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Perspective

Restoring Abandoned Farmland to Mitigate Climate Change on a Full Earth

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SUMMARY

Degraded farmlands have been abandoned worldwide, especially in high- and middle-income countries. These lands help combat climate change as they undergo natural recovery of vegetation and soil carbon and remove carbon dioxide from the atmosphere. However, recovery can be slow, requiring decades to centuries to approach pre-cultivation or natural states, and in some cases, soils remain degraded without active restoration. In this perspective, we present an overview of how carbon capture and storage on abandoned farmland can be accelerated and maximized via managing plant diversity as both a means and an end of restoration, creating and applying biochar to soil, and co-developing with renewable energy as techno-ecological synergies. These strategies can jointly tackle climate change and land degradation while contributing to and reinforcing multiple other Sustainable Development Goals. Although challenges exist, adoption of these strategies could be facilitated by increasing governmental and corporate initiatives at global and regional levels, especially developing carbon-offset markets for agriculture.

INTRODUCTION

Earth's soils and vegetation contain about five times more carbon (C) than the atmosphere holds as carbon dioxide (CO_2).[1] A significant fraction of the increased CO_2 in the atmosphere originated from lands now used for the agricultural production of food (>40% of Earth's ice-free terrestrial surface).[2] Additional natural lands continue to be cleared for the creation of new croplands and pastures, a major source of global greenhouse gas (GHG) emissions. Reversing this process, by restoring degraded and abandoned farmlands, has the potential to remove and store climatically significant amounts of atmospheric C.[3] However, the full life-cycle implications of potential changes in land use must be carefully evaluated if we are to maximize their GHG benefits and prevent net GHG harm, such as from land clearing caused by biofuel expansion.[4]

After prolonged and unsustainable cultivation, agricultural soils become degraded and can release up to two-thirds of their original soil C stores to the atmosphere as CO_2.[1] Soil degradation also includes nutrient loss, reduced microbial activity, and deteriorated physical structure, reducing fertility and the capacity to hold water[5] and leading to their abandonment. Such abandonment is particularly common in middle- and high-income countries that have used agricultural intensification to rapidly increase crop yields, but it also occurs in lower-income countries. In the US, the clearing of new croplands from 1980 to 2016 totaled 5.7–8.3 million hectare (ha), and 38.1–48.1 million ha of croplands were simultaneously abandoned.[6] In the EU, a similar scale of farmland abandonment occurred between 2001 and 2012,[7] and another ~20 million ha of farmland (or 11%) are under high risk of abandonment by 2030.[8] Large-scale farmland abandonment has also occurred in Asia, Latin America, and Africa.[9] Global estimates of abandoned farmland vary among studies, but they are potentially large.[9] For example, a widely cited study[10] estimated worldwide abandoned cropland and pastureland (which have not been converted to forest or urban areas) at 385–472 million ha, which is about 26%–31% of global cropland areas (1,500 million ha).[11] Abandoned farmland can undergo natural succession and often will slowly return to a

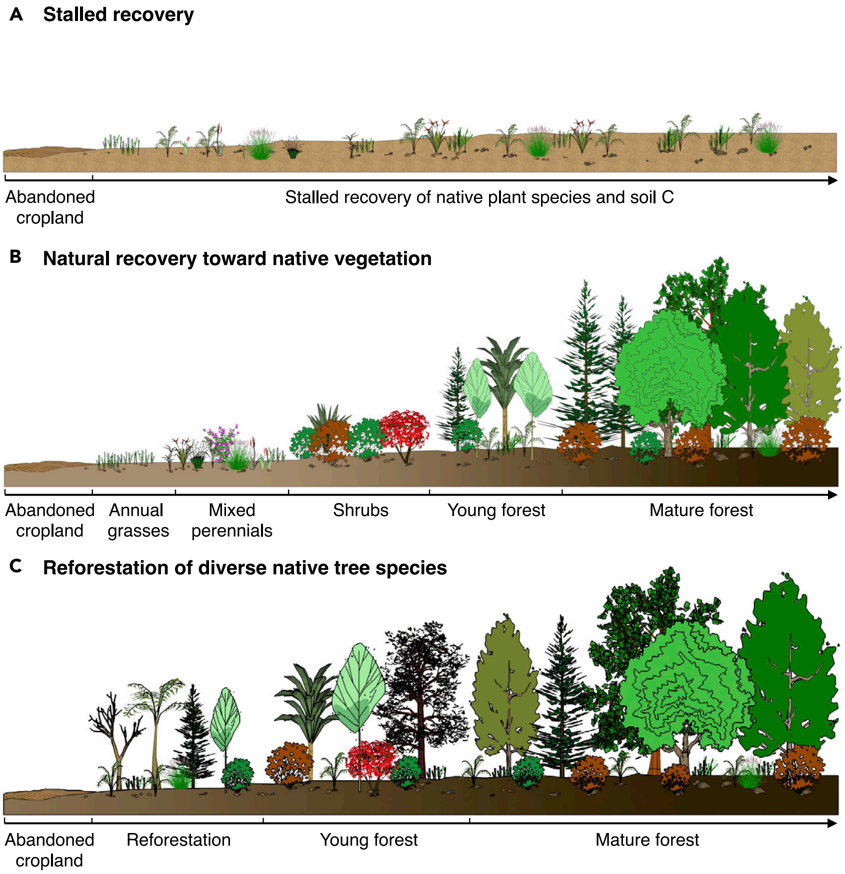

Figure 1. An Illustration of Different Recoveries of Abandoned and Degraded Cropland where the Pre-agricultural Vegetation Was Forest

(A) Stalled recovery, where the degraded land remains degraded, is dominated by annual exotic weeds, and accumulates little soil C.

