Practices for Agricultural Climate Neutrality

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Contributor: Lucas Reijnders

Regarding the achievement of worldwide agricultural climate neutrality, the focus is on a worldwide net-zero emission of cradle-to-farmgate greenhouse gases (GHGs), while, when appropriate, including the biogeophysical impacts of practices on the longwave radiation balance.

agricultural climate neutrality greenhouse gases longwave radiation balance practices uncertainty

1. Introduction

Agriculture impacts climate. Contributions to the direct impact of agriculture on climate can come from the emission of greenhouse gases (GHGs), which have an upward effect on the tropospheric temperature, the generation of aerosols which have a cooling effect and changes in albedo: the proportion of irradiation that is reflected [1]. Changes in albedo can have a warming or cooling effect [2]. Changes in vegetation linked to agriculture may, moreover, impact evapotranspiration and turbulence which in turn can affect the longwave radiation balance [3]. Climate warming linked to agriculture can in turn have impacts that additionally affect climate in ways that may quantitively add to the direct impacts. These indirect agricultural impacts on climate can be changes in albedo (e.g., due to reduced occurrence of ice in the Arctic), increased emissions of GHGs (e.g., due to higher soil temperatures in permafrost areas), changes in cloud cover and increases in aerosol emissions (e.g., due to increased numbers of forest fires) [1].

2. Practices That May Contribute to Agricultural Climate Neutrality

2.1. Practices within the Cradle-to-Farmgate System Boundaries

The practices that will be discussed here are ordered on the basis of quantitative statements that have been made as to their potential contribution to climate neutrality, starting with the practice with the largest claimed potential contribution.

2.1.1. Increasing Soil Carbon Stocks

Increasing soil carbon stocks by changing agricultural practices in field farming, focused on reduced tillage (which can reduce the oxidation of soil organic carbon) and increased inputs of organic materials such as harvest residues, has been advocated as a major way to mitigate climate change and achieve carbon neutrality [4][5]. There is a ‘4 per 1000’ Initiative aimed at increasing the yearly accumulation of carbon in agricultural soils, in a way that might offset a yearly GHG emission of about 8–11 petagrams (Pg) of GWP_{100} CO_2 equivalents [6]. In the context of carbon accumulation in agricultural soils, the benefits of adding biochar (pyrolyzed biomass) to soils have been stressed [7][8]. As to the climate benefit of biochar, it must be noted that a cooling effect linked to an expected increase in soil carbon is counteracted by a warming effect due to the impact of biochar on albedo [2][9], the latter not being addressed by Woolf et al. [8] and Stavi and Lal [7]. Whether efforts to increase carbon stocks in mineral soils by changes in agricultural practices can be a major factor in mitigating climate change has been the subject of vigorous debate [5][6][10][11]. A problem regarding predicting carbon sequestration by changed agricultural practices is that the main mechanisms of carbon gains by mineral soils have as yet not been properly identified [12]. All other things being equal, there may be scope for increasing soil carbon stocks by reducing tillage and larger inputs of harvest residues, but the quantitative estimates of actual accumulation are uncertain. In addition, not all other things are equal: the current commitment to additional future warming of climate [1] may impact soil carbon stocks, and the use of biochar to increase soil carbon stocks can lead to additional warming of soils due to its impact on albedo [2]. Available studies suggest that soil warming tends to substantially reduce soil carbon stocks, but the quantification of future warming on carbon stocks is uncertain [13][14][15][16]. It may be concluded that, taking the current commitment to global warming into account, additional soil carbon sequestration in mineral soils by changing agricultural practices is not excluded but the quantification thereof, and thus its contribution to achieving climate neutrality, is very uncertain.

