residue retention and crop rotation also negatively impacted yields by 5.2% and 6.2%, respectively.[96] However, zero tillage combined with crop residue retention and crop rotation increased yields by 7.3% compared to conventional agricultural practices. These results suggest that implementing no-till agriculture as a standalone practice could be damaging to farmers' productivity in some contexts, and therefore zero tillage should be implemented on farmers' plots that already use crop covers and crop rotation.[97]

Findings from another meta-analysis on South Asian farmers by Jat et al. (2020) suggest that the partial or total adoption of CA practices can contribute to higher yields in cropping systems with maize, wheat, and/or rice, ranging from 3% to 5.5% compared with conventional agriculture.[98] These findings were supported by an SSA-focused meta-analysis that found average yields increase by 3.7% (for maize, sorghum, cowpea, rice, soybean, and cotton cropping systems).[99] The authors found that maize yield increased an average of 4% with zero or reduced tillage as a standalone practice, but increased by 8.4% when combined with mulching and intercropping/crop rotation. Perhaps most importantly, Jat et al. (2020) concluded that while yields may not be as significant when zero or reduced tillage was adopted alone, scaling conservation agriculture in South Asia does not require strict adherence to total adoption for farmers to gain benefits from CA.[100] Field trials in the Indo-Gangetic Plains in wheat cropping systems suggest much higher yields in South Asia from CA, with yields increasing by 19–32% on average compared to lower averages in other cropping systems or in other geographies.[101]

Further, observed productivity gains from CA were also associated with higher farmer profits. Profit increases ranged between 20–40% in South Asia, depending on the combination of practices adopted and the cropping systems.[102] Findings also suggest that yield and profit increases from adopting CA practices in South Asia are higher for maize and wheat than for rice cropping systems.[103] Heterogeneity in soil texture also affected productivity, as yields were higher in loamy soils than in clay or sandy soils.[104]

Table 2: Research on Farmer Outcomes and Conservation Agriculture

Study	Study Information	Changes in Yields
Kichamu-Wachara et al. (2021)	Meta-analysis of 60 on-station and on-farm studies in SSA and North Africa [517 paired observations for crop yields, 163 paired observations for soil carbon, and 98 paired observations for soil nitrogen; maize (n=398); wheat (n = 168); sorghum (n=24) legumes (beans, lentils, cowpea, and soybean; n=58) and tubers (yam and sweet potato; n=13)]	Minimum-to-no tillage as a standalone practice does not significantly impact productivity. When farmers combine conservation tillage with crop residue retention or green manure, yields increase by 9.3% compared to conventional agriculture.
Pittelkow et al. (2015)	Global meta-analysis using data from on-station field experiments for 48 different crop species [5,463 paired (no till-to-conventional till) observations for crop yields from 610 studies]	Zero-tillage alone reduces yields by 9.9% compared with conventional tillage. Zero-tillage combined with crop rotation and crop residue retention significantly enhances yields by 7.3%.
Corbeels et al. (2020)	Meta-analysis using data from field experiments for maize, sorghum, cowpea, rice, soybean, and cotton cropping systems in SSA [992 paired (conservation-to-conventional till) observations for crop yields from 87 field experiments with over half of the studies on maize]	Average yields (across crops) increase by only 3.7% compared with conventional tillage. Average maize yields increase by 4% with zero or reduced tillage and by 8.4% when combined with mulching and intercropping/crop rotation. Using herbicides, yields with CA increase by 4.7% over conventional tillage, whereas no difference in yields is observed between CA and conventional tillage without herbicides.
Jat et al. (2020)	Meta-analysis using rice-wheat, maize-wheat, and rice-maize cropping systems in South Asia [9,686 paired site-year conventional vs. conservation practices comparisons from 1,353 field experiments]	Significant positive effects are seen on yields across the three cropping systems, with impacts ranging from 3% to 5.5%. Maize–wheat cropping systems see an 18.6% increase in yields, followed by yield increases in rice–wheat (5.1%) and rice–maize (3.6%) cropping systems.
Keil et al. (2015)	Field trials on zero-tillage methods in wheat cultivation in the Indo Gangetic Plains [1000 farm households in Bihar; random sampling clustered at the village level, stratified by zero-tillage adopters/non-adopters]	Yields increase by 19% from adopting CA practices compared with conventional tillage. Establishment costs and increased annual household income decrease by an estimated 6% among a random sample of farmers in Bihar.
Keil et al. (2020)	Field trials on zero-tillage methods in wheat cultivation in the Indo Gangetic Plains [961 farm households in Bihar from the same sample from Keil et al., 2015]; random sampling clustered at the village level, stratified by zero-tillage adopters/non-adopters	Using the same sample from Keil et al. (2015), the authors find that zero-tillage increases mean wheat yields by 32.1%, relative to conventional tillage. Yield increases are consistent across varying climatic conditions over a four-year period, including periods of drought and excess rainfall.

C. Barriers to Adoption and Implementation

CA adoption often requires significant upfront investment from smallholder farmers, which they are often not able to afford. For example, reduced tillage requires specialized equipment and may also necessitate higher levels of herbicide for weed control to maintain yields.[105] Crop residues serve multiple purposes on the farm, including as livestock fodder, so may not be available to leave on the field.[106] Cover crops may not easily fit into existing crop rotations nor be economical to plant, and often require increased capital and labor investments in seeds, additional crop expenditures, and labor in planting an additional crop cycle.[107] There may also be environments, i.e., extremely dry or cold areas, in which cover crops will not be able to survive.

The order of adoption of individual CA practices also matters for yield and climate change mitigation outcomes, such as whether farmers adopt zero or reduced tillage before or after they adopt cover crops and crop rotations. Smallholder farmers must thus have access to training or other sources of information on how to properly implement CA practices for optimal yield and climate change mitigation outcomes.

These capital and labor costs of CA adoption may or may not be balanced by productivity gains. Despite a number of demonstrated benefits for soil fertility, soil erosion, and biodiversity, the relatively low productivity gains, or even negative productivity impacts, in the short term in most empirical studies, as well as the aforementioned costs of adoption, help to explain the low CA adoption rates by smallholder farmers to date, especially in African geographies.[108] Smallholder farmers are less likely to adopt new practices without financial incentives from higher yields and/or higher profits, especially in the short term.[109] Future research should more concretely analyze mechanisms behind farmer yield and profit changes associated with CA in order to increase farmer adoption.

4. Agroforestry

Agroforestry is a land use system that integrates woody perennials with crop or grazing lands to sequester carbon in above-ground biomass and increase SOC. Beyond its carbon sequestration benefits, farmers are often motivated to adopt agroforestry as it has direct economic benefits, from the provision of firewood to fodder production to wind breaks. Often defined as more than 10% cover of trees and shrubs on a farm plot, agroforestry practices are particularly common in some regions in Asia, with approximately 78% of agricultural land in Southeast Asia, 50% in East Asia, and 27% in South Asia incorporating elements of agroforestry.[110]

A. Agroforestry and Agriculture

Types of agroforestry and agroforestry practices differ based on the climate, geography, and cropping system, although all systems combine ecological systems of woody perennials with crops, livestock, or both. The Food and Agriculture Organization of the United Nations (FAO) identifies three different types of agroforestry: 1) agrosilvicultural (trees combined with crops); (2) silvopastoral (trees combined with animals); and (3) agrosilvopastoral (trees combined with animals and crops).[111] Choices of the type of agroforestry and related practices to adopt by farmers are often based on specific contexts, such as geography, soil type, historical or indigenous practices, and the local environmental conditions. Many agroforestry practices are based on indigenous farming systems that are context-specific methods for achieving both higher yields and profits.[112]

Definitions of agroforestry can also incorporate or promote practices such as afforestation (planting trees on land that was not previously a forest) or reforestation (planting or restocking trees in degraded forests).[113] While afforestation and reforestation can contribute to restoration of degraded land as well as to carbon drawdown, this piece will focus on agroforestry and its intersection with working, agricultural land, primarily combining cropping and/or livestock systems with trees, shrubs, bamboos, or palms.

Table 3 defines the most common practices to integrate agroforestry into agricultural land, namely alley cropping, hedgerows, dispersed intercropping, multistrata agroforests, parklands, windbreaks, boundary planting, and improved fallows. Additional practices, including biomass transfer (incorporating leaves, twigs, and other pruned materials into soil before planting) and using mulch (using pruned materials as protective covering), are common practices that are associated with agroforestry but differ from the practice of planting woody perennial crops like trees and shrubs.[114] Farmers will choose to adopt different agroforestry practices depending on their needs, constraints, and productivity aims, leading to the variety of different practices under the wider umbrella of agroforestry. Today, agroforestry encompasses a variety of practices and methods, meaning that full predictability of effects in a specific context remains challenging.

Table 3: Agroforestry Practices and Relevant Empirical Research on Practices

Agroforestry Practices	Description of Practice
Alley cropping	Crops are planted in between rows of shrubs or trees
Hedgerows	Shrubs are planted closely together to form a barrier between separate fields
Dispersed intercropping	Trees are planted and scattered in crop fields
Multistrata agroforests	Perennial tree crops (often cocoa, coffee, and tea) are planted along with shade trees
Parklands	Multipurpose trees are planted and scattered across farmlands
Windbreaks	Trees are planted in rows to provide protection from the wind
Boundary planting	Trees are planted to define different farms
Planted fallows (improved fallows)	Farmers rest cropland between cultivation cycles by growing fast producing species

Source: Kuyah et al. (2019)[115]

B. Climate Change Mitigation and Agroforestry

Benefits of agroforestry vary depending on what practices are adopted in which cropping system and in which ecological zone. However, empirical evidence about agroforestry demonstrates improvements to both climate change mitigation potential and farmer productivity and profitability. In terms of climate impacts, agroforestry demonstrates strong mitigation potential through soil organic carbon sequestration, as well as carbon storage in woody biomass. In the humid and sub-humid tropics, agroforestry increased soil organic carbon by an average of 21% across 119 studies.[116] Another meta-analysis of 78 studies across 30 countries revealed that, compared with agriculture and pasture, agroforestry systems held soil organic carbon stocks that were 27% higher in arid and semi-arid regions, 26% higher in lowland humid tropics, 5.8% higher in Mediterranean regions, but 5.3% lower in temperate regions.[117] These results are encouraging in Global South geographies, which include farmers both in humid and sub-humid tropics, and in arid and semi-arid climate zones.

Evidence also suggests that organic carbon storage potential was higher with longer-term agroforestry projects with 10 to 20 years of agroforestry practices rather than projects that were assessed at fewer than 10 years.[118] Other meta-analyses demonstrate positive outcomes on soil organic carbon sequestration.[119] The estimates of potential increase in carbon storage through above-ground biomass largely depends on the type of woody perennial as well as the agroforestry practice used.

Positive environmental impacts of agroforestry adoption extend beyond climate change mitigation. A review of biodiversity present in agroforestry systems confirmed that agroforestry practices led to higher floral, faunal, and soil microbial diversity compared to monocropping systems, adjacent agricultural land, and some forests.[120] Another review of empirical research by Bhagwat et al. (2008) concludes that, despite wide variation across studies, the mean values for richness of biodiversity in agroforestry systems is 60% higher than forest biodiveristy.[121] Studies on agroforestry also demonstrate positive effects on soil erosion, including higher infiltration rates and soil macroaggregates, lower runoff, and greater stability of soil structure. In a meta-analysis of 119 studies on soil health impacts from agroforestry in the humid and sub-humid tropics, Muchane et al. (2020) find that agroforestry can lower soil erosion by 50%,[122] increase nitrogen storage by 13%, and increase available nitrogen by 46% compared with monocultures.[123] Other positive impacts of agroforestry, including improved pest control, reduced weeds, and lower plant damage due to disease and pests, were found in a meta-analysis of 42 studies, by Pumariño et al. (2015).[124]

Climate change mitigation as well as soil health benefits of agroforestry rely on the continuation of agroforestry practices; positive outcomes of climate change mitigation and productivity can only be achieved if farmers do not return to conventional or historical practices. The potential lack of permanence limits climate change mitigation if farmers are forced or choose to remove their woody perennials or change their cropping pattern. In contrast to many other agricultural investments, agroforestry takes longer for farmers to earn profits from investing in agroforestry practices. For instance, many conventional agricultural investments generate profitable returns in one to two years, whereas agroforestry practice could take three to eight years for farmers to see significant profit increases.[125] Therefore, farmers may incur extra costs in the first years of agroforestry practice (such as higher input or labor costs) or even generate lower yields, which may dissuade farmers from adopting practices based on environmental benefits alone.

C. Farmer Outcomes from Agroforestry Practices

Overall, farmer outcomes from agroforestry appear positive. However, studies in both Africa and Asia demonstrate a wide range of farmer outcomes depending on cropping system, type of agroforestry, soil type, climate, and other environmental factors. Research to date, described in detail below, suggests stronger yield outcomes when agroforestry is adopted in Sub-Saharan African contexts than in Asian contexts, and appropriate planning and research before project implementation appears to significantly decrease risks of negative yield outcomes.

i. Sub-Saharan Africa

Empirical research demonstrates agroforestry can improve farmer productivity and profitability, especially in Sub-Saharan Africa. In a meta-analysis of 126 peer-reviewed studies across Sub-Saharan Africa, 77% of on-farm plots and 68% of on-station plots saw some level of yield increase from the implementation of agroforestry. Diving more specifically into agroforestry practices such as improved fallows, alley cropping, as well as the associated practice of biomass transfer, 85%, 77%, and 93% of plots which implemented those practices, respectively, saw a yield increase.[126] The level of yield increase depends on a plot's specific characteristics, like soil type and base soil fertility, as well as its agroecological conditions.

Agroforestry practices like the ones listed in Table 3 above improves yields in both semi-arid and humid conditions, compared to the conditions where farmers did not adopt agroforestry practices,[127] and yields were significantly higher in most soil types. Studies have shown negative yield outcomes from agroforestry implementation in sandy and rice soil, but these differences could also be attributed to general poor soil health or other environmental factors.[128] A few agroforestry practices and agroforestry management techniques, namely hedgerows and constricting growth of woody perennials through pruning or excessive shade, do more commonly lead to negative yield outcomes, but overall effects are positive[129] and are well supported in various sources of empirical research and meta-analyses on Sub-Saharan Africa.[130]

ii. Asia

Studies on the effects of agroforestry practices on production capacities in Asia lead to more mixed results than SSA results, with both positive and negative results. In a meta-analysis of 14 studies, Kumar (2006) finds that agroforestry generates positive yield effects with crops such as rice, ginger, and galanga, but can produce lower yields in fodder plants and other grain crops.[131] Results in farmer yield in Asian countries were more affected than SSA countries by cropping system type, soil type, and agroforestry practice used, and exact impacts need to be studied further to understand fully which practices lead to higher or lower productivity, and why. Agroforestry programs which adequately account for these environmental factors in Asian geographies can lead to positive outcomes in both farmer productivity and profitability. Despite the lack of clear effects on productivity in Asian contexts, there is strong evidence to support the implementation of agroforestry systems in Asian geographies when sufficient planning and research (such as randomized control trials) are included to ensure more positive farmer outcomes.

D. Barriers to Adoption and Implementation

The most significant barrier to agroforestry adoption by smallholder farmers is the longer-term nature of yield and profit increases, as well as associated initial capital costs of the trees themselves, and potentially taking some land out of production. While other agricultural changes, like variety or crop type, may only take one to two years to improve farmer productivity, many agroforestry practices require three to eight years to increase yields and associated farmer profits.[132] In periods of economic stress or uncertainty, farmers may cut down woody perennials for firewood or other livelihood uses, thus negating potential long-term productivity benefits as well as the carbon storage effects of agroforestry.

Socio-economic factors, such as household and livelihood security, access to land and capital, labor availability, gender dynamics, land tenure, farm size, and knowledge of agroforestry also affect farmer adoption of agroforestry.[133] For example, agroforestry may require developing woody perennial cultivation skills that farmers are not familiar with, and farmers may lack the capital for agroforestry inputs and labor expenses. If farmers are uncertain about their long-term land tenure, they may be less likely to adopt practices like agroforestry that have little or no short-term yield or profit increases.[134]

However, Roshetko et al. (2007) suggest that, when land tenure is secure, smallholder adoption of agroforestry systems will occur if three key conditions are met: (1) quality access to appropriate seeds and seedlings; (2) developed agroforestry system management skills; and (3) improved market linkages, including in the demand for products of agroforestry systems[135] Otherwise stated, if smallholder farmers have the necessary materials, including knowledge, for agroforestry practices, and have access to fair and stable marketplaces for their crops or tree products, the farmers are much more likely to adopt agroforestry. Another possible solution to increase agroforestry adoption is to offer transition-period financial assistance until farmers recoup their agroforestry investment.[136]

5. Biochar

Created by high temperature pyrolysis or degasification of organic material in an anaerobic environment, biochar can be made from a variety of materials, including crop residues, manure, aquatic weeds, forest residues, or wood waste. The use of man-made amendments to soils dates back centuries; for example, the Amazonian indigenous peoples created terra preta,[137] a highly fertile anthropogenic soil, through low-temperature burning of organics. Biochar today has evolved from terra preta,[138] but it serves similar goals of improving soil health in degraded soils and, as we now understand, increasing soil carbon sequestration.