(B) Natural recovery toward native forest, where the degraded land undergoes several phases from annual grasses to mixed perennials and shrubs and eventually to mature forest, a process that increases soil health (e.g., soil structure, water-holding capacity, fertility, and biotic diversity) and C stocks, as reflected in the darkening of soils.

(C) Reforestation of diverse native tree species after land abandonment could accelerate the process of vegetation and soil recovery. Note that in this example, the pre-agricultural vegetation was forest, and it can also be other types such as grassland and shrubland.

vegetated condition similar to its pre-agricultural state.[12] As this occurs, it can sequester C in vegetation and soils.[13] Severely degraded farmlands that have lost a large fraction of their original soil C have a particularly high capacity for C sequestration.[14] In some cases, however, recovery is very slow or might not occur at all given that some lands remain degraded for decades without active restoration.[15]

Here, we focus on ways to accelerate and maximize the GHG benefits that could be achieved via optimal management of degraded lands arising from agricultural abandonment. Given that the global human population is projected to reach ~11 billion by 2100 and the global per-capita real buying power is projected to increase even more rapidly,[16] we are heading toward an era in which we truly have a full Earth. Thus, finding ways to optimally meet multiple human needs, including for secure and sufficient food supplies and a planet that is kept livable through minimizing global climate change, is essential. In that spirit, we take a big-picture look at several strategies that can accelerate succession—and maximize capture and storage of C—of abandoned farmland. We build upon and extend the body of knowledge around natural climate solutions[17] by focusing on emerging strategies such as restoring plant diversity,[18] creating and applying biochar,[19] and co-developing renewable energy.[20] Abandoned farmland has a degraded ability to provide benefits from the perspective of either economic productivity or biodiversity habitat. These strategies can substantially increase the potential of climate-change mitigation of abandoned farmland while restoring soil fertility, promoting biodiversity, and enhancing other ecosystem services. In other words, they can jointly tackle climate change and land degradation while providing other ecological, environmental, and societal benefits. Below, we elaborate on the mechanisms of each strategy, demonstrate them with case studies, and identify caveats, knowledge gaps, and research needs. We further discuss the broader implications of these strategies, e.g., potential contributions to the United Nations (UN) Sustainable Development Goals (SDGs). Lastly, we discuss emerging policy and market initiatives that could facilitate wide-scale adoption of these strategies.

RESTORATION OF PLANT DIVERSITY

Degraded and abandoned farmlands undergo natural succession and recovery, or passive restoration,[21] potentially toward their pre-disturbance vegetation (Figure 1B). During this process, they sequester atmospheric C in plants and soil to become a globally significant C sink,[22] or they can be actively restored to grassland, shrubland, and forest.[21] Both passive and active means can be important ways to restore degraded lands, increase their C stocks, and enhance other ecosystem services. Many factors contribute to the success of restoration, such as legacies of cultivation, inherent soil properties, and surrounding vegetation.[15] In some cases, degraded land can self-recover within a few decades,[15] and active interventions to convert it to forest or grassland could disturb the recovery.[23] Reviews of global forest recovery, for example, have found that active restoration does not consistently outperform passive restoration.[24] In other cases, however, degraded land remains so or recovers very slowly (Figure 1A). Isbell et al., for example, found that relative to nearby natural vegetation, some abandoned farmlands in Minnesota had only ~75% of plant diversity and 50% of plant productivity nearly a century after abandonment.[25] In such cases, active restoration can aid and accelerate the recovery (Figure 1C).[15] For example, the Miyawaki method has been shown to accelerate forest restoration by planting a dense mixture of mid-late successional species.[26] One of the largest active-restoration projects in the world is China's Grain-for-Green Program (GGP), which has substantially increased C storage on marginal farmlands (e.g., steep slopes) over the past few decades.[27] A review of 63 GGP sites on the Loess Plateau found that rates of soil organic C sequestration on restored grasslands, shrublands, or forests were 92%–215% higher than those under natural recovery.[28]

Active restoration that intentionally promotes the diversity of plant species could further promote total C storage on degraded land. Managing for plant diversity has not been widely practiced in restorations,[29] as reflected in the dominant use of monocultures in global reforestation or afforestation efforts.[30,31] However, decades of ecological experiments have identified biodiversity as a major determinant of ecosystem functioning, including ecosystem productivity and soil C storage.[32,33] Growing evidence indicates that incorporating diverse plant species in ecological restorations can facilitate soil C storage and ecosystem recovery.[18,34–36] Below, we provide an overview of the relevant research and mechanisms of biodiversity's effects on C storage by focusing on forests and grasslands.