2.1.2. Forest Conservation

The recent development of worldwide agriculture is linked to deforestation [17]. Most of the deforestation is in the tropics, where >90% of deforestation is linked to agriculture [18]. Deforestation causes large emissions of GHGs and for this reason forest conservation has been advocated as a substantial contributor to the reduction in agricultural greenhouse gas emissions (e.g., [19]). Griscom et al. [19] have estimated that forest conservation might reduce the yearly emissions of GHGs by about 3.5 Pg of GWP_{100} CO_2 equivalents. A large part thereof can be allocated as avoided emissions from agriculture. Real-world conservation of forests has, however, proved problematical. It is estimated that of all timber traded worldwide, 15–30% comes from illegal logging in protected forests [20]. The weakness of national forest protection frameworks and neglect or even maltreatment of local populations negatively impact the actual reduction in GHG emissions linked to forest conservation [21]. There is also the occurrence of leakage: the induction of activities that have the opposite effect of greenhouse gas emission reduction, as they are associated with additional emissions of GHGs [22][23]. Leakage, in the case of forest conservation, is partly linked to the migration of local people, who see their livelihoods negatively impacted by forest conservation, and participate in deforestation elsewhere, and partly linked to international and national shifts in the demand for wood and land that can increase greenhouse gas emissions [23]. For instance, better forest conservation in Vietnam has been associated with increased deforestation in neighboring countries [23]. Furthermore, there is the risk that carbon stocks accumulated in protected forests may be lost by forest fires, severe storms, drought and pests, which may be exacerbated by climate change [24][25][26][27][28][29]. Finally. there is the matter of expected further population growth, which increases the demand for food and for that reason, especially in poor societies, tends to be a driver of deforestation [30]. These factors make the real-world feasibility of reducing the yearly emissions of GHGs by about 3.5 Pg of GWP_{100} CO_2 equivalents by forest conservation very uncertain.

2.1.3. Reducing Enteric Methane Emissions by Ruminants

Enteric methane emissions have a large contribution to the greenhouse gas emissions associated with animal husbandry by ruminants (cows, sheep, goats) and are estimated to contribute about 40% to the worldwide GHG emissions linked to animal husbandry (in GWP_{100} CO_2 equivalents) [31]. This amounts to a yearly emission of about 2.3 Pg GWP_{100} CO_2 equivalents. Most of the options to reduce CH_4 emissions focus on changes in the composition of feed [32]. One may find estimates of nationwide enteric methane emission reductions linked to changes in feed composition varying from 30–90% [33][34]. If the latter estimate is taken, changes in feed composition could reduce the yearly emission of greenhouse gases by about 2.1 Pg GWP_{100} CO_2 equivalents. In experimental settings, substantially reduced CH_4 emissions achieved by changing the composition of feed have been shown, but these studies do not exclude the possibility that these reductions are transient [32]. Research regarding the impact of persistent changes in feed composition on methane emissions is lacking [32]. For this reason, quantitative reduction estimates regarding future CH_4 emission by ruminants linked to changes in feed composition are presently very uncertain. Long-term studies on the impact of changing feed composition on enteric methane emissions by ruminants are necessary to reduce this uncertainty.

2.1.4. Replacement of Fossil Fuel Inputs by Solar and Wind Energy

The GHG emissions linked to fossil fuel-powered agricultural machinery are substantial: the current use of fossil fuels by agricultural machinery can be estimated to be responsible for a greenhouse gas emission of 1.0–1.1 Pg of GWP_{100} CO_2 equivalents (based on data provided by Scherer and Verberg [35] and Pellegrini and Fernandez [36]). Both farm-based production of renewable energy and improved farm machinery could be conducive to cutting this emission. Farms can be used for the production of renewable energy. Currently, product outputs of agriculture which can serve the supply of food are used for the production of liquid biofuels. Apart from the use of sugarcane for ethanol production, this presently does not lead to a net reduction in GHG emissions when substituting for liquid fossil fuels such as petrol and diesel [37]. Moreover, as the demand for food is expected to increase greatly in the coming decades, the option of energy crops becomes even less attractive [33]. As to the use of lignocellulosic harvest residues for biofuel, it should be noted that there is a case for applying at least a part thereof to the soil to prevent a reduction in soil carbon stocks, serve soil fertility and protect against soil erosion [38][39]. The remainder of the harvest residues may be applied to the production of power and heating (e.g., [33][39][40]). If these applications substitute fossil fuels, the resulting net reduction in the emission can be used as an offset for greenhouse gas emissions linked to the cradle-to-farmgate lifecycle of agricultural production [33].

