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Review

Climate-Neutral Agriculture?

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Abstract: 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. Increasing soil carbon stocks and afforestation have been suggested as practices that could be currently (roughly) sufficient to achieve agricultural climate neutrality. It appears that in both cases the quantitative contributions to climate neutrality that can actually be delivered are very uncertain. There is also much uncertainty about the quantitative climate benefits with regard to forest conservation, changing feed composition to reduce enteric methane emission by ruminants, agroforestry and the use of nitrification and urease inhibitors to decrease the emission of N_2O. There is a case for much future work aimed at reducing the present uncertainties. The replacing of animal husbandry-based protein production by plant-based protein production that can reduce agricultural GHG emissions by about 50%, is technically feasible but at variance with trends in worldwide food consumption. There is a case for a major effort to reverse these trends. Phasing out fossil fuel inputs, improving nitrogen-use efficiency, net-zero GHG-emission fertilizer inputs and reducing methane emissions by rice paddies can cut the current worldwide agricultural GHG emissions by about 22%.

Keywords: agricultural climate neutrality; greenhouse gases; net-zero emissions; longwave radiation balance; practices; uncertainty

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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].

The climate neutrality of agriculture has emerged as a subject in the scientific literature [4–10]. The scope of the studies [4–10] is limited as to geographical coverage and types of agricultural production, Climate neutrality has also emerged in the certification of agricultural products [11]. Additionally, there are publications pointing out that specific practices can be important contributors to climate-change mitigation regarding agriculture [12–25]. These publications consider reducing the emissions of agricultural GHGs and/or increasing carbon sequestration. Commonly, in these studies the direct emissions of greenhouse gases due to agriculture are considered. Increases in GHG emissions due to the contribution of agriculture to climate change are not commonly included in considerations pertinent to agricultural climate neutrality or climate-change mitigation.

System boundaries to agricultural systems considered in the context of climate neutrality (see Figure 1) can vary. Efforts to achieve climate neutrality may exclusively refer to a farm or a set of farms (e.g., [6,11]). The term 'farms' here includes plantations, ranches and greenhouses for horticulture. Changes in agroecosystem carbon stocks to establish or operate farms are included within the system boundaries of farms. System boundaries exclusively encompassing farms may be considered too limited. In farming, physical inputs can be used that have been generated outside the farm. Examples of such physical inputs are machinery, water, fuels, electricity, feed, fertilizers and pesticides. The production and transport of these inputs can be associated with substantial-to-large contributions to the cradle-to-farmgate emissions of greenhouse gases (e.g., [26–29]). The term 'farmgate' denotes the place where agricultural outputs leave the farm. In lifecycle assessments regarding animal husbandry [27,28], substantial-to-large contributions to cradle-to-farmgate emissions of GHGs can originate in the feed acquired from outside the farm—in lifecycle assessments of plant-based agriculture, inputs of energy and synthetic fertilizers can have substantial-to-large contributions to cradle-to-farmgate emissions of GHG [26,29]. To determine the net contribution of agriculture to climate change, system boundaries may be drawn in such a way that physical inputs produced outside the farm are included in efforts to achieve climate neutrality (see Figure 1). Such cradle-to-farmgate system boundaries will be used here in assessing contributions to agricultural climate neutrality.