Biochar is created by pyrolysis, the process of heating biomass to between 300°C and 700°C in conditions with very low oxygen levels.[139] Biochar retains between 10% to 70% of the carbon from the original biomass, with biochar carbon retention averaging around 50%.[140] The carbon sequestration potential of biochar is based on the difference between the rate of decomposition of the original biomass before pyrolysis and the decomposition rate of the created biochar. Organic matter decomposition rates vary greatly depending on the soil type, environment, and material, as well as the ratio of labile carbon (which easily breaks down and is biodegradable) to recalcitrant carbon (which is more resistant to degradation).[141] In biochar there is a higher proportion of recalcitrant carbon compared with the original biomass. For biochar to be effective for carbon sequestration, scientific estimates suggest that the created biochar's labile to recalcitrant carbon ratio should be less than 10%.[142] The method of pyrolysis will also affect the amount of carbon captured in the biochar, and the efficiency of the biochar creation process. Burning biomass generates GHG emissions, so it is important that biochar pyrolysis systems are efficient and convert as much carbon as possible in the biochar.[143] Biochar created from woody biomass (compared to manure or other biomass sources) increases this conversion fraction and hence the potential for carbon sequestration in soil. [144]

The effects of biochar amendments on carbon sequestration as well as farmer outcomes, such as yields, vary drastically depending on the biomass input material, the method of biochar production, and the depth and method of biochar application to soil.[145] There are two components to "biochar best practice": the first relates to preparation of biochar as a product, including source materials, and the second relates to how and where it is applied. Estimates of biochar's effectiveness in sequestering carbon vary considerably based on the assumptions for these two issues, and the use of biochar for SOC sequestration has not been well demonstrated beyond research settings. For example, biochar feedstock selection by farmers is largely determined by the availability of feedstock materials, capacities for production and collection of feedstock, use tradeoffs, transport, and storage capacities, rather than its carbon storage potential.[146] Therefore, many smallholder farmers do not and often cannot adhere to best practice guidelines for biochar production, and there is a large variation in biochar quality.

Nitrous oxide emissions from biochar depend on the the pyrolysis process, and on the nitrification and denitrification process in soil amended with biochar.[147] Nitrous oxide emissions are released in biomass decomposition, which means that the calculated mitigation potential of the biochar amendment depends on how much would be emitted if biochar were not created from the feedstock. Inefficient pyrolysis can also affect nitrous oxide emissions when burning the biomass. These mechanisms are currently poorly understood, so future research will need to move beyond observing outcomes, by looking at mechanisms for increased or decreased nitrous oxide emissions from biochar amendments. The fate and form of carbon and nitrogen must be fully accounted for beyond the field level to understand the GHG reduction benefits from biochar or any other innovation.

Methane is also released in natural decomposition of biomass in the absence of oxygen (such as in fully flooded rice systems). Projected methane emissions from biochar will depend both on the expected decomposition environment of feedstock biomass, if not converted to biochar, and pyrolysis efficiency. Methane emission interactions and mechanisms remain poorly understood and will need further research to predict adequately how biochar production and applications will change methane emissions.[148]

Other factors, such as water management practices, alternative uses for feedstock biomass, energy used to create biochar, and changes in fertilizer demand could impact emission estimates and climate change mitigation potential. To simplify calculations and generate practical estimates of biochar's mitigation potential, most meta-analyses and studies focus on soil organic carbon sequestration and nitrous oxide emissions directly emitted from biochar creation and application.

Another environmental benefit associated with biochar is the use of pyrolytic cookstoves, a household method of biochar creation commonly known as gasifiers, in place of traditional, open fire cooking methods. Around 2.4 billion people worldwide still rely on inefficient cooking methods, like open fires, for their daily cooking.[149] These inefficient cooking methods create significant household air pollution which contributes to 3.2 million premature deaths each year.[150] Pyrolytic stoves such as those used for biochar creation reduce indoor air pollution as they improve biomass burning efficiency. One study found using a gasifier instead of a traditional open fire reduced CO, CO_2, and $PM_{2.5}$ concentrations at meal times by 57%, 41%, and 79% respectively.[151] Although the transition to pyrolytic stoves does not involve using biochar as a soil amendment for carbon sequestration, it demonstrates how other practices associated with biochar production can reinforce its positive environmental effects.

The Standardized Product Definition and Product Testing Guidelines for Biochar That Is Used in Soil (called the IBI Biochar Standards) acts as the most standardized set of regulations on biochar creation and application, although a number of other certificate programs exist, including the IBI Biochar Certificate or European Biochar Certificate, to prove biochar quality for consumers. According to IBI Standards, biochar from feedstock must be a combination of biomass and diluents, with less than 2% of contaminants (by dry weight).[152] Diluents are inorganic materials (such as clay, gravel, or other inorganic particles) that will not carbonize when the rest of the biochar burns.[153] Contaminants include unsuitable inorganic materials for biochar production, including fossil fuels or fossil-fuel-derived compounds, glass, or metal.[154] Further, biochar made from manure or human waste must be clear of any hazardous material or wastes.[155] IBI Standards do not require strict practices in production or storage requirements, but they publish a list of best management practices (BMPs) that should be combined with local regulations and testing protocols, including testing of basic utility properties, toxicant assessment, and advanced analysis and testing of soil enhancement properties.[156]

Biochar projects from around the world are testing and deploying biochar amendments in farmers' fields, and results from on-farm trials and on-station trials show biochar has the potential to increase productivity and climate change mitigation (Tables 4 and 5). However, continued empirical research is needed on biochar's performance in these contexts, given the high level of variability in biochar types, as well as biochar's effects in different ecological zones and cropping systems.

A. Mitigation Potential of Biochar

GHG mitigation from biochar can be from increasing carbon storage of soils as well as reducing nitrous oxide and methane emissions from biomass decay. The most significant mitigation potential from biochar, comes from carbon storage and sequestration increases in soils with biochar amendments.

Given high heterogeneity in biochar application and composition, researchers are still learning about the mitigation potential of biochar in multiple geographies and contexts. Empirical evidence has shown positive impacts on soil health, water-holding capacity, and crop yields in research conducted in the North and South Americas, Europe, Australia, and China.[157] Effects of biochar amendments in on-farm trials remain inconclusive in Asia and Africa, as there remains insufficient data on climate change mitigation and productivity in smallholder contexts. Existing studies with on-farm trials with small sample sizes demonstrate a range of effects based on differences in biochar source, quantity applied, soil type, geography, and cropping system. Despite high variability in results between individual studies, meta-analyses on the climate impacts of biochar suggest positive climate change mitigation results from on-station research (Table 4).

Meta-analyses demonstrated positive effects of biochar amendments on soil organic carbon storage and sequestration (Table 4). A global meta-analysis including data from both field experiments and pot/incubation experiments saw an increase in SOC stocks by 29% and 75%, respectively.[158] Co-applications of organic fertilizer with biochar amendments also significantly boosted SOC storage across studies.[159] These results were supported by findings from another global meta-analysis which found biochar increased SOC by 32.9% with biochar application alone and by 34.8% with biochar combined with chemical fertilizers. The use of biochar alone was associated with lower crop yields, whereas biochar combined with chemical fertilizers were positively correlated with higher yields.[160] These results suggest that further analysis should be conducted on the mechanisms at play between biochar amendments and chemical fertilizer application. The authors found that most study variation could be explained by heterogeneity in water (humidity, rainfall, and water management), soil (SOC, pH, and soil type) and biochar (feedstock material, pyrolysis method, pH, application rate, and carbon/nitrogen ratio) properties,[161] although sufficient evidence on how these differences affect mitigation outcomes remains lacking.

In terms of nitrous oxide emissions, one meta-analysis found a 54% reduction in soil nitrous oxide emissions following biochar amendments.[162] Based on their results, authors of this meta-analysis concluded that biochar created from wood and herbaceous biomass led to significant reductions in nitrous oxide emissions, whereas biochar from manure led to a negligible net impact across studies (although individual study results ranged from a 46% decrease in nitrous oxide emissions to a 39% increase in emissions).[163] Generally, however, there exists a lack of understanding of key mechanisms affecting biochar's impact on nitrous oxide emissions,[164] which explains the high degree of heterogeneity across studies within the meta-analysis. Another meta-analysis found biochar amendments reduced nitrous oxide emissions by 38%, although these effects declined and nitrous oxide emission reductions became negligible after about one year.[165] Effects of nitrous oxide emission reductions with biochar amendments were largest with rice and sandy soils.[166] The meta-analysis also found negligible effects on soil nitrate concentrations, but biochar amendments reduced nitrate leaching by 13%.[167]

The overall estimated effect of biochar amendments on annual net emissions varies, depending on the model and calculation methods used. Estimates range from 0.7–1.3 GtC eq yr^{-1} to 5.5–9.5 GtC eq yr^{-1}, which largely differ based on model assumptions and projections of SOC capabilities and of reductions in nitrous oxide and methane emissions.[168] This wide range demonstrates the lack of consensus on biochar's climate change mitigation potential and further suggests how existing studies often fail to encompass on-farm variability and mechanisms that affect GHG emissions. Ultimately, future research needs to both assess biochar's viability in on-farm trials, specifically in smallholder contexts in Africa and Asia, and delve further into interacting mechanisms affecting emissions.

Table 4: Summary of Research on Mitigation Potential from Biochar Amendments

Study	Study Information	Changes in Mitigation Potential
Borchard et al. (2019)	Meta-analysis using 88 peer-reviewed studies (n=701 observations, with 120 observations for nitrate leaching, 146 observations for nitrate soil concentration, and 435 observations for cumulative N_2O emissions)	Biochar amendment reduces N_2O emissions by 38% and NO_3 leaching by 13%. N_2O emissions decrease the most in rice and sandy soils. N_2O emission reductions are negligible after the first year. Soil NO_3 concentrations are unaffected by biochar amendments.
Gross et al. (2021)	Global meta-analysis with data from 64 studies, including both field studies (n=412) and non-field experiments (n=182)	There is a mean increase in SOC stocks by 29% from field experiences (duration of 1–10 years and application between 1–100 Mg ha^{-1}). There is a mean increase in SOC stocks by 75% in pot and incubation experiments. SOC accumulation is higher in field experiences with a 6–10 year duration compared to a 1–5 year duration. Organic fertilizer combined with biochar increases SOC.
Xu et al. (2021)	Meta-analysis using data from 143 studies analyzing differences between biochar, and biochar combined with chemical fertilizers (n=1080 paired crop yield observations)	GWP decreases by 27.1% from biochar amendments alone, and 14.3% from biochar amendments combined with chemical fertilizers. There are almost no differences in terms of increasing SOC (32.9 % [B] and 34.8 % [BF] respectively).
Cayuela et al. (2014)	Meta-analysis which includes quantitative data from 30 studies (n=261 experiments)	N_2O emissions decrease by 54% with biochar treatments in field and laboratory experiments.
Woolf et al. (2010)	Authors derived a biomass-availability scenario for an estimate of the maximum sustainable technical potential of biochar to mitigate climate change	Annual net emissions of carbon dioxide CO2, CH_4, and N_2O could be decreased by up to 1.8 Pg CO_2-C equivalent per year (12% of current anthropogenic CO_2-C_e emissions). Total net emissions per 100 years could decrease by 130 Pg CO_2-C_e.
Smith (2016)	Review of literature using over 20 studies	Biochar has a negative emission potential between 0.7–1.3 GtC eq yr^{-1}.
Lehmann et al. (2006)	Authors calculate emission projections based on projections of the use of renewable fuels in the year 2100	Up to 5.5–9.5 GtC eq yr^{-1} can be sequestered by 2100 using biochar (*Note:* study assumes total paradigm shift in energy consumption).

N.B. Observation refers to a single point of data collected from an on-farm, research farm, laboratory, or pot experiment. Observations are paired, meaning that one observation is paired with another in similar conditions, so that changes between the treatment and control is evident. In these meta-analyses, the wide range of experiments means that paired observations demonstrated changes of treatments in the most consistent way possible.

B. Farmer Outcomes from Biochar Application

Several meta-analyses have been conducted to assess how biochar applications impact farmer outcomes such as crop yield (Table 5). Most meta-analyses show small positive productivity effects when looking at grand means (average of means from studies included in the meta-analysis), but individual studies demonstrate a large range of yield changes, and uncertainty about productivity increases or decreases from biochar amendments. For example, in a meta-analysis of 16 studies, the authors find a grand mean increase of 10%, but the individual studies and observations show crop yield changes ranging from a 28% decrease in yield to a 39% increase.[169] Table 5 summarizes productivity findings from meta-analyses: increases in grand yields range from 10% to 25%, although means from individual studies demonstrate both positive and negative yield outcomes from biochar application.

Results vary on how biochar alone affects crop yields, but combining biochar with other soil amendments (including fertilizers and organic products) increases crop yields. Findings from one meta-analysis suggest that use of biochar alone does not significantly increase yields, but biochar combined with inorganic fertilizers and/or organic amendments leads to yield increases of 48% and 15% against non-fertilized and fertilized controls, respectively.[170] However, these results contradict findings from another meta-analysis, as a larger scale global analysis finds that biochar alone does increase crop yield by 15.1%. Similar to the other meta-analysis, biochar combined with chemical fertilizers leads to a significant increase (48.4%) in crop yield.[171] While results suggest that biochar can improve crop productivity, the high variability in results across studies and meta-analyses indicates many factors impact how biochar amendments affect crop yields. These factors include ecological/climate zone, soil type, type of crop, application quantity, type of biochar applied, and additional inorganic or organic fertilizer application.

Recent research has been trying to ascertain why yields are lower in some cases, and to alleviate farmer concerns over decreased productivity from biochar amendments. Soil properties (including texture, pH, fertility, and nutrient balances) impact yield results and can help explain variation and inconsistencies in results. Empirical evidence suggests that both medium and coarse soils textures yield higher productivity, whereas biochar application does not significantly impact yields in fine textured soils.[172] Yield impacts are higher in acidic and in neutral pH soils compared to alkaline soils; meta-analyses results show that a high pH decreases biochar's effect on yield increases.[173] Biochar amendments are more effective in increasing yields in high SOC contexts, especially when combined with chemical fertilizers.[174]

Biochar composition also affects biochar's effects on productivity, as some biochar properties are negatively correlated with higher yields.[175] When biochar amendments consist of a higher carbon to nitrogen ratio (which is affected by both pyrolysis and feedstock material), biochar amendments may still increase yields, but could decrease the relative positive impact of biochar on productivity if biochar amendments contribute to nitrogen immobilization. Findings are generally inconclusive about how biochar application rates affect productivity, as researchers conclude other factors may play a more critical role in yield outcomes. Most studies suggest there is no significant difference in yield effects between biochar applications ranging from 10-100 t ha^{-1}.[176]

Geography also had strong effects on biochar efficacy, which implies that biochar may not be a practice that is globally applicable for farmers, and may explain variations in outcomes between global meta-analyses. Biochar application contributes to a 25% increase in yields in the tropics, but almost no effect on yield in temperate climates.[177] In another meta-analysis a few years later by the same authors, the authors find that biochar amendments in temperate climates actually decrease crop yields.[178]

Table 5: Research on Effects of Biochar Amendments on Productivity

Study	Study Information	Changes in Productivity
Jeffery et al. (2011)	Statistical meta-analysis with data from 16 studies (n=177 treatments)	There is a 10% increase of average yield from biochar application (grand mean).[179] Changes in yield range from -28% to 39%.[180]
Xu et al. (2021)	Global meta-analysis on impact of biochar versus combined biochar and chemical fertilizers (n=455 experiments)	Crop yield increases by 15.1% from biochar amendments (B) and by 48.4 % from biochar amendments combined with chemical fertilizers (BF). Higher SOC increases yields from B and BF amendments. Higher biochar carbon to nitrogen ratio (C:N ratio) and soil pH lessen crop yields from B and BF amendments.[181]
Liu et al. (2013)	Weighted meta-analysis with data from 103 studies (n=880 paired observations)	There is an 11% increase in average yield from biochar application (grand mean).[182]
Jeffery et al. (2017)	Meta-analysis with data from 109 studies (n=1125 observations)	There is a 13% increase in average yield from biochar application (grand mean).[183] There is a 25% increase in average yield from biochar application in the tropics, but no effect or negative effects on yield in temperate latitudes.[184]
Ye et al. (2020)	Meta-analysis of 56 studies (n=264 observations)	Use of biochar alone does not significantly increase yields. Biochar combined with inorganic fertilizers and/or organic amendments increases yields by 48% (against non-fertilized controls) and by 15% (against fertilized controls).[185]

C. Barriers to Adoption and Implementation

There are few studies of farmers producing and using biochar for their own fields. Mechanisms that affect biochar's impact on SOC, GHG emissions, and yields thus remain poorly understood. Given the high variability and the lack of consensus in the literature about the effects of biochar, further research is needed to understand how biochar amendments affect farm-level productivity and mitigation objectives in Global South countries.