In forest biomes, the reforestation or afforestation of former croplands increases C storage because forests take up and store more C per unit land area than non-forested ecosystems,[37] e.g., 17-fold more biomass per unit area than croplands on average globally.[37] C in living woody biomass has a long mean residence time (decades to centuries),[38] so C allocated to wood will remain stored over timescales that are meaningful for slowing climate change unless trees are harvested or otherwise disturbed. Furthermore, inputs of forest litterfall, root detritus, and coarse woody debris to soils build soil organic C stocks in forests relative to annual crops, although initial conversion from cropland to forest could cause transient periods of soil C stasis or even loss.[39]

Greater forest diversity has been linked to higher productivity and biomass in both experimental[40] and observational[41] analyses, although diversity effects are not always apparent.[42] These relationships are most likely supported by a range of mechanisms, including complementary resource use, selection effects, interactions with the plant microbiome, and possibly resistance to natural enemies.[40] For example, in manipulations of tree diversity, species in diverse stands occupied canopy volumes in complementary ways, increasing light interception compared with that in less diverse stands.[43] More diverse stands also exhibited niche partitioning related to belowground resource use.[44] Both the dispersion and identity of functional traits helped to explain variation in net primary production and biomass C stocks across diverse forest types in Spain, indicating the importance of complementarity and selection effects.[45] Forest composition and selection effects can be more important than complementary resource use in driving variation in forest biomass C stocks among stands. For example, in diverse old-growth forest in India, biomass C stocks were negatively related to diversity, and conifer-dominated stands had higher biomass C than hardwood-dominated stands.[46] Interactions with other trophic levels could also mediate the effects of tree diversity on productivity. For example, greater diversity in the leaf microbiome contributed to effects of identity and richness of tree species on productivity in boreal forest experimental stands.[47]

Diversity and composition of forest stands could also influence soil organic C stocks.[48] Higher net primary productivity resulting from greater diversity or compositional effects translates into greater detritus inputs to soils. Effects of forest diversity and composition on soil C stocks also reflect their influence on the decomposition of litter and soil organic matter (through effects on litter chemistry, microclimate, soil chemistry, and decomposer communities). For example, tree species can vary greatly in the C and nutrient chemistry of their leaves and roots and have cascading effects on litter chemistry, soil pH and cation chemistry, and soil decomposer composition and activity, all of which affect litter and soil organic C decomposition. Microclimate variation arising from species variation in canopy cover and light interception also can influence litter decomposition.[49] Growing evidence suggests that mycorrhizal fungi contribute disproportionately to organic matter inputs to soils and that mycorrhizal type strongly influences litter and soil organic C decomposition through diverse mechanisms.[50] For example, arbuscular mycorrhizal fungi (AMF) can promote soil organic C decomposition through priming effects, whereas ectomycorrhizal fungi (EMF) slow rates of decomposition by inhibiting the activity of saprotrophic fungi and because host species and the fungi themselves produce relatively slowly decomposing detritus. However, although greater C stocks are evident in the surface soils of EMF- relative to AMF-dominated forest stands, patterns in deeper soils are inconsistent.[50]

As in forests, greater plant diversity in grasslands is linked to greater aboveground productivity[51,52] and greater belowground C storage in roots and soil.[18,53] In contrast to forest C, most grassland C is stored in soil, and converting annual cropland to perennial grasses can increase soil C stock by 19%–39%.[54,55] Several mechanisms account for the positive effects of plant diversity on soil C storage.[18,53,56] First, more diverse plant mixtures are often more productive[51,52] (e.g., as a result of species complementarity and efficient use of limiting resources) and thus have more root biomass—a major determinant of the formation of soil organic matter.[57,58] An important driver of this mechanism is the nitrogen (N) added by legume species,[58] which, combined with C4 grasses, lead to increased plant productivity, increased direct input of litter and senesced roots, and presumably also increased release of C to the soil through roots to arbuscular mycorrhizal fungi. But diversity can still increase C storage without legumes,[56] presumably because lower N leaching and higher N retention lead to greater productivity and C accumulation. Second, variation in plant traits, such as growth rate, is associated with tissue quality, which directly influences plant tissue decomposition and soil C accrual.[59,60] Third, plant traits can indirectly affect soil C accrual by altering the diversity and activity of the soil microbial community—through symbiotic mutualisms, root architecture, and exudates.[53] These mechanisms have been demonstrated in several long-term grassland experiments.[18,53,56] Given the complexity, more studies are needed to better understand both the underlying mechanisms driving soil C storage[61] and how diversity restorations can accelerate it. Recent studies, however, have shown some promising results. In grassland experiments in Minnesota, for example, high-