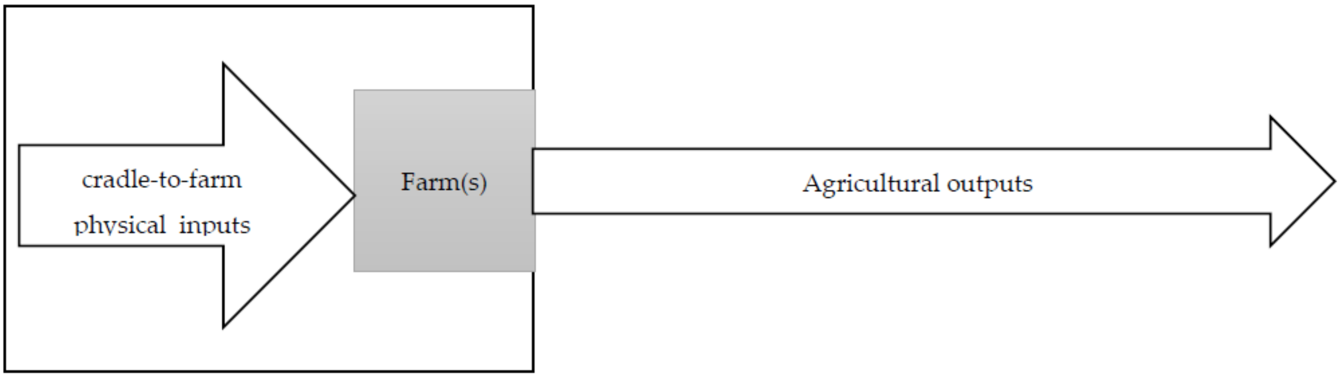

Figure 1. System boundaries for agricultural systems and their impacts on climate. For climate impacts of farm(s), including changes in agroecosystem stocks for establishment: ▪. For cradle-to-farmgate climate impacts of agricultural product outputs: □.

The greenhouse gases that are commonly considered in achieving agricultural climate neutrality are in Table 1. CO_2, CH_4 and N_2O are the main GHGs linked to the cradle-to-farmgate lifecycle stages of agricultural product outputs [17]. Table 1 shows the global warming potentials (GWP) of these GHGs relative to the greenhouse gas CO_2. Global warming potentials are presented as values covering a period of 20 or 100 years. The values covering a period of 100 years (GWP_{100}) are commonly used and will also be used in what follows. It may be noted, though, that for the greenhouse gas CH_4, which has a substantially lower atmospheric persistence than the other GHGs in Table 1 [30], the global warming potential covering a period of 20 years (GWP_{20}) is much larger than the GWP_{100}. If radiative forcing should be limited rapidly, there is, in view of Table 1, a case to prioritize the reduction in (agricultural) methane emissions (see Sections 4.1.4 and 4.1.7).

The current worldwide yearly emissions of the GHGs linked to the cradle-to-farmgate lifecycle of agricultural outputs has been estimated at about 25% of the yearly worldwide emissions of greenhouse gases (as GWP_{100} CO_2 equivalents) [17], which corresponds with the emission of about 10 petagrams (Pg) of GWP_{100} CO_2 equivalents [14].

Table 1. Greenhouse gases commonly considered in achieving agricultural climate neutrality with their global warming potentials relative to CO_2 [31–34].

Greenhouse Gas	Global Warming Potential over a Period of 100 Years (GWP_{100}) Relative to CO_2	Global Warming over a Period of 20 Years (GWP_{20}) Relative to CO_2
CO_2	1	1
CH_4	28–36	83–85
N_2O	265–298	264–289

In this review, practices that have been proposed as important contributions to mitigating the contribution of agriculture to climate change in scientific literature [4–10,12–25] will be discussed to establish the contributions to agricultural climate neutrality that they can deliver. To the best of my knowledge, this is the first time that this has been done. The methodology used will be briefly presented in Section 2. Agricultural climate neutrality is defined in various ways. This matter will be addressed in Section 3. Section 4 will consider practices that may contribute to worldwide agricultural climate neutrality. Section 5 presents the conclusions of this paper.

2. Methodology

The methodology for the gathering of information for this review from the databases of Google Scholar and the publishers MDPI, Springer Nature, Elsevier and Wiley was as follows. Firstly, a search was made using the terms agriculture, farming, crop production, livestock production and climate neutral(ity). This generated a set of publications [4–10]. The practices presented for achieving climate neutrality in these publications are all discussed in this paper, with the practice of farm efficiency [7] restricted to energy efficiency (Section 4.1.5) and fertilizer-use efficiency (Sections 4.1.8 and 4.1.9), without considering rebound effects. With the exception of afforestation (Section 4.2), all practices in these studies [4–10] were within the cradle-to-farmgate system boundaries (Section 4.1). Secondly, the databases were searched with the terms agriculture, climate-change mitigation and review. This produced a set of publications [12–25] which included the following practices for reducing net agricultural GHG emissions that were not covered in the publications [4–10] found in the first search: forest conservation (Section 4.1.3), agroforestry (Section 4.1.6) and reducing the methane emission from rice paddies (Section 4.1.7). The publications collected [4–10,12–25] contained statements regarding potential quantitative climate benefits relevant to the worldwide application of the practices considered in this paper. The publications also contained quantitative information as to the worldwide net greenhouse gas emissions within the system boundaries of Figure 1. An additional search was carried out to obtain missing data regarding agricultural N_2O emissions and the net emissions of GHGs linked to fossil fuel and fertilizer inputs into farming and animal husbandry. Subsequently, the databases were searched for information shedding light on the correctness of the statements in the publications [4–10,12–25] regarding potential climate benefits.