Agricultural land is also used for the production of wind power and solar power. Wind power and photovoltaic solar power tend to generate much more energy per m^2 of land than energy crop production. A study regarding three locations across Europe found that, per m^2, wind power generated about 100 times as much energy as energy crops, and photovoltaic modules about 40 times as much as energy crops. [41], are currently associated with substantial lifecycle GHG emissions, but such emissions are much lower than for fossil fuel-based power production [42][43][44] and can be lowered further by a general phase-out of fossil fuel use. Photovoltaic modules installed on farm buildings or agricultural machinery do not compete with crop production. Wind power and photovoltaic modules on agricultural soil can lead to reductions in crop yields. The cradle-to-farmgate greenhouse gas emissions of crop cultivation elsewhere to meet the inelastic demand for food [45][46] have to be accounted for in estimating the climate benefit of agricultural wind power and solar parks on agricultural land. The installations involved can have other owners, but to the extent farm-ownership applies, the installations can directly impact agricultural GHG emissions as they may serve electricity demand on the farm. When the farm owning the installations is a (net) exporter of electricity, the replacement of fossil fuel-based electricity production can be used as an offset for greenhouse gas emissions linked to the cradle-to-farmgate lifecycle of agricultural production. The capital costs of installations for wind and photovoltaic power may be a challenge when implementing the option of farm-owned installations. It is estimated that phasing out fossil fuelks on farms may reduce agricultural the global warming potential of yearly greenhouse gas emisions by about 1 Pg of carbondioxide equivalents..

2.1.5. Replacing Field Farming by Agroforestry

One option to increase the agroecosystem carbon stocks that has been advocated as an important contribution to mitigating climate change is a shift from field farming to agroforestry [7][47][48][49][50][51]. Agroforestry is a set of practices that intercrop trees or shrubs with crops such as grains, vegetables and forages [7][47][49]. Actual gains in carbon stock may concern increased root biomass in soils and increased aboveground biomass, if compared with field farming [7][50][51]. Furthermore, the carbon stock in humus and (partly) decomposed litter can be substantial [51] and the emission of CO_2 from soils can be reduced [48]. The quantity of carbon stock gains depends on the type of agroforestry [7][50][51] and on climate. In temperate climates and under arid conditions, carbon sequestration in agroforestry tends to be lower than under warm and humid climate conditions [52]. Root carbon stocks in agroforestry have been found to be 1.3−20 × 10^6 g per ha and carbon stocks in aboveground biomass 6−172 × 10^6 g per ha [7]. Griscom et al. [19] estimated that a shift to agroforestry might reduce yearly agricultural GHG emissions by about 0.9 Pg of GWP_{100} CO_2 equivalents.

The real-world contribution of agroforestry to climate neutrality depends on crop yields. Under comparable conditions, both higher and lower yields per ha of arable crops in agroforestry have been reported [48][53][54][55]. In the case that trees or shrubs do not serve for food production, and when yields of food crops per ha are lower than those of field farming in comparable conditions, it should be taken into account that the difference between the two systems is likely to be made up by farming elsewhere, as the demand for food is inelastic [45][46]. The climate benefit from agroforestry with lower yields should be corrected by greenhouse gas emissions linked to making up the difference elsewhere, which could reduce the yearly climate benefit of 0.9 Pg of GWP_{100} CO_2 equivalents claimed by Griscom et al. [19]. An additional matter to consider is the location-specific impact of a shift from field farming to agroforestry on albedo, evapotranspiration and turbulence that can affect the longwave radiation balance [49][56][57]. Changes in the radiation balance are covered in some agroforestry models, such as APSIM and DynACof [56], but comprehensive studies of agroforestry on the longwave radiation balance have not been found. It would seem likely that, in the tropics, longwave radiation balances biogeophysically impacted by agroforestry do not invalidate the cooling effect of carbon sequestration, but elsewhere this would seem less likely (cf. [57]). In view thereof, it might well be that the net cooling effect of worldwide agroforestry could be substantially less than the cooling effect linked to a net decrease in agricultural GHG emissions by 0.9 Pg of GWP_{100} CO_2 equivalents. Comprehensive studies are needed for better estimates regarding the impact of agroforestry on climate.