In addition, quality biochar creation requires farmers to gain new technical skills and knowledge about the pyrolysis process. The current infrastructure for such skills training of smallholder farmers, for example in SSA, remain limited.[186] And while some studies suggest biochar is an affordable technology, there are many factors which affect those costs. If farmers already have access to pyrolytic mechanisms and can use crop residues or other safe agricultural waste materials for biochar production, then capital costs to farmers will be lower than if they need to purchase a pyrolytic stove or obtain sufficient feedstock material from outside sources. The lack of clarity on biochar's impacts on yields and climate change mitigation, combined with variability in capital and labor costs of biochar creation and application, demonstrates research gaps and barriers to household adoption of biochar. Commercial biochar production may be a more feasible pathway, as evidenced by emerging enterprises like the Finnish Carbofex which produces biochar at an industrial level. There are as yet few examples of commercial biochar in the Global South beyond one-off projects proving viability.[187]

6. The Voluntary Carbon Credit Market

One emerging pathway to finance farmers' adoption of carbon sequestration strategies is the voluntary carbon credit market. The voluntary carbon credit market provides entities like private sector companies, governments, or individuals a way to buy and sell carbon offset credits. One carbon offset represents the reduction of one metric tonne of carbon dioxide or GHG emissions;[188]; offsets are often used by organizations to reach their GHG emissions targets. The demand for voluntary carbon credits is projected to grow by a factor of 15 and be worth more than $50 billion USD by 2030.[189] Much of this growth will be driven by corporations seeking to meet their net zero commitments,[190] for example Netflix's announcement it will be net zero from 2022 onwards. To meet this demand, there must a rapid increase in the number of quality carbon credit projects which meet the following key criteria:

- **Additionality**: GHG reductions are additional if they would not have occurred unless there was a market for their reduction through offset credits.[191] If the reductions would have happened anyway, then purchasing such non-additional offset credits instead of reducing one's own emissions is meaningless as there is no net GHG removal. For agriculture-based carbon sequestration projects, this means that projects must demonstrate that the practices leading to sequestration would not have been adopted by farmers in the absence of the program. In practice, this often looks likes ensuring projects operate in an area where there is low baseline adoption of the relevant agronomic practices. These baseline adoptions rates can be hard to quantify, which is part of what makes it difficult for land-based carbon sequestration projects to meet the additionality criteria.
- **Permanence**: The effects of CO_2 emissions are very long-lived. Although most of the carbon in CO_2 emissions will eventually be removed from the atmosphere, around 25% will remain in the atmosphere for hundreds to thousands of years.[192] Carbon offset credits should therefore be associated with GHG reductions with a similar time scale, i.e., for all intents and purposes permanently reduce the amount of carbon in the atmosphere. Most land-based carbon sequestration projects, however, are impermanent. For example, agroforestry projects keep carbon in trees and soils. However, if there is a fire or farmers choose to cut down trees for other uses, some or all of the carbon may be (re)emitted, leading to a reversal.
- **Measurement, Reporting, Verification**: All carbon offset credits require measurement, reporting, and verification (MRV) systems to build credible mitigation. For soil carbon, these MRV systems are very much still in a developmental state, with varying accounting methodologies by various

voluntary market registries.[193] While the regulated, not-for-profit organizations (VERRA, CAR, Gold Standard) share their documentation publicly, there are many private, for-profit actors (Nori) also selling credits which do not provide this level of transparency. CarbonPlan, a non-profit industry watchdog, reported in a review of soil carbon protocols that "robust crediting of soil carbon is hard and that none of the existing protocols is doing enough to guarantee good outcomes."[194] This is partly because of the inherent difficulty in measuring soil carbon, which for now cannot be accurately assessed without empirical data, e.g., from time- and cost-intensive soil sampling.

There are other determinants of a quality carbon offset credit project, but the above are the critical ones to ensure projects are delivering the outcomes they promise. Right now there is not enough coordination amongst the actors in the voluntary carbon credit market to create systems which help support projects to meet these criteria. CarbonPlan developed a metric called the Verification Confidence Levels (VCL) which summarizes their "uncertainty mapping for each [carbon dioxide removal] pathway and represents [their] confidence that carbon removal outcomes can be accurately quantified using the best scientific understanding, measurement, and modeling approaches available today." The VCL has a scale of 1 to 5, with 5 being the most confident. For terrestrial biomass sinking projects, i.e., those projects that use land as a carbon sink, the VCLs fall anywhere between 2 and 4. This wide interval in outcome certainty illustrates the market's need to invest in scalable MRV systems, as well as in the development of market infrastructure, such as transparent standards and carbon credit markets, to ensure climate change mitigation outcomes are met.

In addition to ensuring climate change mitigation outcomes are met, another aspect of the voluntary carbon market that remains to be determined is its ability to appropriately compensate farmers for their carbon storage. Prices for nature-based carbon sequestration projects remain low and volatile, ranging from \$5–\$15/ton of carbon from 2021 to 2022.[195] Most project developers take a percentage of that price to sustain their own operations, which means the ultimate amount going to farmers is probably less than that sticker price. For example, rough back of the envelope calculations from PxD's conversations with a carbon credit project developer found that, for a sample of farmers in India, their plots on average sequestered 2.5 tons acre^{-1} year^{-1}. For that project developer, farmers receive 55% of the carbon price; however, a further 15% buffer must be held in reserve in case of carbon reversals. At a high estimate of \$15 ton^{-1} of carbon, this means that farmers would ultimately receive \$17.5 acre^{-1} year^{-1}. PxD farmers farm, on average, 3 acres which means the total annual payout from this project developer would be \$52.50. The average agricultural household in India's monthly income is INR 10,218 (~\$124 USD) or around \$1,480 annually, so this payment represents around 3.5% of that annual income.[196]

Although much of the current climate change mitigation financing momentum is driven by the voluntary carbon credit market, due to the challenges described above in developing quality carbon credit projects, many stakeholders are pushing for the field to go beyond CO_2 equivalents as an outcome, to better incorporate the co-benefits of carbon sequestration activities like increased biodiversity and improved water quality.[197] In order to support this expansion, there needs to be significant investment in the measurement of both climate outcomes for carbon and other related environmental outcomes. For example, the Science Based Targets Network is a collaboration of leading global non-profit and mission driven organizations working to develop science-based targets for climate change mitigation, which address outcomes for both nature and climate.

7. Conclusion

Changing the way we use land, particularly in agriculture, is an important pathway for mitigating climate change. Land is a crucial carbon sink and there are concrete ways smallholder farmers can participate in leveraging that carbon sink for environmental benefits. Conservation agriculture practices, agroforestry, and biochar are three opportunities for carbon storage, with a growing evidence base. However, their carbon storage potentials are context specific, and supporting their successful adoption in the smallholder-farmer context requires careful consideration of that context, both from a scientific and socio-economic point of view. Incorporating farmers as equal stakeholders in the development of carbon sequestration projects will help achieve these steps, whether it's by better understanding the landscapes in which they farm, and their constraints around a particular agricultural practice, or by co-designing meaningful incentives for their environmental services.

There will also be a need for substantial investment in climate change mitigation in the Global South, with a focus on what is actionable in its specific contexts, and an understanding that there will not be a one-size-fits-all approach to creating a sustainable-agriculture future. For example, there have not been sufficient on-farm trials with smallholder farmers in SSA or Asia to fully understand the effects of conservation agriculture, agroforestry, or biochar on climate change mitigation outcomes in those contexts. While this literature survey shows promise in these approaches, there is a critical need for additional research which considers the economic and market realities farmers face. Considerable investment must also be made to support the market infrastructure that climate change mitigation opportunities need; necessary investments vary from establishing standard MRV for the voluntary carbon market, to ensuring technology which supports sustainable agriculture (e.g., Happy Seeder) is accessible. Thus far, however, climate finance for climate mitigation is severely lacking, with a financing gap of 66%.[198] This gap is especially large for the Global South; as the Rockefeller Foundation stated in a recent report (2022), "Just as negative climate impacts fall disproportionately on emerging markets and developing economies (EMDEs), so do funding gaps, owing to higher project and sovereign risks." It is thus crucial for actors in this space to push for further climate change mitigation investment in the Global South so we can better equip smallholders to be agents of climate change mitigation, and to direct tangible returns, whether through payments for their environmental services or private agronomic benefits, to participating communities.

8 References

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from the atmosphere. The idea is to stabilize carbon in solid and dissolved forms so that it doesn't cause the atmosphere to warm. The process shows tremendous promise for reducing the human "carbon footprint." There are two main types of carbon sequestration: biological and geological.").

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lifetimes, because it does not consider impacts that happen more than 20 years after the emissions occur. Because all GWPs are calculated relative to CO_2, GWPs based on a shorter timeframe will be larger for gases with lifetimes shorter than that of CO_2, and smaller for gases with lifetimes longer than CO_2. For example, for CH_4, which has a short lifetime, the 100-year GWP of 27–30 is much less than the 20-year GWP of 81–83. For CF_4, with a lifetime of 50,000 years, the 100-year GWP of 7380 is larger than the 20-year GWP of 5300.”).

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low in smallholder subsistence farming. When added to AFOLU emissions, the estimated share of food systems in global anthropogenic emissions is 21–-37%. {5.4.5, Table 5.4}").

32 Paustian K., Larson E., Kent J., Marx E., & Swan A. (2019) *Soil C Sequestration as a Biological Negative Emission Strategy*, Front. Clim. 1–8, 7 ("Despite somewhat different scope (land types included) and assumptions (practices considered), there is fairly close alignment among global estimates (Figure 1), suggesting a technical soil C sequestration potential of 2–5 Gt CO$_2$ per year, for what were characterized in the section above as existing best conservation management practices.").

33 Intergovernmental Panel on Climate Change (2022) *Summary for Policymakers*, in Climate change 2022: impacts, adaptation, and vulnerability, *Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Pörtner H.-O., et al. (eds.), SPM-37 ("AFOLU mitigation options, when sustainably implemented, can deliver large-scale GHG emission reductions and enhanced removals, but cannot fully compensate for delayed action in other sectors. . .Improved and sustainable crop and livestock management, and carbon sequestration in agriculture (the latter including soil carbon management in croplands and grasslands, agroforestry and biochar), can contribute 1.8–4.1 GtCO$_2$-eq yr^{-1} reduction. . .The largest share of this economic potential [4.2–7.4 GtCO$_2$-eq yr^{-1}] comes from the conservation, improved management, and restoration of forests and other ecosystems (coastal wetlands, peatlands, savannas and grasslands), with reduced deforestation in tropical regions having the highest total mitigation.").

34 Kichamu-Wachira E., Xu Z., Reardon-Smith K., Biggs D., Wachira G., & Omidvar N. (2021) *Effects of climate-smart agricultural practices on crop yields, soil carbon, and nitrogen pools in Africa: a meta-analysis*, J. Soils Sediments 21(4): 1587–1597, 1595 ("While our study has quantitatively shown the effect of CSA management on SOC concentration, yield, and soil TN, we were unable to capture enough studies in Africa to test the effect of GM on SOC and soil TN under different conditions and management. Therefore, more research is needed in these areas to highlight the importance of GM on climate mitigation in both the medium term and long term.").

35 Smith P., et al. (2020) *How to measure, report and verify soil carbon change to realize the potential of soil carbon sequestration for atmospheric greenhouse gas removal*, Glob. Change Biol. 26(1): 219–241, 220 ("Furthermore, the reversibility of C sequestration, when practices that retain C are not maintained, or due to climate variability or climate change, increases uncertainty in the time frames needed to monitor SOC enhancement activities (Rumpel et al., 2019).").

36 Seghieri J., Droy I., Hadgu K., & Place F. (2021) *Introduction to the special issue "scaling up of agroforestry innovations: enhancing food, nutrition and income security"* AGROFOR. SYST. , 95(7): 1245–49, 1246. ("Following FAO (2018) and HLPE (2019) recommendations, success of innovation scaling up requires a political commitments including transformations in policies and budgets that are long term and powerful enough to be able to catalyze deep transformations within power relations and land tenure rights that are currently big barriers to widespread adoptions.")

37 Lal R. (2016) *Beyond COP 21: Potential and challenges of the "4 per Thousand" initiative*, J. Soil Water Conserv. 71(1): 20A-25A, 24A ("Adoption of RMPs (e.g., residues retention, covercropping, controlled grazing, converting agriculturally marginal lands to a perennial vegetation cover, and soil amendments) would require financial resources. Cost of additional N, P, and S for C sequestration must also be considered. Payments for soil C sequestration, at a just and fair price equivalent to the societal value of soil C (Lal 2014), would be essential. A protocol must be in place to implement such a scheme, backed by firm commitment of funding support.").

38 Jat M. L., Chakraborty D., Ladha J. K., Rana D. S., Gathala M. K., McDonald A., & Gerard B. (2020) *Conservation agriculture for sustainable intensification in South Asia*, Nat. Sustain. 3(4): 336–343, 336

("Numerous favourable impacts have been reported in the global literature on CA, including for crop yields, resource (labour, water, energy) use efficiencies, timeliness of cropping practices, soil quality and ecosystem services[8–13]. Nevertheless, a meta-analysis of global yield data from 48 crops across 63 countries reported limited yield gains with full CA or with some components of CA14, a result that has drawn into question the wisdom of making CA a sustainable intensification priority for agricultural development programs.").

39 World Bank (2022) STATE AND TRENDS OF CARBON PRICING 2022, Washington, DC ("Carbon credit markets grew 48% in 2021. The total number of credits issued from international, domestic, and independent credit mechanisms increased from 327 million to 478 million.").

40 World Bank (2022) STATE AND TRENDS OF CARBON PRICING 2022, Washington, DC ("For the first time, the total value of the voluntary carbon market exceeded more than USD 1 billion in November 2021.[88]").

41 Science Based Targets (2021) SBTI CORPORATE NET-ZERO STANDARD, 1–64, 8 ("To contribute to societal net-zero goals, companies must deeply reduce emissions and counterbalance the impact of any emissions that remain. The SBTi Net-Zero Standard defines corporate net-zero as: Reducing scope 1, 2, and 3 emissions to zero or to a residual level that is consistent with reaching net-zero emissions at the global or sector level in eligible 1.5°C-aligned pathways Neutralizing any residual emissions at the net-zero target year and any GHG emissions released into the atmosphere thereafter.").

42 Lal R. (2018) *Digging deeper: A holistic perspective of factors affecting soil organic carbon sequestration in agroecosystems*, GLOB. CHANGE BIOL. 24(8): 3285–3301, 3285 ("Thus, sequestration of SOC could be achieved by (i) increasing growth of plants within a land unit, (ii) retaining the plant biomass (above and below ground) within the land unit to be converted into SOC, (iii) protecting and stabilization of the SOC in the land unit against erosion and decomposition, and (iv) enhancing synergisms between soil, plants, and atmospheric processes to create a positive soil/ecosystem C budget until the soil C sink capacity is saturated. The SOC and its management through judicious land use, and soil/crop/livestock management are the crucial parameters of SOC sequestration.").

43 Food and Agriculture Organization of the United Nations, *Conservation Agriculture* (*last visited* 16 November 2022) ("Conservation Agriculture is a farming system that promotes minimum soil disturbance (i.e. no tillage), maintenance of a permanent soil cover, and diversification of plant species. It enhances biodiversity and natural biological processes above and below the ground surface, which contribute to increased water and nutrient use efficiency and to improved and sustained crop production.").

44 World Agroforestry, *What is Agroforestry?* (*last visited* 23 January 2023) ("Agroforestry is the interaction of agriculture and trees, including the agricultural use of trees. This comprises trees on farms and in agricultural landscapes, farming in forests and along forest margins and tree-crop production, including cocoa, coffee, rubber and oil palm.").

45 Zomer R. J., Neufeldt H., Xu J., Ahrends A., Bossio D., Trabucco A., van Noordwijk M., & Wang M. (2016) *Global Tree Cover and Biomass Carbon on Agricultural Land: The contribution of agroforestry to global and national carbon budgets*, SCI. REP. 6(1): 29987, 1–12, 1 ("Remote sensing data show that in 2010, 43% of all agricultural land globally had at least 10% tree cover and that this has increased by 2% over the previous ten years.").