3. Definitions of Agricultural Climate Neutrality

Several definitions of climate neutrality for agriculture referring to greenhouse gases are currently used (see Box 1).

Box 1. Definitions of climate neutrality for agriculture referring to greenhouse gases.

1. Net-zero emission of agricultural GHHG emissions (in CO_2 equivalents) [5,7,8,11]
2. Net-zero increase in radiative forcing by agricultural GHG emissions [6]
3. Net-zero change in current average temperature as impacted by agricultural GHGs [35]

A net-zero change in radiative forcing implies a commitment to a substantial additional rise in temperature [1,36], which would seem at variance with climate neutrality. With that in mind, the second definition will not be used here. The United Nations' Paris Agreement on climate change included a commitment to achieve net-zero GHG emissions in the second half of the present century and the European Union have set a target for achieving this goal by 2050 [37]. No allocation of targets to economic sectors has been made, as yet, under the United Nations Framework Convention on Climate Change or by the European Union. Still, for instance, Danish agricultural organisations have agreed on a net-zero emission of agricultural greenhouse gases to be met by 2050 [7]. When the third definition applies, a target for net-zero emission of worldwide agricultural GHGs should presumably be met well before 2050. In addition, when appropriate, in Section 2 the biogeophysical impacts on the longwave radiation balance of practices that may contribute to achieving agricultural climate neutrality will be considered. These impacts are linked to changes in albedo, evapotranspiration and turbulence.

4. Practices That May Contribute to Agricultural Climate Neutrality

Practices have been suggested that, when applied worldwide, may be important contributions to mitigating the agricultural contribution to climate change. These partly regard increasing carbon sequestration and partly reducing greenhouse gas emissions. Such practices, when within the cradle-to-farmgate system boundaries presented in Figure 1, are addressed in Section 4.1. Section 4.2 discusses the suggested practice of afforestation for achieving climate neutrality, which is outside the cradle-to-farmgate system boundaries outlined in Figure 1. The focus in Sections 4.1 and 4.2 is on the feasibility of achieving important contributions to agricultural climate neutrality. Much thereof is with regard to the feasibility within the realm of the natural sciences. In several cases, matters outside the realm of the natural sciences were found to be crucial as to the real-world feasibility of achieving important contributions. These matters are briefly addressed. In all cases, there are economic matters that impact the real-world feasibility of the proposed practices (e.g., [14,24]), but a comprehensive discussion thereof is outside the scope of the present review. Section 4.3 summarizes what may be concluded from Sections 4.1 and 4.2.

4.1. 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.

4.1.1. 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 [9,15]. 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 [38]. In the context of carbon accumulation in agricultural soils, the benefits of adding biochar (pyrolyzed biomass) to soils have been stressed [12,39]. 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 [2,40], the latter not being addressed by Woolf et al. [39] and Stavi and Lal [12]. 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 [15,38,41,42]. 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 [43]. 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 [44–47]. 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.

There have been efforts to reverse the large carbon losses in drainage-based agriculture on peatlands by rewetting the soils. To the extent that these efforts have been monitored, it appears that greenhouse gas emissions (as GWP_{100} CO_2 equivalents) can be reduced by 70–80%, if compared with drained peatland [48]. Re-wetting peatlands would not allow for their traditional agricultural use, such as for animal husbandry and plantations, but may allow for paludiculture, producing plant-biomass as a basis for potential product outputs [49,50]. A study of GHG emissions for existing wet peatlands generating biomass used as a proxy for re-wetted peatlands with paludiculture did show that net carbonaceous greenhouse gas emissions were substantially lowered, if compared with drainage-based agriculture, but only in one case out of six was a there a net-zero emission [50]. Though data are limited, it would seem likely that the rewetting of peatland can lead to a large reduction in the net emission of GHGs. Net increases in soil carbon of rewetted peatlands have not been demonstrated.