2.1.6. Reducing Methane Emissions from Rice Paddies

Methane emissions for rice paddies have been estimated to contribute about 30% to worldwide agricultural methane emissions [58] and about 6% to worldwide agricultural greenhouse gas emissions (as GWP_{100} CO_2 equivalents), which corresponds to about 0.6 Pg GWP_{100} CO_2 equivalents. Changes in irrigation management aimed at reducing anaerobic conditions in soils, reducing tillage and using rice varieties that can be cropped with relatively low CH_4 emissions have been suggested as practices that can substantially reduce CH_4 emissions [58][59]. Reduced tillage, dedicated rice varieties and changed irrigation practices that do not negatively affect crop yields (which include alternate wetting and drying, mid-season irrigation and intermittent irrigation) might allow for a reduction in the current emissions by about 0.4 Pg GWP_{100} CO_2 equivalents [7][60].

2.1.7. Net-Zero GHG Emission Fertilizer Inputs into Farming

On the basis of data provided by Levi and Cullen [61], it may be estimated that cradle-to-farm synthetic fertilizers are linked to a greenhouse gas emission of about 0.6 Pg of GWP_{100} CO_2 equivalents. Improving the use efficiency of synthetic fertilizers can substantially cut this emission (e.g., [62]). Ouikhalfan et al. [63] have reviewed a set of technological options that might contribute to a net-zero GHG emission fertilizer industry. Some of these options are associated with relatively large reductions in cradle-to-farm greenhouse gas emissions. A large share of the cradle-to farm GHG emissions is linked to fixed-N fertilizers [61][62][63][64]. These originate in the Haber–Bosch process for the generation of ammonia. The Haber–Bosch process currently uses air, water and fossil CH_4 to generate N_2/H_2 synthesis gas for the production of ammonia. Pfromm [65] has proposed the production of N_2/H_2 synthesis gas for the Haber–Bosch process by cryogenic separation of N_2 from air and generating H_2 by electrolysis of water, both powered by wind energy. Soloveichick [66] suggested the electrochemical synthesis of ammonia as an alternative to the Haber–Bosch process. This process can be based on solar or wind power. Both proposals would lead to a major reduction in cradle-to-farm greenhouse gas emissions of synthetic fixed-N fertilizers. Concentrated solar thermal systems can, when insolation is adequate, be used for the supply of process heat in fertilizer, including fixed N and phosphate production [67][68]. Net-zero GHG emission fertilizer inputs into farming would seem technically feasible. This would allow for a mitigation potential of about 0.6 Pg of GWP_{100} CO_2 equivalents. Realizing this potential would seem to need strong incentives.