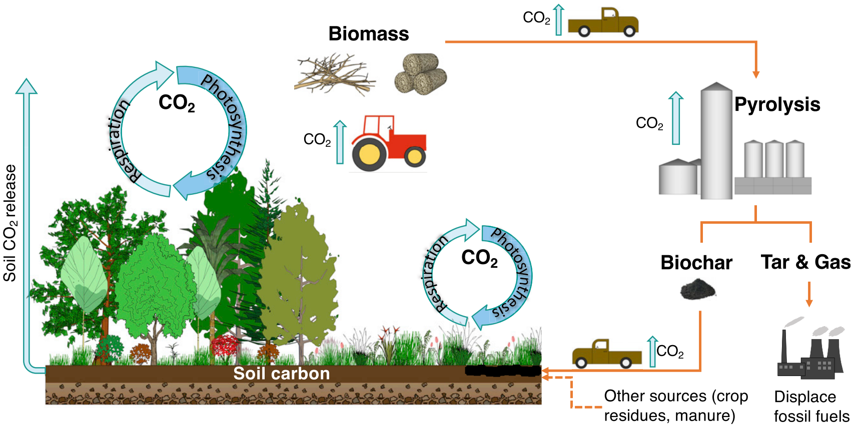

Figure 2. A Biochar-To-Soil System Based on Restored Forest or Grassland on Abandoned Farmland

Feedstocks come from forest residues or grasses and are transported to local small-scale or centralized large-scale pyrolysis plants for conversion into biochar, which is then returned to the soil for C sequestration. Biochar made from other sources, such as crop residues and manure (e.g., from nearby farms), can also be applied. The other co-products of pyrolysis, primarily tar and gas, can be further processed into bioenergy and then displace fossil fuels.

diversity mixtures (with 32 planted species and never weeded) stored about three times as much soil C as monocultures over a 22-year period.[18] Also, in a large-scale survey of natural and restored ecosystems in China, plant diversity was shown to significantly increase soil C across grasslands, shrublands, and forests.[62]

BIOCHAR APPLICATION TO SOIL

Although the total C stock of degraded land increases during restoration, it will eventually saturate.[13] Biochar, a charcoal-like suite of chemicals, can break such biophysical limits of land C storage by directly adding to stable soil C constituents,[63] given that most C in biochar is highly stable because of its polycyclic and aromatic structures with high aryl C contents and high C/N ratios. Biochar is a C-rich product of the pyrolysis process that is used for making liquid biofuels or electricity via heating plant material at temperatures above 300°C anaerobically.[64] Interest in using biochar for various purposes, including land restoration and climate-change mitigation, has been growing,[65] partly because of studies of *terra preta de índio* (Amazonian dark earth) in the Amazon Basin created by Amerindian populations 500–2,500 years ago.[66] This soil is more fertile in that it has higher soil organic matter, pH, plant nutrient availability, and water-holding capacity than surrounding soils, even after thousands of years since abandonment.[66] How long biochar can remain in soils is uncertain and subject to many factors, but estimates of its half-life range from centuries to millennia.[63] For example, biochar was several thousand years older than nonblack C in some soils.[67] This timescale of biochar stability could contribute to efforts to achieve net-zero GHG emissions in the next few decades to avert harmful climate impacts.

Abandoned farmland restored to forest or grassland can form a closed "biochar-to-soil" system that continually removes CO_2 from the atmosphere and stores it in soil and plants (Figure 2). Life-cycle analyses of such biochar-to-soil systems have generally found substantial net GHG savings.[68] In this system, forest residues and perennial grasses are used as feedstocks, and small-scale or mobile pyrolysis facilities convert them to biochar, which is then returned to the soil. The scale of pyrolysis facilities depends on the area of abandoned farmland and overall availability of biomass from crop residues, animal manure, and food waste. Large-scale, centralized facilities are possible if there is sufficient feedstock biomass in the region. Besides producing biochar, pyrolysis also produces tar and gas, which can be used on site (e.g., for process heat) or further processed for making biogas or bio-oil to displace fossil fuels. For forests, removing residues can reduce wildfire risks—which are increasingly exacerbated by climate change—and enhance stand health.[69] But forest residues also provide important habitats for certain fungi and wildlife, recycle nutrients, and help maintain soil moisture.[69] These ecological and hydrological benefits of forest residues must be considered in determining how much residue should be removed for biochar use. For grassland, late-season harvest has no effect on the diversity of plant species,[70] suggesting that proper management can conserve biodiversity while supplying biomass for biochar and C sequestration.