All in all, a large accumulation of carbon in agricultural soils, as envisaged by the '4 per 1000' Initiative, would seem very uncertain. Reducing the present quantitative uncertainty about the scope for increasing soil carbon stocks requires much additional research.

4.1.2. Shifting from Protein Outputs Based on Animal Husbandry to Protein Outputs Based on Crops

Proteins are an important output of agriculture. A large contributor to this output is animal husbandry which contributes an estimated 14.5% to the worldwide emission of greenhouse gases [51], corresponding with a yearly emission of about 5.8 Pg of GWP_{100} CO_2 equivalents. The cradle-to-farmgate GHG emissions per kg of protein show large variations [7,52]. On the basis of the available data, rough estimates may be made of relative average cradle-to-farmgate greenhouse gas emissions (as GWP_{100} CO_2 equivalents) per kg of protein for outputs of animal husbandry, if compared with soybeans or pulses which contain proteins of a quality similar to those of the outputs of animal husbandry. These are shown in Table 2.

Table 2. Rough estimates of relative average cradle-to-farmgate greenhouse gas emissions (as GWP_{100} CO_2 equivalents) per kg of protein from different sources [7,52].

Protein Source	Rough Estimates of Relative Average Cradle-to-Farmgate Greenhouse Gas Emissions (as GWP_{100} CO_2 Equivalents) per kg Protein
Soybeans, pulses	1
Poultry (meat, eggs)	3–4
Pork	6
Lamb	>20
Beef	>20

The data in Table 2 allow for predictions of reductions in GHG emissions linked to changes in worldwide food consumption that are rather certain. Shifting from animal husbandry to the production of pulses and soybeans might lead to a yearly reduction in worldwide cradle-to-farmgate GHG emissions by about 5 Pg of GWP_{100} CO_2 equivalents. This would reduce the current worldwide cradle-to-farmgate GHG emission by about

50%. Shifting from beef to pork and poultry meat and eggs may also lead to a substantial reduction in cradle-to-farmgate greenhouse gas emissions. Such shifts have the additional potential climate benefit that they reduce the demand for land, which in turn might reduce deforestation and/or make land no longer needed for agricultural production available for increased carbon sequestration [53]. However, current and expected demographic trends and developments in eating habits are at variance with such shifts [17]. Still, in view of the large climate benefits linked to shifting from protein outputs based on animal husbandry to protein outputs based on pulses and soybeans, there is a case for a major effort to reverse the trend in food consumption leading to increased animal husbandry-based cradle-to-farmgate GHG emissions.

4.1.3. Forest Conservation

The recent development of worldwide agriculture is linked to deforestation [54]. Most of the deforestation is in the tropics, where >90% of deforestation is linked to agriculture [55]. 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., [14]). Griscom et al. [14] 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 [56]. 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 [57]. 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 [58,59]. 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 [59]. For instance, better forest conservation in Vietnam has been associated with increased deforestation in neighboring countries [59]. 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 [60–65]. 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 [66]. 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.

4.1.4. 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) [67]. 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 [68]. One may find estimates of nationwide enteric methane emission reductions linked to changes in feed composition varying from 30–90% [7,20]. 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 [68]. Research regarding the impact of persistent changes in feed composition on methane emissions is lacking [68]. 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.

4.1.5. 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 [69] and Pellegrini and Fernandez [70]). 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 [35]. Moreover, as the demand for food is expected to increase greatly in the coming decades, the option of energy crops becomes even less attractive [7]. 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 [71,72]. The remainder of the harvest residues may be applied to the production of power and heating (e.g., [7,72,73]). 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 [7].

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. [74], are currently associated with substantial lifecycle GHG emissions, but such emissions are much lower than for fossil fuel-based power production [75–77] 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 [78,79] 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.