2.1.8. Reducing N_2O Emissions

Based on data provided by Carlson et al. [69], yearly agricultural N_2O emissions may be estimated at about 0.45 Pg of GWP_{100} CO_2 equivalents. N_2O emissions linked to agriculture originate in the microbial conversion of fixed N. Large amounts of the fixed-N input into farming are lost to the environment [62][70]. One option to reduce N_2O emissions is improving nitrogen use efficiency by reducing the amount of fixed nitrogen not used by crops. This amount can be in the order of 70% and may be reduced to an estimated 15–30% by the use of precision agriculture tools, such as drip fertigation, guidance by indicators for the presence of fixed N, optimized timing of fertilizer addition and polymer-coated fertilizers synchronizing fertilizer release with crop demand [70][71][72]. Improving nitrogen-use efficiency might cut the yearly worldwide agricultural N_2O emissions by about 50% or 0.2 Pg of GWP_{100} CO_2 equivalents [73]. Another option, which has been advocated as a major contribution to the reduction in N_2O emissions, is to apply nitrification inhibitors and urease inhibitors [62][74][75]. These inhibitors can be effective in reducing N_2O emissions when they are close to the fertilizer and are therefore usually integrated in fertilizer formulations [74][75][76][77][78]. Most data (from relatively small-scale experiments of limited duration) are available concerning the use of nitrification inhibitors. Woodward et al. [78], reviewing such data, found that the impacts of nitrification inhibitors vary widely, depending on environmental conditions and management practices, and that climate benefits, in practice, are not always achieved. Ruser and Schultz [74] concluded that N_2O emission reductions from agricultural soils of 35% by nitrification inhibitors seem realistic. A review of available data by Adu-Poku et al. [75] rather suggests that the reduction in N_2O emissions by nitrification inhibitors might be about 9%, but estimates the N_2O emission reduction by urease inhibitors at about 47%. As to the possible emergence of resistance to nitrification and urease inhibitors, available data are limited, but it is known that the microorganisms involved in nitrification and urea hydrolysis vary greatly in their sensitivity to current inhibitors [78][79][80][81]. As the long-term use of nitrification and urease inhibitors may well create a strong selection pressure favoring more inhibitor-resistant microbes, there is the possibility that in the longer term the effectiveness of these inhibitors will be reduced. For this reason, the quantitative estimates of the future climate benefits linked to the long-term use of nitrification and urease inhibitors is currently uncertain. Long term studies regarding the impact of nitrification and urease inhibitors on N_2O emissions are needed to reduce the present uncertainty.

2.2. Afforestation Outside the Cradle-to-Farmgate System Boundaries

If it is not possible to achieve climate neutrality within the cradle-to-farmgate system boundaries, there is the option of offsetting net cradle-to-farmgate GHG emissions by activities outside the system boundaries. Kingwell [82] has suggested afforestation projects in Western Australia to offset agricultural greenhouse gas emissions in the same area. Griscom et al. [19] calculated that, worldwide, in 2030, carbon sequestration by afforestation could offset an emission of about 10 petagrams (Pg) CO_2 equivalents, corresponding with the current net yearly emission of agricultural emissions of GHGs (in CO_2 equivalents). There are several problems that beset the estimates regarding the impact of afforestation on climate change. Firstly, afforestation projects not only have a cooling effect linked to carbon sequestration but may also affect the biogeophysical processes in a way that causes warming. For instance, Breil et al. [3] simulated Europe-wide afforestation on grassland and found a warming effect on the European climate. In a similar vein, Liu et al. [83], simulating longwave radiation balances in an area with forests and agricultural areas in the Nenjang river basin (China), found that the forests had a warming effect. In part, the warming effect is linked to differences between agricultural land and forests regarding evapotranspiration and turbulence that can impact the longwave radiation balance [3][83]. Furthermore, the warming effect is linked to changes in albedo [57]. The warming effect of forests tends to be largest in boreal areas and has a decreasing tendency through temperate to tropical regions [57]. The balances between warming and cooling linked to the change in albedo by afforestation may differ considerably over short distances. Rohatyn et al. [57] studied the balance between warming and cooling under dryland conditions in Israel over a distance of 200 km, focusing on the impact of Aleppo pine trees, and found that it took 213 years for the cooling effect of afforestation with these pine trees to surpass the warming effect due to changed albedo under dry conditions, 43 years under wet conditions and 73 years under intermediate conditions. Against this background, only focusing on carbon sequestration when considering the impact of afforestation on climate, as in the studies of Griscom et al. [19] and Kingwell [82], is inappropriate (also [3]). Furthermore, as in the case of forest conservation, there is the matter of leakage and reductions of carbon stock by pests and extreme weather.

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