Besides being an external C input, biochar can decrease soil CO_2, CH_4, and N_2O fluxes, but large uncertainties remain. First, biochar can increase or decrease decomposition of soil organic matter by stimulating or inhibiting microbial activities, also known as positive or negative soil-priming effects, respectively.[71] The positive priming effect is generally short lived,[72] whereas the negative priming effect occurs more often.[73] The negative effect is attributed to the protection of soil organic matter from microbial consumption via chemical adsorption on the biochar surface, the promotion of organo-mineral associations, or the formation of soil aggregates.[74] For instance, in a decade-long grassland experiment, biochar helped build native soil organic C via rhizo-deposit stabilization.[19] As with CO_2 emissions, conflicting results have been reported on the effects of biochar on soil CH_4 and N_2O emissions. For example, biochar reduced CH_4 emissions in paddy soils by ~50%–90% as a result of the increased abundance of methanotrophic proteobacteria and inhibition of methanogenic archaeal growth in one study,[75] whereas it significantly increased CH_4 emissions and decreased N_2O emissions in paddy soils in another study.[76] Karhu et al. documented a near doubling of soil CH_4 uptake but no effect on N_2O emissions after applying biochar in an agricultural site previously planted with organic crops.[77] Sánchez-García et al. reported different responses of N_2O emissions to biochar application in two different soils and identified biochar-stimulated nitrification as the main cause of increased N_2O emissions.[78] The negative effect of biochar on N_2O emissions could be due to a biochar-induced increase in the abundance of N_2-fixing microorganisms and improvement in microbial reduction of nitrous oxide.[79]

Meta-analyses have shown that biochar generally reduces N_2O emissions,[80] offers the potential to suppress CH_4 release (especially in flooded and/or acidic soils),[81] and increases native soil organic matter.[82] Even though these are promising results, suggesting potentially greater climate benefits of biochar than direct C sequestration, they might not apply to a particular location of abandoned land. The variable results reported in the literature suggest that responses of soil GHGs to biochar addition are context specific. They most likely depend on biochar and soil properties[83] and are also influenced by many other factors such as climate and management practices. We need to better understand the mechanisms by which biochar affects soil GHG fluxes, especially how different abiotic and biotic factors contribute to such effects, to determine the total GHG-mitigation potential of biochar applied to degraded soils and to inform restoration efforts that minimize the negative impacts of biochar and maximize its positive impacts.

CO-DEVELOPMENT OF RENEWABLE ENERGY

Abandoned farmlands that have flat topography are also ideal recipient environments for the co-development of renewable energy and C-sequestration actions. The co-development of renewable energy and C-sequestration actions could represent a “wholism,” where the summed potential for C savings is unusually large.[84,85] Renewable energy on abandoned farmland can be intentionally engineered and developed as a techno-ecological synergy (TES).[20] By definition, TESs support technological and ecological outcomes in the same area. During construction and operation, wind and solar infrastructure on abandoned farmland can be constructed and operated with “light on the land” approaches that minimize the disturbance of vegetation and soil, thereby reducing C losses—but it is possible to achieve much more. Applying the principles of TES to renewable energy and C sequestration on abandoned agricultural land begins with an accounting of the existing supply and demand of ecosystem goods and services at the appropriate spatiotemporal scale for each renewable-energy project and recipient environment (i.e., project site). Next, information gained from this accounting is used for determining optimal ecological outcomes, which are co-developed with desired technological outcomes (e.g., low-C electricity). Thus, costs associated with TES include those incurred by the development of renewable energy itself as well as robust investments of capital into and management of the ecosystems involved, including, for example, the restoration of vegetation and soils and/or soil amendments that facilitate soil C sequestration.[20,84]

Enhancing C savings in abandoned agricultural land via TES necessitates an understanding of interactions among energy infrastructure, species, and the environment. For example, photovoltaic (PV) solar energy is adversely affected by shading and therefore is ideal to co-locate with plants that are relatively short in stature, notably grasses and other grassland species. Grasslands are a diverse biome notable for high levels of soil organic C and can be more resilient C sinks than forests in places that are under increasing climate-change impacts, such as drought and fire.[86] However, the outplanting of taller plant species, such as maize (*Zea mays*, 1.5–2 m), can in fact be accommodated under and near solar-energy infrastructure with elevated mounting systems, leading to some unexpected yet favorable outcomes. For example, a low-density ($5.0\ \mathrm{kW\ m^{-2}}$), stilt-mounted PV solar-energy system with elevated panels spaced 1.67 m apart increased corn biomass by 4.9% in comparison with a control (no PV).[85] Further, recent advances in wavelength-selective transparent PV that preferentially harvest ultraviolet (UV) and near-infrared (NIR) radiation[87] and transmit photosynthetically active radiation can be advantageous for plants with high potential for C sequestration, such as grasses and cereals, because excess exposure to background UV radiation can reduce their nutrition, biomass, and yield.

Renewable-energy development that incorporates TES principles to support C savings, and other ecosystem services, on abandoned farmland is challenging in that the avoidance of ecological and sociological risks across geographically diverse landscapes is essential. However, knowledge of these risks is increasing. For example, in the Yufutsu Plain of northern Japan, Kitazawa et al. found that the species richness of “openland” birds (defined as birds inhabiting grasslands and wetlands) was higher in abandoned farmland than in areas with ground-mounted solar-energy power plants but that species richness of openland birds in solar-energy power plants was not significantly different than that recorded in pasture and cropland.[88] This result was probably driven by the large number of openland birds that nest in trees given that these were more abundant in abandoned farmland than in areas within solar-energy power plants.[88] It is, however, conceivable that designs of PV arrays can accommodate some trees and their growth (via spacing) without compromising solar-energy generation or economy of scale. Overall, the case of solar development in the Yufutsu Plain illustrates that the development of renewable energy in abandoned farmland could reduce some ecosystem goods and services, in this case, nesting habitat for avian species. Given the modularity of renewable energy, especially that of PV solar energy, TES-based engineering might be able to mitigate such ecological risks and augment ecosystem goods and services from baselines, including those emphasizing C savings.[20]