Using all-electric farming machinery with improved energy-efficiency and powered by solar power or wind power, to replace current machinery powered by fossil fuels, could provide a substantial contribution to the reduction in cradle-to-farmgate agricultural emissions of CO_2 [16]. It should be noted, though, that in the case of traction, the production of such machinery is likely to be more energy-intensive than the production of the fossil-fuel-powered machinery which is replaced [80]. A variety of all-electric agricultural machinery, that could replace fossil-fuel-powered machinery, has become commercially available. For crop production, this involves commercial electric tractors, multipurpose on-farm electric vehicles and a variety of electric robots (for, e.g., weeding, spraying, seeding) [16]. The development of electric harvesting machinery for cereals has been described [81] and electrical machinery for combine-harvesting of wheat and rice has been designed [82]. Furthermore, there are applications of electric machinery in farming, which are currently operating with an electricity supply based on fossil fuels, that can switch to solar or wind power. There is, furthermore, the application of electric machinery in fruit harvesting [83]. In capital-intensive dairy farming, electric machinery for the harvesting and cooling of milk is commonly used [84], while electric automated feeding systems are emerging [85]. A major effort is needed to increase the commercial availability of commercial electric farm machinery [16] and to lower the GHG emissions linked to the production of such machinery. The capital cost of electric machinery to replace machinery powered by fossil fuels can be a challenge [86]. Indeed, it would seem that strong incentives are needed for cutting emissions linked to farm-based energy consumption. Still, reducing the emission of greenhouse gases linked to the current inputs of energy into farms by 1.0 Pg of GWP_{100} CO_2 equivalents would not seem beyond technical feasibility.

4.1.6. 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 [12,87–91]. Agroforestry is a set of practices that intercrop trees or shrubs with crops such as grains, vegetables and forages [12,87,89]. Actual gains in carbon stock may concern increased root biomass in soils and increased aboveground biomass, if compared with field farming [12,90,91]. Furthermore, the carbon stock in humus and (partly) decomposed litter can be substantial [91] and the emission of CO_2 from soils can be reduced [88]. The quantity of carbon stock gains depends on the type of agroforestry [12,90,91] 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 [92]. Root carbon stocks in agroforestry have been found to be $1.3-20 \times 10^6$ g per ha and carbon stocks in aboveground biomass $6-172 \times 10^6$ g per ha [12]. Griscom et al. [14] 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 [88,93–95]. 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 [78,79]. 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. [14]. 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 [89,96,97]. Changes in the radiation balance are covered in some agroforestry models, such as APSIM and DynACof [96], 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. [97]). 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.

4.1.7. Reducing Methane Emissions from Rice Paddies

Methane emissions for rice paddies have been estimated to contribute about 30% to worldwide agricultural methane emissions [21] 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 [21,98]. 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 [12,99].

4.1.8. Net-Zero GHG Emission Fertilizer Inputs into Farming

On the basis of data provided by Levi and Cullen [100], 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 (cf. Section 4.1.9) can substantially cut this emission (e.g., [25]). Ouikhalfan et al. [23] 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 [23,25,100,101]. 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 [102] 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 [103] 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 [104,105]. 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.

4.1.9. Reducing N_2O Emissions

Based on data provided by Carlson et al. [106], 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 [25,107]. 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 [19,107,108]. 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 [109]. 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 [13,22,25]. 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 [13,18,22,110,111]. Most data (from relatively small-scale experiments of limited duration) are available concerning the use of nitrification inhibitors. Woodward et al. [111], 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 [13] 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. [22] 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 [111–114]. 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.

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

If it is not possible to achieve climate neutrality within the cradle-to-farmgate system boundaries presented in Figure 1, there is the option of offsetting net cradle-to-farmgate GHG emissions by activities outside the system boundaries. Kingwell [5] has suggested afforestation projects in Western Australia to offset agricultural greenhouse gas emissions in the same area. Griscom et al. [14] 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. [115], 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 [3,115]. Furthermore, the warming effect is linked to changes in albedo [97]. The warming effect of forests tends to be largest in boreal areas and has a decreasing tendency through temperate to tropical regions [97]. The balances between warming and cooling linked to the change in albedo by afforestation may differ considerably over short distances. Rohatyn et al. [97] 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. [14] and Kingwell [5], is inappropriate (also [3]). Furthermore, as in the case of forest conservation, there is the matter of leakage, cf. Section 4.1.3. I have been unable to find reliable estimates of leakage associated with recent or current afforestation projects. The risk that carbon stocks may be lost by forest fires, severe storms, drought and pests, which may be exacerbated by climate change [60–65], also applies to afforestation projects. In view of these problems, quantifying the worldwide climate benefit of afforestation would seem very uncertain.