46 Gwenzi W., Chaukura N., Mukome F. N. D., Machado S., & Nyamasoka B. (2015) *Biochar production and applications in sub-Saharan Africa: Opportunities, constraints, risks and uncertainties*, J. ENVIRON. MANAGE. 150: 250–261, 251 ("Biochar, a carbonized solid by-product of bioenergy production through high-temperature pyrolysis or degasification of organic material under low oxygen conditions, has garnered research attention in recent years.").

47 Gwenzi W., Chaukura N., Mukome F. N. D., Machado S., & Nyamasoka B. (2015) *Biochar production and applications in sub-Saharan Africa: Opportunities, constraints, risks and uncertainties*, J. Environ. Manage. 150: 250–261, 251 ("The choice of feedstock biomass for biochar production depends on local availability of material and cost of acquisition including haulage costs. Feedstocks in Zimbabwe and other countries in SSA include crop residues, manure, wood wastes from forestry, wastes from agro-processing industries, aquatic weeds and municipal solid wastes and sewage sludge.").

48 Lal R. (2011) *Soil carbon sequestration SOLAW Background Thematic Report- TR04B*, Food and Agriculture Organization of the United Nations, 1–36, 9 ("Transfer of atmospheric CO_2 into the pedologic pools by use of judicious management of soils and vegetation, involves numerous agronomic interactions. Principal agronomic techniques include: reduction or elimination of mechanical tillage and adoption of no-till (NT) or minimum till; use of crop residues or synthetic materials as surface mulch in conjunction with incorporation of cover crops into the rotation cycle; adoption of conservation-effective measures to minimize soil and water losses by surface runoff and accelerated erosion bioengineering; enhancement of soil fertility through integrated nutrient management (INM) that combines practices for improving organic matter management (in situ), enhancing soil biological processes involving biological nitrogen fixation (BNF), and mycorrhizae, and additions of organic wastes (biosolids, slurry) and synthetic fertilizers; conservation of water in the root zone to increase the green water component by reducing losses through runoff (blue water) and evaporation (grey water), and increasing use efficiency through application of drip irrigation/fertigation techniques; improvement of grazing systems that enhance the diet of livestock and reduce their enteric emissions; and better use of complex farming systems including mixed crop-livestock and agroforestry techniques that efficiently use resources, enhance biodiversity and mimic the natural ecosystems.").

49 Zingore S., Mutegi J., Agesa B., Tamene L. D., & Kihara J. (2015) *Soil degradation in sub-Saharan Africa and crop production options for soil rehabilitation*, Better Crops Plant Food 99(1): 24–26, 26 ("Integrated soil fertility management (ISFM) provides a framework where both organic and inorganic fertilizers can be provided to the soils to improve soil fertility and boost soil organic C (Vanlauwe et al., 2010). Among the common ISFM practices in SSA are intercropping and rotation of cereals with legumes, manure application, and application of both organic and inorganic materials either simultaneously or sequentially to the same crops. The inclusion of legumes in cereal systems allows cereals to benefit from the N that is fixed by legumes. This enables better crop production, enhancement of soil fertility, and availability of more above and belowground biomass for transfer to the croplands.").

50 Giller K. E., Witter E., Corbeels M., & Tittonell P. (2009) *Conservation agriculture and smallholder farming in Africa: The heretics' view*, Field Crops Res. 114(1): 23–34, 26 ("We conclude therefore that although introduction of CA can result in yield benefits in the long-term, in the short-term (and this may be up to nearly 10 years! – see Fig. 1) yield losses or no yield benefits are just as likely.").

51 Matthews H. D., Zickfeld K., Dickau M., MacIsaac A. J., Mathesius S., Nzotungicimpaye C.-M., & Luers A. (2022) *Temporary nature-based carbon removal can lower peak warming in a well-below 2 °C scenario*, Commun. Earth Environ. 3(1): 65, 1–8, 2 ("However, the permanence of carbon storage in natural ecosystems cannot in reality be guaranteed, given its vulnerability to both human-driven (e.g., deforestation or other land-use change) and climate-related (e.g., wildfire, drought, or insect) disturbances that could occur at any time in the foreseeable or unforeseeable future.").

52 Smith P. (2005) *An overview of the permanence of soil organic carbon stocks: influence of direct human-induced, indirect and natural effects*, Eur. J. Soil Sci. 56(5): 673–680, 674 ("If a land-management or land-use change is reversed or discontinued, the C accumulated will be lost, usually more rapidly than it was accumulated.").

53 Matthews H. D., Zickfeld K., Dickau M., MacIsaac A. J., Mathesius S., Nzotungicimpaye C.-M.,

& Luers A. (2022) *Temporary nature-based carbon removal can lower peak warming in a well-below 2 °C scenario*, Commun. Earth Environ. 3(1): 65, 1–8, 5 ("Our results show that successful carbon sequestration via NbCS can have climate benefit, even in the case that the carbon storage is temporary such that the stored carbon is returned to the atmosphere later this century. However, the most important climate benefit—a decrease in the level of peak warming—is only realized in a scenario where fossil fuel CO_2 emissions are decreased rapidly to net-zero, resulting in global temperatures that peak and decline during the time period that NbCS-stored carbon remains sequestered in nature.").

54 Food and Agriculture Organization of the United Nations (2005) *Chapter 2* in The importance of soil organic matter: Key to drought-resistant soil and sustained food production ("During the decomposition process, microorganisms convert the carbon structures of fresh residues into transformed carbon products in the soil.").

55 Beauchamp E. G. (1997) *Nitrous oxide emission from agricultural soils*, Can. J. Soil Sci. 77(2): 113–123, 114 ("Denitrification is an anaerobic process carried out by mainly facultative heterotrophic bacteria and is dependent on organic C and NO_3 – (or other N oxides) concentrations.").

56 Gougoulias C., Clark J. M., & Shaw L. J. (2014) *The role of soil microbes in the global carbon cycle: tracking the below-ground microbial processing of plant-derived carbon for manipulating carbon dynamics in agricultural systems*, J. Sci. Food Agric. 94(12): 2362–2371, 2364 ("Hence the availability of other key elements essential for life, particularly N and P, and other environmental factors such as pH, soil texture and mineralogy, temperature and soil water content control the rate at which microbes consume and respire carbon.").

57 University of Minnesota Extension, *Understanding nitrogen in soils* (*last visited* 18 December 2022) ("Immobilization, or the tie up of soil N, can temporarily reduce the amount of plant-available N. Bacteria that decompose high-carbon, low-N residues, such as corn stalks or small grain straw, need more N to digest the material than is present in the residue.").

58 Lugato E., Leip A., & Jones A. (2018) *Mitigation potential of soil carbon management overestimated by neglecting N_2O emissions*, Nat. Clim. Change 8(3): 219–223, 22 ("While existing data on C sequestration in agricultural soils are focusing on the C cycle, we showed that agricultural practices introducing additional N can potentially turn the agroecosystems to a net GHG source[28] in the long term.").

59 Chivenge P., Sharma S., Bunquin M. A., & Hellin J. (2021) *Improving Nitrogen Use Efficiency—A Key for Sustainable Rice Production Systems*, Front. Sustain. Food Syst. 5: 737412. 7 ("Our mini-review clearly shows that SSNM in rice cropping systems increases rice yield, profit, and N use efficiency while reducing N losses and GHG emissions when compared with the farmer practice.").

60 Olson K. R., Al-Kaisi M. M., Lal R., & Lowery B. (2014) *Experimental Consideration, Treatments, and Methods in Determining Soil Organic Carbon Sequestration Rates*, Soil Sci. Soc. Am. J. 78(2): 348–360, Table 1.

61 Stewart C. E., Paustian K., Conant R. T., Plante A. F., & Six J. (2007) *Soil carbon saturation: concept, evidence and evaluation*, Biogeochemistry 86(1): 19–31, 20 ("This lack of response in SOC levels to varying levels of C input, over many years, and the apparent dependency between C stabilization efficiency and soil C content, suggests the possibility of an upper limit or 'saturation level' for soil carbon (Six et al. 2002).").

62 Chenu C., Angers D. A., Barré P., Derrien D., Arrouays D., & Balesdent J. (2019) *Increasing organic stocks in agricultural soils: Knowledge gaps and potential innovations*, Soil Tillage Res. 188: 41–52, 45 ("The carbon storage potential of a soil may be defined as the maximum gain in soil OC stock attainable under a given climate, soil type and timeline (e.g. time required to attain a new stock after IPCC time period: 20 y, or a new equilibrium).").

63 Liu C., Lu M., Cui J., Li B., & Fang C. (2014) *Effects of straw carbon input on carbon dynamics in agricultural soils: a meta-analysis*, Glob. Change Biol. 20(5): 1366–1381, 1376 ("A soil with a low initial soil C content has a large saturation deficit that lead to a faster initial C sequestration rate and a longer total duration to reach the same C saturation (West & Six, 2007). Duration of C sequestration has a significant impact on soil C saturation, as longer duration favoring straw C to transform into SOC. Our study revealed that 12 years on average were required for the soil to reach C saturation (or a steady state of C) under continuous straw return.").

64 Ashton M. S., Tyrrell M. L., Spalding D., & Gentry B. (Eds.) (2012) Managing Forest Carbon in a Changing Climate, Springer Netherlands: Dordrecht 1, 1– 414, 389 ("The amount of carbon retained in an ecosystem (increase in biomass); it is equal to the difference between the amount of carbon produced through photosynthesis (GPP) and the amount of energy that is used for respiration (R).")

65 Hertel T. W., Ramankutty N., & Baldos U. L. C. (2014) *Global market integration increases likelihood that a future African Green Revolution could increase crop land use and CO2 emissions*, Proc. Nat'l. Acad. Sci. 111(38): 13799–13804, 13799 ("One side of the debate is best characterized by Norman Borlaug's assertion that agricultural innovation is land sparing. In other words, Borlaug argued that intensifying agricultural production is better for the environment overall because the same amount of food could be produced using less land, thereby sparing land for nature.").

66 Griscom B. W., et al. (2017) *Natural climate solutions*, Proc. Nat'l. Acad. Sci. 114(44): 11645–11650, 11648 ("Forest pathways offer over two-thirds of cost-effective NCS mitigation needed to hold warming to below 2 °C and about half of low-cost mitigation opportunities (SI Appendix, Table S4)."). *See also* Goldstein A., et al. (2020) *Protecting irrecoverable carbon in Earth's ecosystems*, Nat. Clim. Change 10(4): 287–295, 287 ("Here, we show that a range of ecosystems contain 'irrecoverable carbon' that is vulnerable to release upon land use conversion and, once lost, is not recoverable on timescales relevant to avoiding dangerous climate impacts. Globally, ecosystems highly affected by human land-use decisions contain at least 260 Gt of irrecoverable carbon, with particularly high densities in peatlands, mangroves, old-growth forests and marshes.").

67 Rudel T. K., Schneider L., Uriarte M., Turner B. L., DeFries R., Lawrence D., Geoghegan J., Hecht S., Ickowitz A., Lambin E. F., Birkenholtz T., Baptista S., & Grau R. (2009) *Agricultural intensification and changes in cultivated areas, 1970–2005*, Proc. Nat'l. Acad. Sci. 106(49): 20675–20780, 20678 ("In most countries yields increased, but cultivated areas did not decline. This pattern raises questions about the ability of agricultural intensification to spare land, at least through declines in cultivated areas.").

68 Dhanda S., Yadav A., Yadav D. B., & Chauhan B. S. (2022) *Emerging Issues and Potential Opportunities in the Rice–Wheat Cropping System of North-Western India*, Front. Plant Sci., 13: 832683, 1–14, 2 ("Rice and wheat are the exhaustive cereal crops that lead to a heavy depletion of soil nutrients, and the problem is further aggravated when farmers burn the rice crop residue left in their fields after mechanized harvesting. The left-over rice residue in the fields interferes with tillage and sowing operations of the successive wheat crop; therefore, farmers usually prefer to burn rice residue. About 2 M farmers in the northwest and some parts of eastern India burn an estimated 23 mt of rice residue every year (NAAS, 2017).").

69 Amorim H. C. S., Ashworth A. J., Brye K. R., Wienhold B. J., Savin M. C., Owens P. R., & Silva S. H. G. (2021) *Soil quality indices as affected by long-term burning, irrigation, tillage, and fertility management*, Soil Sci. Soc. Am. J. 85(2): 379–395, 385 ("Conversely, burning crop residues reduces the amount of plant material returned to the soil, which may lead to a decrease in SOM and SOC over time compared with soils under no-burning management (Norman et al., 2016).").

70 Ravindra K., Singh T., & Mor S. (2019) *Emissions of air pollutants from primary crop residue burning in India and their mitigation strategies for cleaner emissions*, J. Clean. Prod. 208, 261–273, 261 ("The uncontrolled burning of crop residue leads to atmospheric emissions of various pollutants such as Particulate matter (PM$_{10}$, PM$_{2.5}$), Carbon monoxide (CO), Carbon dioxide (CO$_2$), Sulphur dioxide (SO$_2$), Oxides of nitrogen (NO$_x$), Ammonia (NH$_3$), Methane (CH$_4$), Elemental Carbon (EC), Organic Carbon (OC), Volatile Organic Compounds (VOCs), Polycyclic Aromatic Hydrocarbons (PAHs) as reported by Awasthi et al. (2011); Jain et al. (2014) for India; Zhang et al. (2018) for China and Oanh et al. (2018) for south-east Asia.").

71 Cho R. (22 March 2016) *The Damaging Effects of Black Carbon*, Columbia Climate School ("A major constituent of soot, black carbon is the most solar energy-absorbing component of particulate matter and can absorb one million times more energy than CO2."; Because black carbon absorbs solar energy, it warms the atmosphere. When it falls to earth with precipitation, it darkens the surface of snow and ice, reducing their albedo (the reflecting power of a surface), warming the snow, and hastening melting.").

72 Li C., Bosch C., Kang S., Andersson A., Chen P., Zhang Q., Cong Z., Chen B., Qin D., & Gustafsson Ö. (2016) *Sources of black carbon to the Himalayan–Tibetan Plateau glaciers*, Nat. Commun. 7(1): 12574 1–7, 5 ("Taken together, the Δ^{14}C/δ^{13}C-BC signals further decipher the sources of BC across the TP, revealing an approximately equal influence of biomass combustion sources within the southern TP/Himalayas that mainly stem from emissions from the IGP." *And* "The long-range transport to and deposition of BC aerosols in the TP is attracting considerable attention because of BC's effects on the transformation of hydrological and radiative forcing in the East and South Asian regions. In addition, BC aerosols are believed to play a considerable role in the melting of mid-latitude glaciers because of both the heating of aloft air masses transported into the TP and the albedo effects of deposited BC.").

73 Nair M., Bherwani H., Mirza S., Anjum S., & Kumar R. (2021) *Valuing burden of premature mortality attributable to air pollution in major million-plus non-attainment cities of India*, Sci. Rep. 11(1): 22771, 1–15, 14 ("PM$_{2.5}$ attributable total premature mortality cases were estimated to be 80,447, resulting in a total economic loss of about 90,185 million US$ for the year 2017.").

74 Shyamsundar P., et al. (2019) *Fields on fire: Alternatives to crop residue burning in India*, Science 365(6453): 536–538, 536 ("Regulations are in place to reduce agricultural fires, but burning continues because of uncertainty regarding policy implementation and regarding access and returns to alternative technologies.").

75 Dutta T. (28 Nov 2021) *India's farmers happy as ban on smoky stubble burning repealed*, The National News ("Stubble-burning, which involves farmers setting fire to leftover rice straw, was banned by an environmental court in 2015."; "The farmers' demand was to decriminalise stubble-burning. The Government of India has agreed to this demand," Agriculture Minister Narendra Singh Tomar told an Indian news agency.").

76 Liu T., Mickley L. J., Singh S., Jain M., DeFries R. S., & Marlier M. E. (2020) *Crop residue burning practices across north India inferred from household survey data: Bridging gaps in satellite observations*, Atmospheric Environ. X 8 100091, 1–13, 7 ("Relative to Punjab, the more recent adoption of crop residue burning at the household-level in Haryana, Bihar, and UP, along with the current low rate of burning (12–46%) among survey households in these states, suggests high potential growth in agricultural fire activity (Fig. 1a, Table S4). For example, assuming a future scenario in which all households across the IGP harvest rice mechanically, the rate of crop residue burning in terms of landholding area would increase by just 2–27% in Punjab and Haryana, compared to 2016–2017, but by 67–207% in UP and Bihar (Table S4).").

77 McDonald A. J., et al. (2020) *Indian agriculture, air pollution, and public health in the age of COVID*, World Dev. 135: 105064, 1–2, 1 ("As India plans an ambitious economic stimulus package to buttress the economy from the fallout of COVID-19, new strategies like providing cash incentives to farmers to forego residue burning (i.e. payments for ecosystem and public health services) may help jumpstart markets for sustainable production technologies and appropriately incentivize crop diversification. Every crisis presents an opportunity for positive change; there is no time like the pre- sent to make open agricultural burning a relic of the past in India.").