In addition, siting of renewable energy on abandoned farmland can be considered “land sparing” if the site for development would otherwise have been located in productive farmlands.[89] The latter could result in the permanent loss of agriculturally productive land, raising concerns about food security. Such concerns are especially prominent in places where land for growing food and fiber is increasingly scarce and competitively displaced by other land uses (e.g., urban sprawl). It could also result in indirect land-use change, that is, natural lands in other localities are cleared for the creation of croplands to replace those converted to power generation. The massive diversion of maize from food and feed to ethanol production has resulted in large-scale clearing of perennial vegetation domestically[90] and probably elsewhere.[4] Co-developing renewable energy on abandoned farmland therefore minimizes these risks. Across Japan, for example, the development of ground-mounted solar energy has increased competition for land and the perception of competition for land needed for energy development, food production, and conservation.[91] Coupled with a re-introduction of agricultural activities and/or planting of native plants, the development of PV solar energy on abandoned agricultural lands, especially facilities installed on high, elevated systems, could reduce land scarcity.

Indeed, Irie and Kawahara found that the acceptance of solar-energy development on agricultural land by Japanese people increased if the development did not reduce the amount of land usable for farming or the overall value of the land.[91] In California, marginal farmlands, notable for higher levels of salinity and lower levels of moisture than prime agricultural land, can be subject to higher occurrences of abandonment. In a study of land-sparing opportunities for solar-energy development in the Central Valley of California, Hoffacker et al. identified 850 km^2 of salt- and sodic-affected soils; these marginalized agricultural lands could meet California's projected electricity consumption needs for 2025 (321 TWh) approximately four times over.[92]

BIOENERGY IS A LESS EFFECTIVE CLIMATE SOLUTION

Another use of abandoned farmland is dedicated bioenergy crops,[10] and some deep decarbonization plans rely heavily on the expansion of bioenergy to replace fossil fuels.[93] However, although bioenergy can mitigate climate change, especially when increasing soil C,[94] it is not as effective as the other strategies examined here. Below, we discuss the relative implications of bioenergy versus biochar and wind and solar energy for C emissions, land use, and the economic feasibility of displacing fossil fuels.

Bioenergy is by far the least efficient form of non-fossil energy, from a land-use perspective.[95] Biomass can be directly combusted to produce electricity. Compared with electricity production from biomass, however, that from solar or wind energy is more efficient from the perspective of land use,[96] C emissions,[97] and cost.[98] Wind energy has much lower C emissions than biomass, whereas solar energy is comparable, although both are highly variable in their emissions across locations and project specifics.[99] However, this comparison does not count emissions from biomass combustion, under the assumption that the residue would have ended up decomposing anyway. When emissions from biomass combustion are included, solar energy has a much lower C footprint than combusting biomass. More broadly, replacing fossil-based electricity with solar power leaves biomass uncombusted and available to be sequestered, such as via biochar, enabling a C-negative system. Although capturing and storing combusted C is possible, this technology still faces many geographic, technological, and economic constraints and uncertainties that limit widespread application.[100] One advantage of biomass is that it can be stored inexpensively, allowing electricity to be produced on demand. However, the cost of renewables coupled with storage is reaching price parity with biomass,[98] and new energy-storage technologies are being developed to further reduce these costs.[101] In short, compared with wind and solar energy, biomass presents few advantages for reducing GHG emissions.

An alternative use of biomass is conversion into cellulosic ethanol, which can displace gasoline, but here again, the electrification of vehicles is better from the perspective of land use, cost, and C emissions. Electric vehicles are already cost competitive when fuel and maintenance savings are considered.[102] Electric vehicles are widely expected to displace fossil-fuel vehicles, although there is uncertainty in when, and projections about how quickly this will happen are accelerating.[103] Near-term technological improvements in electric vehicles, namely in the cost and range of batteries,[104] are likely to accelerate this shift. For example, the Tesla Model 3 was the most popular vehicle sold in California in the first quarter of 2020.[105] Electric vehicles are more efficient than combustion engines; with the same feedstock, C emissions per kilometer from converting biomass to electricity for use in an electric vehicle are lower than those from converting biomass to a liquid fuel for use in an internal-combustion vehicle.[106] Manufacturing electric vehicles is more intensive, but this is more than offset by the increased efficiency and reduced emissions from the electricity versus gasoline, and this benefit will only increase as the electricity grid decarbonizes.[107] The increase in electric vehicles necessary to displace gasoline-powered vehicles could be limited by mineral availability,[108] but new technologies are emerging to overcome these constraints.[101]