78 Shyamsundar P., et al. (2019) *Fields on fire: Alternatives to crop residue burning in India*, Science 365(6453): 536–538, 538 ("Scaling adoption in the initial stages to ~50% of the rice-wheat cropped area will require some ~16,000 Happy Seeder machines (see table S13 for alternative scenarios). This would entail an investment of ~INR 2.4 billion (~US $34.5 million), which is less than one-quarter of the subsidy currently allocated to finance residue management.").

79 Singh J. (21 Dec 2019) *Pest attack on wheat sown using stubble management machine*, The Times of India ("Yamunanagar: A Yamunanagar farmer has complained of a pest attack on his wheat crop, which was sown after managing paddy stubble through mulching of residue. Mohan Lal of Kandrauli village said pink stem borer and bollworm had damaged 10 acres of the 26 acres of wheat he had sown. He said he mulched paddy residue in 16 acres and sown wheat using Happy Seeder. 'Of the 16 acres, 10 acres have been attacked by pests. Paddy residue is becoming a breeding ground for pests and three acres of wheat are severely damaged.'").

80 Rathore V. (22 Oct 2021) *The Hits and Misses of the Pusa Capsule, the Delhi Government's Solution to Stubble Burning*, The Bastion ("Since many fields in Jhuljhuli are low-lying, waterlogging in the fields is an annual occurrence in the village. But, this year has been worse than the last few. Jitender, Deepak Yadav's brother, questions if perhaps it is this geography and the fields' high water content that could explain their unsuccessful trial with the Pusa decomposer last year. 'Maybe the capsule requires certain moisture, temperature, and soil conditions to successfully decompose stubble. The high moisture content of our fields might not have been conducive,' he says. 'But, we are not sure of this, because there was no information provided to us on how to use the mixture and in what conditions.'").

81 Aquino D., Del Barrio A., Trach N. X., Hai N. T., Khang D. N., Toan N. T., & Van Hung N. (2020) *Rice Straw-Based Fodder for Ruminants*, in Sustainable Rice Straw Management, Gummert M., Hung N. V., Chivenge P., & Douthwaite B. (eds.), Springer International Publishing: Cham, 1–175, 8 ("Rice straw has low nutritional value (low protein content and poor digestibility) compared to grasses, thus it cannot support the nutrients required by high-yielding milk cows and buffaloes.").

82 Shyamsundar P., et al. (2019) *Fields on fire: Alternatives to crop residue burning in India*, Science 365(6453): 536–538, 538 ("The main market for baled residue is a small number of power plants in the state of Punjab that use residue to produce 0.5% of the state's electricity.").

83 Jack B. K., Jayachandran S., Kala N., & Pande R. (2022) *Money (Not) to Burn: Payments for Ecosystem Services to Reduce Crop Residue Burning*, National Bureau of Economic Research 30690, 1–38, 24–25. ("We show that crop residue burning, which has significant environmental and human health costs, can be reduced through well-designed PES payments. In particular, program design that takes institutional constraints and farmer concerns into account can significantly improve efficacy. Providing a portion of the contract payment upfront results in larger reductions in burning than providing the entire payment after participants have completed costly behavior change. Despite higher "wasted" payments (to farmers who continue to burn), PES with upfront payments is cost effective, resulting in burning reductions that provide benefits far in excess of their cost.").

84 Food and Agriculture Organization of the United Nations, *Conservation Agriculture* (*last visited* 16

November 2022) ("Conservation Agriculture (CA) is a farming system that can prevent losses of arable land while regenerating degraded lands. It promotes maintenance of a permanent soil cover, minimum soil disturbance, and diversification of plant species.").

85 Pilling D., & Bélanger J. (eds.) (2019) THE STATE OF THE WORLD'S BIODIVERSITY FOR FOOD AND AGRICULTURE, Food and Agriculture Organization of the United Nations Commission on Genetic Resources for Food and Agriculture: Rome. 572 pp, 258 ("Most of the countries that provide information on conservation agriculture indicate that the practice has a positive effect on BFA in terms of both taxonomic diversity and population abundance. This is perceived to be the case in all production systems where the practice is applied.") *and* ("The implementation of conservation agriculture leads to significant improvements in soil biological, physical and chemical properties, resulting in improved soil structure and aggregate stability. Soil mulch cover with crop residues increases soil organic matter and carbon sequestration, which contributes to climate change mitigation. Conservation agriculture also augments water-infiltration and water retention capacity, and reduces runoff and direct evaporation from the soil, thus improving the efficiency of water use and the quality of water resources. Conservation agriculture is therefore increasingly being recognized as climate smart.").

86 Food and Agriculture Organization of the United Nations, *Species diversification* (*last visited* 16 November 2022). ("Furthermore, a diversity of crops in rotation leads to a diverse soil flora and fauna, as the roots excrete different organic substances that attract different types of bacteria and fungi, which in turn, play an important role in the transformation of these substances into plant available nutrients. Crop rotation also has an important phytosanitary function as it prevents the carry-over of crop-specific pests and diseases from one crop to the next.").

87 Food and Agriculture Organization of the United Nations, *Minimum mechanical soil disturbance* (*last visited* 16 November 2022). ("Direct seeding involves growing crops without mechanical seedbed preparation and with minimal soil disturbance since the harvest of the previous crop. The term direct seeding is understood in CA systems as synonymous with no-till farming, zero tillage, no-tillage, direct drilling, etc. Planting refers to the precise placing of large seeds (maize and beans for example); whereas seeding usually refers to a continuous flow of seed as in the case of small cereals (wheat and barley for example). The equipment penetrates the soil cover, opens a seeding slot and places the seed into that slot. The size of the seed slot and the associated movement of soil are to be kept at the absolute minimum possible. Ideally the seed slot is completely covered by mulch again after seeding and no loose soil should be visible on the surface.").

88 Food and Agriculture Organization of the United Nations, *Soil organic cover* (*last visited* 17 November 2022). ("While commercial crops have a market value, cover crops are mainly grown for their effect on soil fertility or as livestock fodder. In regions where smaller amounts of biomass are produced, such as semi-arid regions or areas of eroded and degraded soils, cover crops are beneficial as they: Protect the soil during fallow periods. Mobilize and recycle nutrients. Improve the soil structure and break compacted layers and hard pans. Permit a rotation in a monoculture. Can be used to control weeds and pests. Cover crops are grown during fallow periods, between harvest and planting of commercial crops, utilizing the residual soil moisture. Their growth is interrupted either before the next crop is sown, or after sowing the next crop, but before competition between the two crops starts. Cover crops energize crop production, but they also present some challenges. Cover crops are useful for: Protecting the soil, when it does not have a crop. Providing an additional source of organic matter to improve soil structure. Recycling nutrients (especially P2O5 and K2O) and mobilizing them in the soil profile in order to make them more readily available to the following crops. Provide "biological tillage" of the soil; the roots of some crops, especially cruciferous crops, like oil radish are pivotal and able to penetrate compacted or very dense layers, increasing water percolation capacity of the soil. Utilizing easily leached nutrients (especially N).").

89 Food and Agriculture Organization of the United Nations, *Species diversification* (*last visited* 16 November 2022). ("The rotation of crops is not only necessary to offer a diverse "diet" to the soil micro-organisms, but as they root at different soil depths, they are capable of exploring different soil layers for nutrients. Nutrients that have been leached to deeper layers and that are no longer available for the commercial crop, can be "recycled" by the crops in rotation. This way the rotation crops function as biological pumps. Furthermore, a diversity of crops in rotation leads to a diverse soil flora and fauna, as the roots excrete different organic substances that attract different types of bacteria and fungi, which in turn, play an important role in the transformation of these substances into plant available nutrients. Crop rotation also has an important phytosanitary function as it prevents the carry-over of crop-specific pests and diseases from one crop to the next. The effects of crop rotation: Higher diversity in plant production and thus in human and livestock nutrition. Reduction and reduced risk of pest and weed infestations. Greater distribution of channels or biopores created by diverse roots (various forms, sizes and depths). Better distribution of water and nutrients through the soil profile. Exploration for nutrients and water of diverse strata of the soil profile by roots of many different plant species resulting in a greater use of the available nutrients and water. Increased nitrogen fixation through certain plant-soil biota symbionts and improved balance of N/P/K from both organic and mineral sources. Increased humus formation.").

90 Jat M. L., Chakraborty D., Ladha J. K., Rana D. S., Gathala M. K., McDonald A., & Gerard B. (2020) *Conservation agriculture for sustainable intensification in South Asia*, Nat. Sustain. 3(4): 336–343, 338 ("The on-station data revealed methane reductions of 12.8% in CA1 and 75.2% in CA2…By contrast, there were no changes in nitrous oxide emissions.").

91 Kichamu-Wachira E., Xu Z., Reardon-Smith K., Biggs D., Wachira G., & Omidvar N. (2021) *Effects of climate-smart agricultural practices on crop yields, soil carbon, and nitrogen pools in Africa: a meta-analysis*, J. Soils Sediments 21(4): 1587–1597, 1590 ("Overall, SOC concentration significantly increased under all the three CSA practices by 14.7% compared to their controls (Fig. 1b). Conservation tillage increased SOC concentration by 16.4%, while CR increased SOC concentration by 13%. No significant difference was apparent in SOC from GM; this result could be attributed to the number of years the practice was implemented in the studies analyzed (1 year).").

92 Kichamu-Wachira E., Xu Z., Reardon-Smith K., Biggs D., Wachira G., & Omidvar N. (2021) *Effects of climate-smart agricultural practices on crop yields, soil carbon, and nitrogen pools in Africa: a meta-analysis*, J. Soils Sediments 21(4): 1587–1597, 1593 ("Our study also supports the previously reported claim that the use of conservation tillage (i.e., no tillage and reduced tillage) as a stand-alone management practice has no significant impact on yields compared to conventional management (Ogle et al. 2019; Corbeels et al. 2020)") *and* ("The integration of CSA practices promotes climate mitigation and adaptation due to their enhancement of soil quality and crop yield. For instance, our study indicates that incorporating conservation tillage with either GM or CR improved both SOC concentration and yield, likely due to the synergistic effects resulting from the added organic matter and minimal soil disturbance (Liu et al. 2014; Garcia-Franco et al. 2015; Jat et al. 2019; Zhang et al. 2019).").

93 Bai X., Huang Y., Ren W., Coyne M., Jacinthe P., Tao B., Hui D., Yang J., & Matocha C. (2019) *Responses of soil carbon sequestration to climate-smart agriculture practices: A meta-analysis*, Glob. Change Biol. 25(8): 2591–2606, 2591, 2612 ("We found that, on average, biochar applications represented the most effective approach for increasing SOC content (39%), followed by cover crops (6%) and conservation tillage (5%).") *and* ("In addition, some CSA management practices may promote nitrous oxide or methane emissions (e.g., Huang et al., 2018; Kessel et al., 2013; Six, Ogle, Conant, Mosier, & Paustian, 2004; Spokas & Reicosky, 2009), which, to some extent, would offset their benefit on climate change mitigation. Therefore, evaluating the CSA effects should also include non-CO2 greenhouse gases such as nitrous oxide and methane. We call for field experiments that can fully examine key indicators

(such as soil carbon and greenhouse gases) in response to single and combined CSA management practices.”).

94 Kichamu-Wachira E., Xu Z., Reardon-Smith K., Biggs D., Wachira G., & Omidvar N. (2021) *Effects of climate-smart agricultural practices on crop yields, soil carbon, and nitrogen pools in Africa: a meta-analysis*, J. Soils Sediments 21(4): 1587–1597, 1587 (“Conservation tillage and CR increased SOC by 16.4% and 13%, respectively, but no significant difference was observed with GM. Further analysis suggested that integrating CSA practices (conservation tillage and GM; conservation tillage and CR) had a more pronounced effect on both SOC concentration and yield under lower nitrogen fertilizer levels.”).

95 Pittelkow C. M., Liang X., Linquist B. A., van Groenigen K. J., Lee J., Lundy M. E., van Gestel N., Six J., Venterea R. T., & van Kessel C. (2015) *Productivity limits and potentials of the principles of conservation agriculture*, Nature 517(7534): 365–368, 1 (“The largest yield declines occur when no-till is implemented alone (29.9%) or with only one other conservation agriculture principle (25.2 and 26.2% for residue retention and crop rotation, respectively).”).

96 Pittelkow C. M., Liang X., Linquist B. A., van Groenigen K. J., Lee J., Lundy M. E., van Gestel N., Six J., Venterea R. T., & van Kessel C. (2015) *Productivity limits and potentials of the principles of conservation agriculture*, Nature 517(7534): 365–368, 365 (“The largest yield declines occur when no-till is implemented alone (-9.9%) or with only one other conservation agriculture principle (-5.2 and -6.2% for residue retention and crop rotation, respectively).”).

97 Pittelkow C. M., Liang X., Linquist B. A., van Groenigen K. J., Lee J., Lundy M. E., van Gestel N., Six J., Venterea R. T., & van Kessel C. (2015) *Productivity limits and potentials of the principles of conservation agriculture*, Nature 517(7534): 365–368, 365 (“To help close the yield gap with conventional tillage, these findings suggest that instead of implementing no-till as the first step towards conservation agriculture in cropping systems where residue retention and crop rotation are absent (and anticipating that these two principles will follow in time), the primary focus should be on implementing no-till systems that already employ the other two principles.”).

98 Jat M. L., Chakraborty D., Ladha J. K., Rana D. S., Gathala M. K., McDonald A., & Gerard B. (2020) *Conservation agriculture for sustainable intensification in South Asia*, Nat. Sustain. 3(4): 336–343, 339 (“Table 2 | Comparison (percentage change over control) of grain yield, PEY, water use efficiency and net economic return among different CA practices under the rice–wheat, maize–wheat and rice–maize cropping systems”).

99 Corbeels M., Naudin K., Whitbread A. M., Kühne R., & Letourmy P. (2020) *Limits of conservation agriculture to overcome low crop yields in sub-Saharan Africa*, Nat. Food 1(7): 447–454, 447 (“Through a meta-analysis of 933 observations from 16 different countries in sub-Saharan African studies, we show that average yields under CA are only slightly higher than those of conventional tillage systems (3.7% for six major crop species and 4.0% for maize).”) *and* (“When all three CA principles are implemented (RT+M+IR), the CA effect more than doubled (8.4%, CI: [6.1,10.8], P<0.0001) (Fig. 3).”).

100 Jat M. L., Chakraborty D., Ladha J. K., Rana D. S., Gathala M. K., McDonald A., & Gerard B. (2020) *Conservation agriculture for sustainable intensification in South Asia*, Nat. Sustain. 3(4): 336–343, 340 (“Since the benefits of partial adoption of CA practices are consistently observed in the cereal-based cropping systems in South Asia, rigid adherence to an ‘all or nothing’ approach to scaling CA does not seem warranted.”).

101 Keil A., D’souza A., & McDonald A. (2015) *Zero-tillage as a pathway for sustainable wheat intensification in the Eastern Indo-Gangetic Plains: does it work in farmers’ fields?*, Food Secur. 7(5): 983–1001, 983 (“In contrast to the global meta-analysis, we found that the prevailing ZT practices without full

residue retention led to a robust yield gain over conventional-tillage wheat across different agro-ecological zones, amounting to 498 kg ha^{-1} (19 %), on average.") *see also* Keil A., Mitra A., McDonald A., & Malik R. K. (2020) *Zero-tillage wheat provides stable yield and economic benefits under diverse growing season climates in the Eastern Indo-Gangetic Plains*, INT. J. AGRIC. SUSTAIN. 18(6): 567–593, 585 ("Calculating the difference between the estimated counterfactual yield ($Outcome_{pot}$) and the sum of the counterfactual yield plus the estimated ATE[15] in the 'Overall' model, the ATE translates into a yield gain of 660 kg ha^{-1} or 32.1%.").

102 Jat M. L., Chakraborty D., Ladha J. K., Rana D. S., Gathala M. K., McDonald A., & Gerard B. (2020) *Conservation agriculture for sustainable intensification in South Asia*, NAT. SUSTAIN. 3(4): 336–343, 339 ("However, the net economic return was 40.5% higher in CA3 compared with around 20% in CA1 and 26% in CA2, suggesting that a full or close to full extent of CA would maximize the economic benefits, which is an important consideration in the farmers' decision making."

103 Jat M. L., Chakraborty D., Ladha J. K., Rana D. S., Gathala M. K., McDonald A., & Gerard B. (2020) *Conservation agriculture for sustainable intensification in South Asia*, NAT. SUSTAIN. 3(4): 336–343, 339 ("The CA practices tend to perform best for upland crops (for example, maize, wheat) and non-rice cropping systems, a result consistent with earlier findings in South Asia. Higher yield (grain as well as protein) gains with CA in maize–wheat than in the rice-based system provide ample opportunity for much-needed diversification.").

104 Jat M. L., Chakraborty D., Ladha J. K., Rana D. S., Gathala M. K., McDonald A., & Gerard B. (2020) *Conservation agriculture for sustainable intensification in South Asia*, NAT. SUSTAIN., 3(4): 336–343, 339 ("All the crops, including rice, had higher average yields in loam than in clay or sand.").

105 Giller K. E., Witter E., Corbeels M., & Tittonell P. (2009) *Conservation agriculture and smallholder farming in Africa: The heretics' view*, FIELD CROPS RES. 114(1): 23–34, 27 ("We therefore conclude that in the short-term and without the use of herbicides, which will be the case for most smallholder farmers, CA is unlikely to result in significant net savings in total labour requirements while it may increase the labour burden for women. In the long-term, and with the use of herbicides net savings appear to be possible.").

106 Giller K. E., Witter E., Corbeels M., & Tittonell P. (2009) *Conservation agriculture and smallholder farming in Africa: The heretics' view*, FIELD CROPS RES. 114(1): 23–34, 25 ("While benefits of CA are most directly attributed to the mulch of crop residues retained in the field, limited availability of crop residues is under many farming conditions an important constraint for adoption of CA practices." *and* "Further intensification of livestock production in order to improve household income means an increased demand for feed, posing a new claim on the crop residues produced.").

107 Giller K. E., Witter E., Corbeels M., & Tittonell P. (2009) *Conservation agriculture and smallholder farming in Africa: The heretics' view*, FIELD CROPS RES. 114(1): 23–34, 25 ("In practice farmers have been found to not adopt all principles of CA due to various reasons such as limited access to inputs (herbicides, cover crop seeds), labour constraints, or insufficient resources to grow cash crops (see e.g. Baudron et al., 2007; Shetto and Owenya, 2007; Kaumbutho and Kienzle, 2007).").

108 Giller K. E., Witter E., Corbeels M., & Tittonell P. (2009) *Conservation agriculture and smallholder farming in Africa: The heretics' view*, FIELD CROPS RES. 114(1): 23–34, 23 ("CA is said to increase yields, to reduce labour requirements, improve soil fertility and reduce erosion. Yet empirical evidence is not clear and consistent on many of these points nor is it always clear which of the principles of CA contribute to the desired effects.").

109 Giller K. E., Witter E., Corbeels M., & Tittonell P. (2009) *Conservation agriculture and smallholder farming in Africa: The heretics' view*, FIELD CROPS RES. 114(1): 23–34, 31 ("The number of changes in

farming practice required to implement CA can be substantial, whereas the benefits of the changes are likely to be household specific (Erenstein, 1999). Consequently, the private returns to adopting CA are likely to vary between farm households. Farmers in SSA often attribute a substantially higher value to immediate costs and benefits than those incurred or realised in the future due to the constraints of production and food security that they face. Yet, while farmers seek substantial, visible and immediate benefits when considering adoption of CA practices (FAO, 2008b), many of the benefits of employing CA are only realised in the longer term.").

110 Park M. S., Baral H., & Shin S. (2022) *Systematic Approach to Agroforestry Policies and Practices in Asia*, Forests 13(5): 635, 1–7, 1 ("According to a World Agroforestry Centre (ICRAF) working paper, agroforestry covers around one billion hectares or 43% of agricultural lands globally, and involves more than 900 million people. In Asia, agroforestry has played a critical role in local livelihoods since ancient times. If defined as being more than 10% tree cover on agricultural land, agroforestry covers 77.80% of all such land in Southeast Asia, 50.50% in East Asia, 27% in South Asia and 23.60% in Northern and Central Asia.").

111 Food and Agriculture Organization of the United Nations, *Forest and landscape restoration and agroforestry help diversify livelihoods and landscapes and increase land productivity* (*last visited* 18 October 2022) ("Agroforestry is a land-use system that involves the use of perennial woody species with agricultural crops or livestock in a given space and over a given period. The three main types of agroforestry system are: (1) agrosilvicultural (trees combined with crops); (2) silvopastoral (trees combined with animals); and (3) agrosilvopastoral (trees, animals and crops)."

112 Aryal K., Thapa P. S., & Lamichhane D. (2019) *Revisiting Agroforestry for Building Climate Resilient Communities: A Case of Package-Based Integrated Agroforestry Practices in Nepal*, Emerg. Sci. J. 3(5): 303–311, 303 ("Agroforestry is an indigenous farming system to increase production and productivity of land resources.").

113 Intergovernmental Panel on Climate Change *Glossary of Terms* 982, 993 ("**Afforestation** Planting of new forests on lands that historically have not contained forests."; "**Reforestation** Planting of *forests* on lands that have previously contained forests but that have been converted to some other use.").

114 Kuyah S., Whitney C. W., Jonsson M., Sileshi G. W., Öborn I., Muthuri C. W., & Luedeling E. (2019) *Agroforestry delivers a win-win solution for ecosystem services in sub-Saharan Africa. A meta-analysis*, Agron. Sustain. Dev. 39(5): 47, 1–18, 4 ("1. Biomass transfer where harvested leaves and twigs, or material pruned from trees outside the field, are incorporated into the soil prior to planting to improve soil fertility. Trees inside the fields can also be rejuvenated by pruning and prunings incorporated in the soil for crop production. 2. Mulch, where pruning materials are used as protective covering on the surface to suppress weeds, conserve soil moisture, prevent soil erosion, and enrich the soil.").

115 Kuyah S., Whitney C. W., Jonsson M., Sileshi G. W., Öborn I., Muthuri C. W., & Luedeling E. (2019) *Agroforestry delivers a win-win solution for ecosystem services in sub-Saharan Africa. A meta-analysis*, Agron. Sustain. Dev. 39(5): 47.

116 Muchane M. N., Sileshi G. W., Gripenberg S., Jonsson M., Pumariño L., & Barrios E. (2020) *Agroforestry boosts soil health in the humid and sub-humid tropics: A meta-analysis*, Agric. Ecosyst. Environ. 295: 106899, 1–12, 1 ("SOC increased by 21%, N storage increased by 13%, available N by 46% and available P by 11% while soil pH increased by 2% under agroforestry compared to crop monocultures.").

117 Chatterjee N., Nair P. K. Ramachandran., Chakraborty S., & Nair V. D. (2018) *Changes in soil*

carbon stocks across the Forest-Agroforest-Agriculture/Pasture continuum in various agroecological regions: A meta-analysis, Agric. Ecosyst. Environ. 266: 55–67, 55 ("Comparing Agroforest vs. Agriculture or Agroforest vs. Pasture, SOC stocks under AFS were higher by +27% in the ASA region, +26% in LHT, and +5.8% in [MED], but –5.3% in the TEM in the 0–100 cm soil depth.").

118 Chatterjee N., Nair P. K. Ramachandran., Chakraborty S., & Nair V. D. (2018) *Changes in soil carbon stocks across the Forest-Agroforest-Agriculture/Pasture continuum in various agroecological regions: A meta-analysis*, Agric. Ecosyst. Environ. 266: 55–67, 55 ("The Agroforest aged between 10–20 years had higher SOC stock than newly established, as well as <10-year-old systems across all soil-depth classes and agroecological regions.").

119 Kuyah S., Whitney C. W., Jonsson M., Sileshi G. W., Öborn I., Muthuri C. W., & Luedeling E. (2019) *Agroforestry delivers a win-win solution for ecosystem services in sub-Saharan Africa. A meta-analysis*, Agron. Sustain. Dev. 39(5): 47, 1–18, 1 ("A total of 1106 observations were extracted from 126 peer reviewed publications that fulfilled the selection criteria for meta-analysis of studies comparing agroforestry and no agroforestry practices (hereafter control) in sub-Saharan Africa. Across ecological conditions, agroforestry significantly increased crop yield, total soil nitrogen, soil organic carbon, and available phosphorus compared to the control."). *See also* Muchane M. N., Sileshi G. W., Gripenberg S., Jonsson M., Pumariño L., & Barrios E. (2020) *Agroforestry boosts soil health in the humid and sub-humid tropics: A meta-analysis*, Agric. Ecosyst. Environ. 295 106899, 1–12, 1 ("SOC increased by 21%, N storage increased by 13%, available N by 46% and available P by 11% while soil pH increased by 2% under agroforestry compared to crop monocultures.").

120 P. Udawatta R., Rankoth L., & Jose S. (2019) *Agroforestry and Biodiversity*, Sustainability 11(10): 2879, 1–22, 1 ("The review revealed that floral, faunal, and soil microbial diversity were significantly greater in AF as compared to monocropping, adjacent crop lands, and within crop alleys and some forests.").

121 Bhagwat S. A., Willis K. J., Birks H. J. B., & Whittaker R. J. (2008) *Agroforestry: a refuge for tropical biodiversity?* Trends Ecol. Evol. 23(5): 261–267, 263 ("Although there is a wide variation across studies and taxa, the mean values for richness in agroforestry systems are greater than 60% of the forest values.").

122 Muchane M. N., Sileshi G. W., Gripenberg S., Jonsson M., Pumariño L., & Barrios E. (2020) *Agroforestry boosts soil health in the humid and sub-humid tropics: A meta-analysis*, Agric. Ecosyst. Environ. 295: 106899, 1–12, 1 ("The analysis demonstrated that agroforestry can reduce soil erosion rates by 50% compared to crop monocultures. This finding is supported by higher infiltration rates, lower runoff, higher proportion of soil macroaggregates, and greater stability of soil structure under agroforestry. SOC increased by 21%, N storage increased by 13%, available N by 46% and available P by 11% while soil pH increased by 2% under agroforestry compared to crop monocultures.").

123 Muchane M. N., Sileshi G. W., Gripenberg S., Jonsson M., Pumariño L., & Barrios E. (2020) *Agroforestry boosts soil health in the humid and sub-humid tropics: A meta-analysis*, Agric. Ecosyst. Environ. 295: 106899, 1–12, 1 ("SOC increased by 21%, N storage increased by 13%, available N by 46% and available P by 11% while soil pH increased by 2% under agroforestry compared to crop monocultures.").

124 Pumariño L., Sileshi G. W., Gripenberg S., Kaartinen R., Barrios E., Muchane M. N., Midega C., & Jonsson M. (2015) *Effects of agroforestry on pest, disease and weed control: A meta-analysis*, Basic Appl. Ecol. 16(7): 573–582, 578–579 ("Our study suggests that agroforestry is beneficial for pest control. Weeds were less abundant and natural enemies were more abundant in agroforestry systems. Furthermore, in perennial crops, pest abundance was reduced in agroforestry systems. Agroforestry

also seemed to reduce plant damage due to pests and diseases, but for this response variable a likely publication bias was detected, and therefore this result must be treated with care. Together, these results support the general prediction that higher habitat complexity in agroforestry systems will result in better pest control, as suggested in previous meta-analyses on related topics.”).

125 Food and Agriculture Organization of the United Nations, *Forest and landscape restoration and agroforestry help diversify livelihoods and landscapes and increase land productivity* (*last visited* 18 October 2022) (“Agroforestry is a longer-term investment than conventional agriculture, requiring longer profit forecasts and planning; it can also incur high establishment and maintenance costs, sometimes generating net losses in the first few years. On average, agroforestry sees profitable returns after 3–8 years; for annual cropping systems, this period is normally 1–2 years.”).

126 Kuyah S., Whitney C. W., Jonsson M., Sileshi G. W., Öborn I., Muthuri C. W., & Luedeling E. (2019) *Agroforestry delivers a win-win solution for ecosystem services in sub-Saharan Africa. A meta-analysis*, Agron. Sustain. Dev. 39(5): 47, 1–18, 9 (“Alley cropping, biomass transfer, and planted fallows increased crop yield in 77, 93, and 85% of all cases, while hedgerows increased crop yield in 54%.”).

127 Kuyah S., Whitney C. W., Jonsson M., Sileshi G. W., Öborn I., Muthuri C. W., & Luedeling E. (2019) *Agroforestry delivers a win-win solution for ecosystem services in sub-Saharan Africa. A meta-analysis*, Agron. Sustain. Dev. 39(5): 47, 1–18, 6 (“Crop yield was higher in both humid and semi-arid situations compared to the control.”).

128 Kuyah S., Whitney C. W., Jonsson M., Sileshi G. W., Öborn I., Muthuri C. W., & Luedeling E. (2019) *Agroforestry delivers a win-win solution for ecosystem services in sub-Saharan Africa. A meta-analysis*, Agron. Sustain. Dev. 39(5): 47, 1–18, 6 (“With regard to soil types, yields were two times higher under agroforestry with Acrisols, Cambisols, Lixisols, Luvisols, and Nitisols compared to controls.”; *and* “On the contrary, Arenosols and Andosols had some occurrences where the RR was less than 1 (Fig 3). Low crop yield associated with Arenosols and Andosols could be attributed to differences in soil quality.”).

129 Kuyah S., Whitney C. W., Jonsson M., Sileshi G. W., Öborn I., Muthuri C. W., & Luedeling E. (2019) *Agroforestry delivers a win-win solution for ecosystem services in sub-Saharan Africa. A meta-analysis*, Agron. Sustain. Dev. 39(5): 47, 1–18, 6 (“Exceptions were detected for some agroforestry practices (e.g., hedgerows) and some soil types where agroforestry had negative effects. . . In some studies, pruning and shade levels affected outcomes negatively.”).

130 Kuyah S., Whitney C. W., Jonsson M., Sileshi G. W., Öborn I., Muthuri C. W., & Luedeling E. (2019) *Agroforestry delivers a win-win solution for ecosystem services in sub-Saharan Africa. A meta-analysis*, Agron. Sustain. Dev. 39(5): 47.8 (“Agroforestry increased crop yield for trials conducted on both farms and research stations in 77 and 68% of all cases (Fig. 3 and Table 1). Among agroforestry practices, crop yield was higher than controls when alley cropping, biomass transfer, and planted fallows were used, but not for hedgerows (Table 1).”). *See also* Bayala J., Sileshi G. W., Coe R., Kalinganire A., Tchoundjeu Z., Sinclair F., & Garrity D. (2012) *Cereal yield response to conservation agriculture practices in drylands of West Africa: A quantitative synthesis*, J. Arid Environ. 78 13–25, 21 (“The results confirm that the practices studied, with the exception of parkland trees, do on average increase cereal yields, suggesting that building on and attempting to replicate the successes in using conservation agriculture techniques should be pursued.”).

131 Kumar B. M. (2006) *Agroforestry: the new old paradigm for Asian food security*, J. Trop. Agric. 44: 1–14, 8 (“A comparison of the data in Table 1, nevertheless, indicates that crops such as upland rice, ginger (Zingiber officinale), and Kaempferia galanga showed higher productivity in certain agroforestry combinations (over sole crops), while fodder plants and many other grain crops showed relatively lower yields.”).

132 Food and Agriculture Organization of the United Nations *Forest and landscape restoration and agroforestry help diversify livelihoods and landscapes and increase land productivity* (*last visited* 18 October 2022) ("Agroforestry is a longer-term investment than conventional agriculture, requiring longer profit forecasts and planning; it can also incur high establishment and maintenance costs, sometimes generating net losses in the first few years. On average, agroforestry sees profitable returns after 3–8 years; for annual cropping systems, this period is normally 1–2 years.").

133 Glover E. K., Ahmed H. B., & Glover M. K. (2013) *Analysis of Socio-Economic Conditions Influencing Adoption of Agroforestry Practices*, Int. J. Agriculture For. 3(4): 178–184, 179–180 ("While environmental factors such as topography, soil types and climatic factors affect plant growth and development, findings suggest that the main socio-economic factors that determine the actual occurrence of agroforestry are household security, access to capital and incentives, labour, gender, land tenure, farm size and knowledge for management.").

134 Lawin K. G. & Tamini L. D. (2019) *Land Tenure Differences and Adoption of Agri-Environmental Practices: Evidence from Benin*, J. Dev. Stud. 55(2): 177–190, 186 ("Our finding is consistent with the positive effect of tenure security on the adoption of agri-environmental practices reported in the literature. Land tenure differences significantly influence farmers' decision to invest in agri-environmental practices. The intensity of the adoption of agrienvironmental practices is consistently higher on owned plots than on borrowed, rented or sharecropped plots.").

135 Roshetko J. M., Lasco R. D., & Angeles M. S. D. (2007) *Smallholder Agroforestry Systems for Carbon Storage*, Mitig. Adapt. Strateg. Glob. Change 12(2): 219–242, 229 ("When clear land tenure exists, experience indicates that the development of smallholder agroforestry systems can be facilitated by focusing on three key issues – access to quality germplasm of appropriate species; enhancement of agroforestry system management skills; and the development of market linkages.").