Turning biomass into biochar and sequestering the C in soils has greater climate benefits than the combustion that releases it to the atmosphere. For example, estimates of the life-cycle benefits of ethanol from residue are 0.36 Mg of CO_2e per Mg of dry biomass.[109] This is optimistic, however, because it assumes no opportunity cost of using the land for biomass production and a 1:1 displacement of gasoline on an energy basis, whereas the actual displacement considering the rebound effect of ethanol in the fuel market is probably much smaller.[110] A recent review suggested a 1:0.5 displacement ratio,[110] which would reduce the benefit of ethanol to 0.08 Mg of CO_2e per Mg of dry biomass. By comparison, converting that biomass to biochar can cause long-term sequestration of 0.58 Mg of CO_2e per Mg of dry biomass.[17,109] In other words, biochar directly removes atmospheric CO_2, whereas bioenergy mitigates climate change by avoiding future fossil-fuel GHG emissions,[111] a pathway that is subject to large uncertainties, such as the rebound effect.[112] Another advantage of biochar is that pyrolysis ovens are relatively inexpensive and even portable,[113] allowing the creation and nearby application of biochar with relatively small emissions from the transportation of biomass, which can be significant when biomass is transported long distances, as can often be the case for wood pellets or ethanol production.[114] To best help the climate, instead of using land to produce biomass for energy, we recommend using wind and solar energy to generate cheap electricity and using biomass to sequester C in the soil as biochar where it might also increase the productivity of abandoned farmlands.[115]

Broader Implications

In this perspective, we have suggested and examined three strategies for accelerating C capture and storage on abandoned farmland. They are restoring biodiversity, creating and applying biochar, and co-developing renewable energy. Besides C sequestration, these strategies provide many other agronomic, ecological, and environmental benefits for both restoration and the environment at large. Especially in grassland and forest ecosystems, plant diversity increases ecosystem stability and resilience against climate extremes, enhances pollination services, and reduces the prevalence of exotic invasions, pests, and plant diseases.[61] Applying the principles of biodiversity-ecosystem-functioning research in restoration has enhanced restoration success. In the western US, for example, restoring shrub-steppe systems is often hampered by annual grasses, but planting structurally complex and diverse mixtures of shrubs, perennial grasses, and forbs reduced weed invasion in comparison with planting perennial grass monocultures.[116] Further, biochar addition to soil can

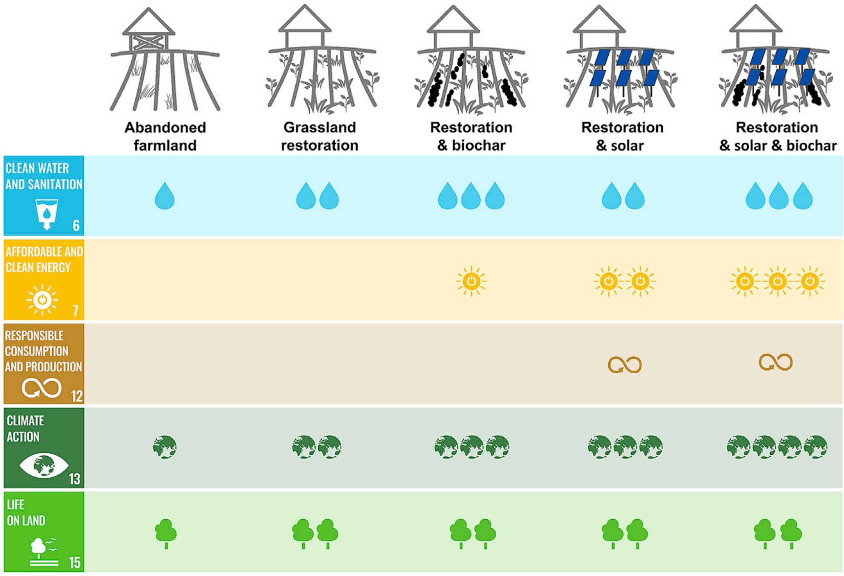

Figure 3. An Illustration of How Different Strategies Contribute to the UN SDGs

Compared with farmland under slow or stalled natural recovery, grassland restoration, together with biochar and solar energy, could greatly increase the land's capacity for climate-change mitigation, contributing greatly to SDG 13 while reinforcing other SDGs. The addition of a small logo under each SDG suggests, qualitatively, a greater contribution.

increase soil water retention and reduce bulk density and loss of nutrients and heavy metals.[69] For example, many agricultural soils have been contaminated by heavy metals, especially copper (Cu); biochar was effective in reducing Cu leaching loss in sandy soils (by up to 48%), most likely because Cu is retained on the biochar surface through complexation.[117] Further, renewable energy installed on abandoned farmland displaces fossil fuels, thus reducing not only GHG emissions but also fossil-fuel-related air pollution, the main contributor to various diseases and premature deaths worldwide.[118] A potential negative effect of forest restoration is reduced water yields, but it can be mitigated by a careful selection of plant species more adapted to water stress.[119] Systematic reviews also suggest that this negative outcome could be biased by a study's temporal and spatial scales, highlighting the need for long-term, large-scale research to better understand how forest restoration affects hydrological balance at the regional level.[119]