136 Glover E. K., Ahmed H. B., & Glover M. K. (2013) *Analysis of Socio-Economic Conditions Influencing Adoption of Agroforestry Practices*, Int. J. Agriculture For. 3(4): 178–184, 180 ("While farmers are often aware of environmental degradation caused by their current practices and understand the long term benefits of AF, they are reluctant to adopt them unless the security of their household is not put at risk and preferably enhanced such as through meeting basic needs e.g. food or poles or through production of goods which can be sold. It could be several years before profit and yield increases happen. For some farmers, this could be an unacceptably long period to wait for a return on their investment, so projects should include some sort of transition period until benefits begin to pay back.").

137 Bezerra J., Turnhout E., Vasquez I. M., Rittl T. F., Arts B., & Kuyper T. W. (2019) *The promises of the Amazonian soil: shifts in discourses of Terra Preta and biochar*, J. Environ. Policy Plan. 21(5): 623–635, 623 ("However, biochar has a long history. It was inspired by Terra Preta, a highly fertile soil of anthropogenic and pre-Columbian origin found in the Amazon. This article uses discourse analysis to explore how the Terra Preta and biochar concepts have been articulated over time and what environmental discourses they resonate with. Our analysis shows that over time, the concept of biochar has slowly become disconnected from Terra Preta. While the concept of Terra Preta continued to be closely connected with Amazonian nature, archaeology and indigenous culture, biochar gained international traction and became embedded in ecological modernisation discourse.").

138 Scholz S. M., Sembres T., Roberts K., Whitman T., Wilson K., & Lehmann J. *Biochar Systems for Smallholders in Developing Countries*, World Bank, 231, 1–208, 2 ("Biochar is a system-defined term referring to black carbon that is produced intentionally to manage carbon for climate change mitigation purposes combined with a downstream application to soils for agricultural effects. It is produced with the intent to be applied to soil as a means of improving soil productivity, carbon storage, or both.

Although the term “biochar” has come into common usage only relatively recently, the practice of amending soils with charcoal for fertility management goes back millennia. Instances can be found in Africa, Asia, and notably in the Amazon basin where the historically managed terra preta, or “dark earths,” stand out for their capacity to store carbon.”).

139 Scholz S. M., Sembres T., Roberts K., Whitman T., Wilson K., & Lehmann J. *Biochar Systems for Smallholders in Developing Countries*, World Bank, 231, 1–208, 2 (“Biochar is the solid product remaining after biomass is heated to temperatures typically between 300°C and 700°C under oxygen-deprived conditions, a process known as “pyrolysis.””).

140 Scholz S. M., Sembres T., Roberts K., Whitman T., Wilson K., & Lehmann J. *Biochar Systems for Smallholders in Developing Countries*, World Bank, 231, 1–208, 2 (“Biochar retains between 10 percent and 70 percent (on average about 50 percent) of the carbon present in the original biomass and slows down the rate of carbon decomposition by one or two orders of magnitude, that is, in the scale of centuries or millennia.”).

141 Scholz S. M., Sembres T., Roberts K., Whitman T., Wilson K., & Lehmann J. *Biochar Systems for Smallholders in Developing Countries*, World Bank, 231, 1–208, 4 (“The rate of decomposition of the biochar and consequently its capacity for carbon storage depends on several factors. Two main factors include the ratio of labile carbon (which is readily degradable) to recalcitrant carbon (which is more resistant to degradation), and on the pyrolysis technique used to produce the biochar.”).

142 Scholz S. M., Sembres T., Roberts K., Whitman T., Wilson K., & Lehmann J. *Biochar Systems for Smallholders in Developing Countries*, World Bank, 231, 1–208, 37 (“According to model-derived estimates, delivering carbon sequestration over the next few hundred years would require either the labile fraction of the biochar to be below 10 percent or the entire biochar to have a mean residence time3 of a thousand years or more (figure 3.2).”).

143 Scholz S. M., Sembres T., Roberts K., Whitman T., Wilson K., & Lehmann J. *Biochar Systems for Smallholders in Developing Countries*, World Bank, 231, 1–208, 37 (“Greater pyrolysis temperatures usually decrease the carbon captured in the biochar (Lehmann 2007), while also increasing the stability of biochars (Zimmerman 2010) and the proportion of stable biochar (Nguyen and Lehmann 2009).”).

144 Scholz S. M., Sembres T., Roberts K., Whitman T., Wilson K., & Lehmann J. *Biochar Systems for Smallholders in Developing Countries*, World Bank, 231, 1–208, 37 (“In addition to the labile to recalcitrant ratio of the biochar, the pyrolysis system used to create the biochar also affects the relative rate of decomposition by impacting the amount of carbon captured in the biochar. Some biochar production techniques may capture less than 40 percent of original carbon due to equipment inefficiency (for example, during initial development stages of biochar stoves), the type of feedstock used (for example, carbon retention through pyrolysis is greater with woody biomass than with manure), or the type of biochar production technology (gasifiers favor a lower biochar to bioenergy production ratio compared to pyrolyzers; see table 2.1).”).

145 Scholz S. M., Sembres T., Roberts K., Whitman T., Wilson K., & Lehmann J. *Biochar Systems for Smallholders in Developing Countries*, World Bank, 231, 1–208, 2 (“It is important to understand how different production conditions can result in different types of biochars and how these chars interact with different types of soils. Three elements critical to every biochar system are (a) the source of biomass, (b) the means of biochar production, and (c) whether and how it is applied to soil (figure ES.1).”).

146 Biochar International, *Biochar Feedstocks* (*last visited* 24 Janauary 2023) (“The choice of feedstock will be affected by the biomass resources in the immediate area and availability. Due to collection, and transport and storage costs, it often makes the most economic sense to use local feedstocks (if they are also an environmentally sustainable option). The most basic costs and benefits to consider

with feedstock choices are highlighted below: Feedstock production and collection: If the feedstock is a residue, such as municipal biomass waste, logging or cropping residues, or a by-product such as bagasse, then production is less an economic issue than if the feedstock is purposely grown for the production of biochar—such as switchgrass—which would include the costs and inputs needed for the growing and harvesting of the crop. Revenue in the form of tipping fees may be obtained from certain waste feedstocks. Use Tradeoff: This would include the potential nutrient value lost from using feedstock for biochar production rather than as a direct fertilizer on the field. How this trade off works will vary on the area and on the feedstock. For example, chicken litter may be valuable in some areas as a direct fertilizer while in other areas it may be treated as a waste and represent a disposal cost. Feedstock transport: When waste biomass is found far from the place where it will be used, transportation costs can be very high. In some situations, it may make sense to densify the biomass by chipping or pelletizing before transport. Feedstock storage and pre-processing: Many feedstocks will need to be dried before pyrolysis. Depending on the feedstock choice, the drying process could occur passively through careful storage or may need more intervention—such as using a drier (thus requiring energy and labor). Energy for drying could in some cases be obtained from the pyrolysis of previous batches of feedstock.”).

147 Liu L., Shen G., Sun M., Cao X., Shang G., & Chen P. (2014) *Effect of biochar on nitrous oxide emission and its potential mechanisms*, J. Air Waste Manag. Assoc. 64(8): 894–902, 894 (“Recent research shows that biochar can alter the rates of nitrogen cycling in soil systems by influencing nitrification and denitrification, which are key sources of the greenhouse gas nitrous oxide (N_2O).”).

148 Jeffery S., Verheijen F. G. A., Kammann C., & Abalos D. (2016) *Biochar effects on methane emissions from soils: A meta-analysis*, Soil Biol. Biochem. 101: 251–258, 252 (“Biochar has been shown to increase (Zhang et al., 2010; Spokas and Bogner, 2011), decrease (Feng et al., 2012; Dong et al., 2013; Reddy et al., 2014), or have no significant effect (Kammann et al., 2012) on CH4 emissions from soils. Mechanisms are usually only assumed or hypothesised and remain unclear.”).

149 World Health Organization (28 November 2022) *Household Air Pollution* (“Worldwide, around 2.4 billion people still cook using solid fuels (such as wood, crop waste, charcoal, coal and dung) and kerosene in open fires and inefficient stoves (1). Most of these people are poor and live in low- and middle-income countries.”).

150 World Health Organization (28 November 2022) *Household Air Pollution* (“Each year, 3.2 million people die prematurely from illnesses attributable to the household air pollution caused by the incomplete combustion of solid fuels and kerosene used for cooking (see household air pollution data for details).”).

151 Gitau J. K., Sundberg C., Mendum R., Mutune J., & Njenga M. (2019) *Use of Biochar-Producing Gasifier Cookstove Improves Energy Use Efficiency and Indoor Air Quality in Rural Households*, Energies, 12(22): 4285 1-19, 1 (“With the gasifier, the average corresponding dinner time CO, CO_2, and $PM_{2.5}$ concentrations were reduced by 57%, 41%, and 79% respectively compared to three-stone open fire.”).

152 IBI Standards: International Biochar Initiative (2015) *Standardized Product Definition and Product Testing Guidelines for Biochar That Is Used in Soil*, version 2.1, 10 (“The materials used as feedstocks for biochar production have direct impacts on the nature and quality of the resulting biochar. Although the focus of this document is on the biochar material, some restrictions have been applied to feedstock contents and quality. To qualify as biochar feedstock under these standards, the feedstock may be a combination of biomass and diluents, but may not contain more than 2% by dry weight of contaminants (following Brinton 2000). Any diluents that constitute 10% or more by dry weight of the feedstock material must be reported as a feedstock component.”).

153 IBI Standards: International Biochar Initiative (2015) *Standardized Product Definition and Product Testing Guidelines for Biochar That Is Used in Soil*, version 2.1, 50 ("Diluent/Dilutant: Inorganic material that is deliberately mixed or inadvertently commingled with biomass feedstock prior to processing. These materials will not carbonize in an equivalent fashion to the biomass. These materials include soils and common constituents of natural soils, such as clays and gravel that may be gathered with biomass or intermixed through prior use of the feedstock biomass. Diluents/dilutants may be found in a diverse range of feedstocks, such as agricultural residues, manures, and municipal solid wastes. (IBI)").

154 IBI Standards: International Biochar Initiative (2015) *Standardized Product Definition and Product Testing Guidelines for Biochar That Is Used in Soil*, version 2.1, 50 ("Contaminant: An undesirable material in a biochar material or biochar feedstock that compromises the quality or usefulness of the biochar or through its presence or concentration causes an adverse effect on the natural environment or impairs human use of the environment (adapted from Canadian Council of Ministers of the Environment, 2005). Contaminants include fossil fuels and fossil fuel-derived chemical compounds, glass, and metal objects. (IBI)").

155 IBI Standards: International Biochar Initiative (2015) *Standardized Product Definition and Product Testing Guidelines for Biochar That Is Used in Soil*, version 2.1, 10 ("Suitable feedstocks include but are not limited to biomass residues, which may contain a minimal quantity of contaminants (see above) as part of the feedstock. Feedstock that may have been grown on contaminated soils is considered to be a processed feedstock and must meet the toxicant assessment testing frequency requirements for processed feedstocks given in Section 5.5 Category B Testing Frequency. Municipal Solid Waste (MSW) containing hazardous materials or wastes may not be included as eligible feedstock under these standards. It is the manufacturer's responsibility to ensure that biochar feedstock materials are free of hazardous materials.").

156 IBI Standards: International Biochar Initiative (2015) *Standardized Product Definition and Product Testing Guidelines for Biochar That Is Used in Soil*, version 2.1, 12 ("These IBI Biochar Standards identify three categories of tests for biochar materials: Test Category A – Basic Utility Properties: Required for all biochars. This set of tests measures the most basic properties required to assess the utility of a biochar material for use in soil. Test Category B – Toxicant Assessment: Required for all biochars. Biochars made from processed feedstocks must be tested more frequently than biochars made from unprocessed feedstocks, as defined in Section 5 General Protocols and Restrictions. Test Category C – Advanced Analysis and Soil Enhancement Properties: Optional for all biochars. Biochar may be tested for advanced analysis and enhancement properties in addition to meeting test requirements for Test Categories A and B. All tests in Test Category C are optional. Manufacturers may report on none, one, some or all of the properties.").

157 Gwenzi W., Chaukura N., Mukome, F. N. D., Machado S., & Nyamasoka, B. (2015) *Biochar Production and Applications in Sub-Saharan Africa: Opportunities, Constraints, Risks and Uncertainties*. J. Environ. Manage. 150: 250–261, 250 ("However, most of the research on biochar production and its applications has been conducted in the USA, Australia, South America, China and Europe. In these regions, the potential role of biochar in improving soil fertility, soil water-holding capacity and crop yields, while sequestering carbon and reducing greenhouse gas emissions is well-documented.").

158 Gross A., Bromm T., & Glaser B. (2021) *Soil Organic Carbon Sequestration after Biochar Application: A Global Meta-Analysis*, Agronomy 11(12): 2474, 1–21, 1 ("Field experiments covered experimental durations between 1 and 10 years with biochar application amounts between 1 and 100 Mg ha^{-1}. They showed a mean increase in soil organic carbon (SOC) stocks by 13.0 Mg ha^{-1} on average, corresponding to 29%. Pot and incubation experiments ranged between 1 and 1278 days and biochar amounts

between 5 g kg^{-1} and 200 g kg^{-1}. They raised SOC by 6.3 g kg^{-1} on average, corresponding to 75%.").

159 Gross A., Bromm T., & Glaser B. (2021) *Soil Organic Carbon Sequestration after Biochar Application: A Global Meta-Analysis*, AGRONOMY 11(12): 2474, 1–21, 1 ("Organic fertilizer co-applications significantly further increased SOC.").

160 Xu H., Cai A., Wu D., Liang G., Xiao J., Xu M., Colinet G., & Zhang W. (2021) *Effects of biochar application on crop productivity, soil carbon sequestration, and global warming potential controlled by biochar C:N ratio and soil pH: A global meta-analysis*, SOIL TILLAGE RES. 213, 1–10, 1 ("Overall, the effect sizes were different between B and BF in both improving crop yield (15.1% and 48.4%, respectively) and decreasing GWP (27.1% and 14.3%, respectively), whereas there were almost no differences in terms of increasing SOC (32.9% and 34.8%, respectively).").

161 Xu H., Cai A., Wu D., Liang G., Xiao J., Xu M., Colinet G., & Zhang W. (2021) *Effects of biochar application on crop productivity, soil carbon sequestration, and global warming potential controlled by biochar C:N ratio and soil pH: A global meta-analysis*, SOIL TILLAGE RES. 213, 1–10, 1 ("The wetness index, soil properties (SOC, pH, and clay), and biochar properties (type, pH, C:N ratio, and application rate) jointly explained 70%–79%, 90%–93%, and 70%–97% of the effect variations in crop yield, SOC, and GWP, respectively.").

162 Cayuela M. L., van Zwieten L., Singh B. P., Jeffery S., Roig A., & Sánchez-Monedero M. A. (2014) *Biochar's role in mitigating soil nitrous oxide emissions: A review and meta-analysis*, AGRIC. ECOSYST. ENVIRON. 191: 5–16, 5 ("Overall, we found that biochar reduced soil N_2O emissions by 54% in laboratory and field studies. The biochar feedstock, pyrolysis conditions and C/N ratio were shown to be key factors influencing emissions of N_2O while a direct correlation was found between the biochar application rate and N_2O emission reductions. Interactions between soil texture and biochar and the chemical form of N fertilizer applied with biochar were also found to have a major influence on soil N_2O emissions.").

163 Cayuela M. L., van Zwieten L., Singh B. P., Jeffery S., Roig A., & Sánchez-Monedero M. A. (2014) *Biochar's role in mitigating soil nitrous oxide emissions: A review and meta-analysis*, AGRIC. ECOSYST. ENVIRON. 191: 5–16, 10 ("The sample mean shows a general strong and significant reduction (−54 ± 6%) in N_2O emissions. The largest number of studies has been undertaken on wood (415 direct comparisons) and herbaceous materials (282 direct comparisons) and in both cases the mean change (reduction) in N_2O emissions was significant. There were a considerable number of studies on manure-based biochars (107 direct comparisons), with the mean effect size close to zero, with a confidence interval from −46% to +39%.").

164 Cayuela M. L., van Zwieten L., Singh B. P., Jeffery S., Roig A., & Sánchez-Monedero M. A. (2014) *Biochar's role in mitigating soil nitrous oxide emissions: A review and meta-analysis*, AGRIC. ECOSYST. ENVIRON. 191: 5–16, 5 ("While there is clear evidence that, in many cases, emissions of N_2O are reduced, there is still a significant lack in understanding of the key mechanisms which result in these changed emissions.").