These strategies also have positive social and economic impacts and, together with the environmental benefits shown above, can support multiple SDGs. The 17 SDGs adopted by the UN are not mutually exclusive, but they can contradict or reinforce each other.[120] Efforts to mitigate climate change via the development of renewable energy (i.e., SDG 7: Affordable and Clean Energy), for example, can undermine other SDGs via adverse impacts of development processes on biodiversity[121] and ecosystem services broadly.[122] In comparison, active restoration of abandoned farmland via the strategies evaluated above can achieve synergies between multiple SDGs (Figure 3). For example, TESs combined with biochar are a powerful approach that ensures progress of SDG 13 (Climate Action) and SDG 7 and also contributes to SDGs 6 (Clean Water and Sanitation), 12 (Responsible Consumption and Production), and 15 (Life on Land) while reinforcing commitments across all other SDGs (Figure 3).

EMERGING POLICY AND MARKET INITIATIVES

Wide-scale adoption of the above strategies could be hindered by various economic, technical, and cultural barriers.[123] However, emerging policy and market initiatives on global and regional scales could help to overcome these barriers and facilitate adoption of the strategies. Globally, the "4 per mille" initiative launched by the French government and approved under the Lima-Paris Action Agenda calls for countries to increase soil C stocks by scaling up regenerative farming, grazing, and land-use practices.[124] Regionally, the EU's Common Agricultural Policy integrates environmental concerns and land stewardship by linking subsidy payments to "cross-compliance" measures that include maintenance of soil organic-matter stocks. In the US, the Conservation Stewardship Program and the Environmental Quality Incentives Program provide cost sharing for farmers using conservation practices. In Australia, the Emissions Reduction Fund, enacted through multiple governmental acts and regulations since 2011, has been promoting C-mitigation practices and, in early 2019, issued the first C credits to a soil C project. China has also vigorously promoted the conservation and restoration of grasslands and marginal croplands and retention of crop residues on farmland, resulting in substantial increases in soil C sequestration in recent decades.[125]

Voluntary initiatives have also increased in recent years to address soil health and C sequestration; the formation of the Ecosystem Services Market Consortium (ESMC) in 2019 was a major milestone. The ESMC consists of major global food companies and seeks to create, by 2022, an ecosystem-service market that buys credits from farmers who sequester C in soil or improve water quality and then sells the credits to companies for meeting their sustainability goals. It intends to have an impact on ∼100 million ha of cropland and pastureland by 2030 and ∼250 million ha by 2050,[126] representing the most ambitious target thus far by voluntary initiatives. Part of the ambition is supported by advanced technologies, such as remote-sensing satellite imagery, that can greatly reduce monitoring costs, which prohibited previous attempts.[127] Other voluntary C-offset markets recently established by individual companies include Nori's Carbon Removal Marketplace and Indigo Ag's Terraton Initiative, the latter of which aims to fund farmers worldwide to adopt regenerative practices. These voluntary initiatives, especially the C-offset markets, offer great potential to promote the adoption of the strategies examined above.

With regard to co-developing renewable-energy infrastructure on abandoned farmland, local geographies and governance can also facilitate or inhibit these efforts. For example, the Williamson Act of 1965, enacted by the California legislature, has partly reduced the abandonment and/or land-use change of millions of acres, including that due to renewable-energy power plants, by incentivizing land use only for agricultural purposes.[128] As currently written, individual counties have the discretion to determine whether solar-energy development, for example, invalidates Williamson Act contracts between landowners and municipalities.[128] Thus, a Williamson Act amendment that honors contracts for all renewable-energy development, if such development can demonstrate its capacity as a TES, could enhance opportunities for co-location of solar energy with C-savings activities on abandoned farmlands. In addition, seven US states have enacted legislations to promote pollinator-friendly solar development to address habitat loss often associated with grid-scale solar development. Overall, these efforts demonstrate that progress in the co-location of renewable energy and C-sequestration actions for enhancing C savings across different governance systems could require adjustments to policy instruments.

CONCLUSIONS

Climate change is one of the most pressing challenges currently facing humanity; degraded and abandoned farmland presents a unique opportunity to address this challenge. Restoring high-diversity mixtures of native species on abandoned farmland could accelerate its recovery toward pre-cultivation vegetation and soil C, especially where natural recovery is slow or stalled. The C-storage capacity of restored ecosystems can be further increased through the incorporation of biochar made from biomass produced by the abandoned land or from other sources. Restored grasslands could also allow for co-development with renewable energy, such as solar power. Quantitative assessments are needed to determine the extent to which these strategies can contribute to reducing global GHG emissions. A better understanding of how plant diversity and biochar interact with local abiotic and biotic factors can help maximize their positive impacts and minimize the negative impacts on soil C sequestration and on emissions of other GHGs, such as CH_4 and N_2O. Developing C-offset markets for the agricultural sector—enabled by continuous technological advances that allow for more rapid, reliable, and cost-effective measurement of soil C changes—holds promise for turning abandoned farmland into a “climate and ecosystem treasure” in the near future.

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