165 Borchard N., Schirrmann M., Cayuela M. L., Kammann C., Wrage-Mönnig N., Estavillo J. M., Fuertes-Mendizábal T., Sigua G., Spokas K., Ippolito J. A., & Novak J. (2019) *Biochar, soil and land-use interactions that reduce nitrate leaching and N_2O emissions: A meta-analysis*, SCI. TOTAL ENVIRON. 651: 2354–2364, 2354 ("The overall N_2O emissions reduction was 38%, but N_2O emission reductions tended to be negligible after one year.").

166 Borchard N., Schirrmann M., Cayuela M. L., Kammann C., Wrage-Mönnig N., Estavillo J. M., Fuertes-Mendizábal T., Sigua G., Spokas K., Ippolito J. A., & Novak J. (2019) *Biochar, soil and land-use*

interactions that reduce nitrate leaching and N_2O emissions: A meta-analysis, Sci. Total Environ. 651: 2354–2364, 2354–2355 ("Biochar had the strongest N_2O-emission reducing effect in rice soils (Anthrosols) and sandy soils (Arenosols).").

167 Borchard N., Schirrmann M., Cayuela M. L., Kammann C., Wrage-Mönnig N., Estavillo J. M., Fuertes-Mendizábal T., Sigua G., Spokas K., Ippolito J. A., & Novak J. (2019) *Biochar, soil and land-use interactions that reduce nitrate leaching and N_2O emissions: A meta-analysis*, Sci. Total Environ. 651: 2354–2364, 2354 ("Overall, soil NO_3^- concentrations remained unaffected while NO_3^- leaching was reduced by 13% with biochar; greater leaching reductions (>26%) occurred over longer experimental times (i.e. >30 days). Biochar had the strongest N_2O-emission reducing effect in rice soils (Anthrosols) and sandy soils (Arenosols).").

168 Smith Pete (2016) *Soil carbon sequestration and biochar as negative emission technologies*, Glob. Change Biol. 22(3): 1315–1324, 1319 ("Of these avoided emissions, about 30% derives from fossil fuel displacement, and about 70% is from biochar storage in soil – so the negative emission component of biochar is 0.7 GtCeq. yr^{-1}, with a maximum technical potential of 1.3 GtCeq. yr^{-1}."). *See also* Lehmann J., Gaunt J., & Rondon M. (2006) *Bio-char Sequestration in Terrestrial Ecosystems – A Review*, Mitig. Adapt. Strateg. Glob. Change 11(2): 403–427, 403 ("Using published projections of the use of renewable fuels in the year 2100, bio-char sequestration could amount to 5.5–9.5 Pg C yr^{-1} if this demand for energy was met through pyrolysis, which would exceed current emissions from fossil fuels (5.4 Pg C yr^{-1}). Bio-char soil management systems can deliver tradable C emissions reduction, and C sequestered is easily accountable, and verifiable.").

169 Jeffery S., Verheijen F. G. A., van der Velde M., & Bastos A. C. (2011) *A quantitative review of the effects of biochar application to soils on crop productivity using meta-analysis*, Agric. Ecosyst. Environ. 144(1): 175–187, 175 ("Results showed an overall small, but statistically significant, benefit of biochar application to soils on crop productivity, with a grand mean increase of 10%. However, the mean results for each analysis performed within the meta-analysis covered a wide range (from −28% to 39%).").

170 Ye L., Camps-Arbestain M., Shen Q., Lehmann J., Singh B., & Sabir M. (2020) *Biochar effects on crop yields with and without fertilizer: A meta-analysis of field studies using separate controls*, Soil Use Manag. 36(1): 2–18, 2c ("Compared with the non-fertilized control, a 26% (CI: 15%–40%) increase in yield was observed with the use of IF only, whereas that of biochar along with IF caused a 48% (CI: 30%–70%) increase. Compared with the use of IF only, the addition of biochar along with IF caused a 15% (CI: 11%–19%) increase in yield, indicating that biochar was as effective as fertilizers in increasing crop yields when added in combination. The use of biochar alone did not increase crop yield regardless of the control considered.").

171 Xu H., Cai A., Wu D., Liang G., Xiao J., Xu M., Colinet G., & Zhang W. (2021) *Effects of biochar application on crop productivity, soil carbon sequestration, and global warming potential controlled by biochar C:N ratio and soil pH: A global meta-analysis*, Soil Tillage Res. 213: 105125, 1–10, 1 ("Overall, the effect sizes were different between B and BF in both improving crop yield (15.1% and 48.4%, respectively) and decreasing GWP (27.1% and 14.3%, respectively), whereas there were almost no differences in terms of increasing SOC (32.9% and 34.8%, respectively).").

172 Jeffery S., Verheijen F. G. A., van der Velde M., & Bastos A. C. (2011) *A quantitative review of the effects of biochar application to soils on crop productivity using meta-analysis*, Agric. Ecosyst. Environ. 144(1): 175–187, 180 ("Significant ($P < 0.05$) increases in crop productivity occurred in soils of both medium and coarse textures. In contrast, no significant ($P > 0.05$) effects of biochar application on crop productivity were found in fine-textured soils.").

173 Jeffery S., Verheijen F. G. A., van der Velde M., & Bastos A. C. (2011) *A quantitative review of the*

effects of biochar application to soils on crop productivity using meta-analysis, Agric. Ecosyst. Environ. 144(1): 175–187, 175 (“The greatest (positive) effects with regard to soil analyses were seen in acidic (14%) and neutral pH soils (13%), and in soils with a coarse (10%) or medium texture (13%).”). *See also* Xu H., Cai A., Wu D., Liang G., Xiao J., Xu M., Colinet G., & Zhang W. (2021) *Effects of biochar application on crop productivity, soil carbon sequestration, and global warming potential controlled by biochar C:N ratio and soil pH: A global meta-analysis*, Soil Tillage Res. 213: 105125, 1–10, 1 (“Increased biochar carbon to nitrogen ratio (C:N ratio) and soil pH decreased the impact of B and BF on crop yield, while increased SOC promoted the impact of BF on crop yield.”).

174 Xu H., Cai A., Wu D., Liang G., Xiao J., Xu M., Colinet G., & Zhang W. (2021) *Effects of biochar application on crop productivity, soil carbon sequestration, and global warming potential controlled by biochar C:N ratio and soil pH: A global meta-analysis*, Soil Tillage Res. 213: 105125, 1–10, 1 (“In addition, the effect sizes of B and BF on crop yield were coupled with these on SOC. Increased biochar carbon to nitrogen ratio (C:N ratio) and soil pH decreased the impact of B and BF on crop yield, while increased SOC promoted the impact of BF on crop yield.”).

175 Xu H., Cai A., Wu D., Liang G., Xiao J., Xu M., Colinet G., & Zhang W. (2021) *Effects of biochar application on crop productivity, soil carbon sequestration, and global warming potential controlled by biochar C:N ratio and soil pH: A global meta-analysis*, Soil Tillage Res. 213: 105125, 1–10, 1 (“The effect size on GWP increased with biochar pH increasing but soil pH decreasing under B and BF. The wetness index, soil properties (SOC, pH, and clay), and biochar properties (type, pH, C:N ratio, and application rate) jointly explained 70%–79%, 90%–93%, and 70%–97% of the effect variations in crop yield, SOC, and GWP, respectively. The biochar C:N ratio and soil pH were the most important factors determining the effect size of biochar application on crop yield, SOC, and GWP.”).

176 Jeffery S., Verheijen F. G. A., van der Velde M., & Bastos A. C. (2011) *A quantitative review of the effects of biochar application to soils on crop productivity using meta-analysis*, Agric. Ecosyst. Environ. 144(1): 175–187, 179 (“However, there was no statistically significant difference ($P > 0.05$) between any of the application rates. Application rates of 10, 25, 50 and 100 t ha^{-1} were all found to significantly increase crop productivity when compared to controls, which received no biochar addition.”).

177 Jeffery S., Abalos D., Prodana M., Bastos A. C., van Groenigen J. W., Hungate B. A., & Verheijen F. (2017) *Biochar boosts tropical but not temperate crop yields*, Environ. Res. Lett. 12(5): 053001, 1–6, 1 (“Here we use a global-scale meta-analysis to show that biochar has, on average, no effect on crop yield in temperate latitudes, yet elicits a 25% average increase in yield in the tropics.”).

178 Jeffery S., Abalos D., Prodana M., Bastos A. C., van Groenigen J. W., Hungate B. A., & Verheijen F. (2017) *Biochar boosts tropical but not temperate crop yields*, Environ. Res. Lett. 12(5): 053001, 1–6, 2 (“We found biochar amendment to soils in temperate regions to significantly decrease crop yield, averaging approximately 3% at a median biochar application rate of 30 t ha.”).

179 Jeffery S., Verheijen F. G. A., van der Velde M., & Bastos A. C. (2011) *A quantitative review of the effects of biochar application to soils on crop productivity using meta-analysis*, Agric. Ecosyst. Environ. 144(1): 175–187, 175 (“Results showed an overall small, but statistically significant, benefit of biochar application to soils on crop productivity, with a grand mean increase of 10%.”).

180 Jeffery S., Verheijen F. G. A., van der Velde M., & Bastos A. C. (2011) *A quantitative review of the effects of biochar application to soils on crop productivity using meta-analysis,* Agric. Ecosyst. Environ. 144(1): 175–187, 175 (“However, the mean results for each analysis performed within the meta-analysis covered a wide range (from −28% to 39%).”).

181 Xu H., Cai A., Wu D., Liang G., Xiao J., Xu M., Colinet G., & Zhang W. (2021) *Effects of biochar application on crop productivity, soil carbon sequestration, and global warming potential controlled by*

biochar C:N ratio and soil pH: A global meta-analysis, Soil and Tillage Research 213: 105125, *See* Table 1.

182 Liu X, Zhang A., Ji C., Joseph S., Bian R., Li L., Pan G., & Paz-Ferreiro J.. (2013) *Biochar's effect on crop productivity and the dependence on experimental conditions—a meta-analysis of literature data*, Plant Soil 373(1-2): 583-594, 583 ("In the published experiments, with biochar amendment rates generally <30 t ha^{-1}, BSA increased crop productivity by 11.0 % on average, while the responses varied with experimental conditions.").

183 Jeffery S., Abalos D., Prodana M., Bastos A. C., van Groenigen J. W., Hungate B. A., & Verheijen F. (2017) *Biochar boosts tropical but not temperate crop yields*, Environ. Res. Lett. 12(5): 053001, 1–6, 2 ("Overall, biochar increased crop yield by a grand mean of 13% (figure 1), similar to previously reported meta-analyses, which were 10% and 11%.").

184 Jeffery S., Abalos D., Prodana M., Bastos A. C., van Groenigen J. W., Hungate B. A., & Verheijen F. (2017) *Biochar boosts tropical but not temperate crop yields*, Environ. Res. Lett. 12(5): 053001, 1–6, 1 ("Here we use a global-scale meta-analysis to show that biochar has, on average, no effect on crop yield in temperate latitudes, yet elicits a 25% average increase in yield in the tropics.").

185 Ye L., Camps-Arbestain M., Shen Q., Lehmann J., Singh B., & Sabir M. (2020) *Biochar effects on crop yields with and without fertilizer: A meta-analysis of field studies using separate controls*, Soil Use Manag. 36(1): 2–18, 2 ("Compared with the non-fertilized control, a 26% (CI: 15%–40%) increase in yield was observed with the use of IF only, whereas that of biochar along with IF caused a 48% (CI: 30%–70%) increase. Compared with the use of IF only, the addition of biochar along with IF caused a 15% (CI: 11%–19%) increase in yield, indicating that biochar was as effective as fertilizers in increasing crop yields when added in combination. The use of biochar alone did not increase crop yield regardless of the control considered.").

186 Gwenzi W., Chaukura N., Mukome F. N. D., Machado S., & Nyamasoka B. (2015) *Biochar production and applications in sub-Saharan Africa: Opportunities, constraints, risks and uncertainties*, J. Environ. Manage. 150: 250–261, 250 ("Biochar has gained international research attention, but few studies have investigated the potential of biochar to address the challenges in SSA. . . Biochar products have energy values comparable or higher than those of traditional biomass fuels; thereby making them ideal alternative sources of energy especially for poor households without access to electricity. Before the benefits of biochar can be realized in SSA, there is need to overcome multiple risks and constraints such as lack of finance, socio-economic constraints including negative perceptions and attitudes among both researchers and consumers, and environmental and public health risks.").

187 Scholz S. M., Sembres T., Roberts K., Whitman T., Wilson K., & Lehmann J. (2014) Biochar Systems for Smallholders in Developing Countries: Levering the Current Knowledge and Exploring Future Potential for Climate-Smart Agriculture, World Bank, 1–208, 8 ("The majority of biochar production systems were identified as small, tending toward household- and farm-scale systems.").

188 Carbon Offset Guide, *What is a Carbon Offset?* (*last visited* 23 January 2023) ("A carbon offset credit is a transferrable instrument certified by governments or independent certification bodies to represent an emission reduction of one metric tonne of CO2, or an equivalent amount of other GHGs.").

189 Balufelder C., Levy C., Mannion P., and Pinner D. (29 January 2021) *A blueprint for scaling voluntary carbon markets to meet the climate challenge*, McKinsey ("The Taskforce on Scaling Voluntary Carbon Markets (TSVCM), sponsored by the Institute of International Finance (IIF) with knowledge support from McKinsey, estimates that demand for carbon credits could increase by a factor of 15 or

more by 2030 and by a factor of up to 100 by 2050. Overall, the market for carbon credits could be worth upward of $50 billion in 2030.”).

190 World Bank (2022) State and Trends of Carbon Pricing 2022, Washington, DC (“Growing corporate net zero commitments are driving demand in the voluntary carbon market segment.”).

191 Carbon Offset Guide, *Additionality* (*last visited* 23 January 2023) (“GHG reductions are additional if they would not have occurred in the absence of a market for offset credits. If the reductions would have happened anyway – i.e., without any prospect for project owners to sell carbon offset credits – then they are not additional. Additionality is essential for the quality of carbon offset credits – if their associated GHG reductions are not additional, then purchasing offset credits in lieu of reducing your own emissions will make climate change worse.”).

192 Carbon Offset Guide, *Permanence* (*last visited* 23 January 2023) (“Most of the carbon in a tonne of CO2 emitted today will – eventually – be removed from the atmosphere. However, around 25% remains in the atmosphere for hundreds to thousands of years.[1] To compensate for this, offset credits must be associated with GHG reductions that are similarly permanent. If a GHG reduction or removal is “reversed” (i.e., GHGs are subsequently emitted so that no net reduction occurs),[2] then it no longer serves a compensatory function.”).

193 Zelikova J., Chay F., Freeman J., and Cullenward D. (15 July 2023) *A buyer’s guide to soil carbon offsets* CarbonPlan (“A number of protocols for crediting soil carbon have emerged to tackle this complexity. Some were developed by third-party offset registries like Verra and Gold Standard, while others come from new companies like Nori and the Regen Network. Each protocol specifies the detailed rules under which projects claim credits that can be sold to buyers. More than a dozen protocols exist, and they vary across key dimensions like scientific rigor, additionality, and durability. As a result, getting to the bottom of what these different protocols require is not an easy task.”).

194 Zelikova J., Chay F., Freeman J., and Cullenward D. (15 July 2023) *A buyer’s guide to soil carbon offsets* CarbonPlan (“Our findings reveal that robust crediting of soil carbon is hard and that none of the existing protocols is doing enough to guarantee good outcomes.”).

195 World Bank (2022) State and Trends of Carbon Pricing 2022, Washington, DC, Figure 14.

196 Ministry of Statistics & Programme Implementation (2019), *NSS REPORT NO. 587: Situation Assessment of Agricultural Households and Land and Livestock Holdings of Households in Rural India*, Press Release, PIB Delhi, Table 6.6.1.

197 Schallert B., Stevenson M., Weber C., and Farsan A. (2020) *Beyond Science-Based Targets: A Blueprint for Corporate Action on Climate and Nature*, World Wildlife Fund for Nature and Boston Consulting Group, 1–18, 5 (“From the desire to offset a company’s remaining emissions came a voluntary carbon market that also measures outcomes in CO2e units but that in some cases is not simultaneously able to deliver needed environmental and social co-benefits and/or broader systemic change.”).

198 The Rockefeller Foundation and Boston Consulting Group (2022) What Gets Measured Gets Financed, 1–72, 14 (“For example, mitigation initiatives will require an average annual investment of roughly $3.4 trillion from 2020 to 2025. CPI climate finance estimates for mitigation efforts alone (roughly $570 billion) suggest an overall financing gap of 83%. When we include data sources that consider some forms of transition finance and some forms of “other” financing, as defined in Chapter 1 of this report, we arrive at a figure of $1.3 trillion, or a financing gap of 66%.”).

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