4.3. Discussion

Regarding two of the practices, increasing soil carbon stocks and afforestation, discussed in Sections 4.1 and 4.2, quantitative claims have been made to suggest that they could be currently (roughly) sufficient to achieve agricultural climate neutrality. It appears that, in both cases, the quantitative contributions to agricultural climate neutrality that these practices can actually deliver are very uncertain. There is also much uncertainty about quantitative climate benefits with regard to forest conservation (Section 4.1.3), changing feed composition to reduce enteric methane emission by ruminants (with a claimed climate benefit of about 2.1 Pg GWP_{100} CO_2 equivalents) (Section 4.1.4), agroforestry (Section 4.1.6) and the use of nitrification and urease inhibitors to decrease the emission of N_2O (Section 4.1.8).

The replacement of animal husbandry-based protein production by plant-based protein production, using soybean and pulses (which can reduce cradle-to-farmgate agricultural greenhouse gas emissions by about 50%) is technically feasible but at variance with current and expected trends in worldwide food consumption. There is a case for a major effort to reverse these trends. Other practices discussed in Section 4.1 and the estimates of net reductions in current yearly agricultural GHG emissions that might be achieved by their worldwide implementation are summarized in Table 3. The sum of the net reductions presented in Table 3 is 2.2 Pg of GWP_{100} CO_2 equivalents. It can be concluded that the feasibility of achieving climate neutrality by the practices discussed in Sections 4.1 and 4.2 is presently uncertain.

Table 3. Estimates of net reductions in current greenhouse gas emissions that might be achieved when practices discussed in Section 4.1 are applied worldwide.

Practice	Number of Section Where This Practice Is Discussed	Estimate of Net Reduction in Yearly Current GHG Emissions That Might Be Achieved When Applied Worldwide in Pg of GWP_{100} CO_2 Equivalents.
Replacement of fossil fuel inputs by solar and wind energy	4.1.5	1
Reducing methane emissions from rice paddies	4.1.7	about 0.4
Net-zero greenhouse gas emission fertilizer inputs	4.1.8	about 0.6
Reducing N_2O emission by improving nitrogen efficiency	4.1.9	about 0.2

5. Conclusions

In determining agricultural greenhouse gas emissions and the impact of practices aimed at achieving climate neutrality, a cradle-to-farmgate perspective is preferable. The current worldwide yearly net cradle-to-farmgate emission of GHGs has been estimated at about 25% of the yearly worldwide emission of greenhouse gases and amounts to about 10 Pg of GWP_{100} CO_2 equivalents/year. As to achieving agricultural climate neutrality, the focus here has been on a worldwide net-zero emission of cradle-to-farmgate greenhouse gases while, when appropriate, including the biogeophysical impacts of practices on the longwave radiation balance. Practices which have been mentioned as important contributors to mitigating the agricultural contribution to climate change have been discussed. Increasing soil carbon stocks and afforestation have been suggested as practices that could be currently (roughly) sufficient to achieve agricultural climate neutrality. It appears that in both cases the quantitative contributions to climate neutrality which these practices can actually deliver are very uncertain. There is also much uncertainty about the quantitative climate benefits with regard to forest conservation, changing feed composition to reduce enteric methane emission by ruminants, agroforestry and the use of nitrification and urease inhibitors to decrease the emission of N_2O. The replacement of animal husbandry-based protein production by plant-based protein production, using soybean and pulses, that reduces yearly agricultural GHG emissions by about 5 Pg of GWP_{100} CO_2 equivalents, is technically feasible but at variance with current and expected trends in worldwide food consumption. There is a case for a major effort to reverse these trends; replacing fossil fuel inputs by solar and wind energy and net-zero greenhouse gas emission fertilizer inputs with a combined estimated net yearly GHG emission reduction of about 1.6 Pg of GWP_{100} CO_2 equivalents seem technically feasible, but the realization thereof would seem to require strong incentives. Reducing methane emissions from rice paddies and reducing N_2O emissions by improving nitrogen efficiency might have a combined estimated net yearly GHG emission reduction of about 0.6 Pg of GWP_{100} CO_2 equivalents. It can be concluded that the feasibility of achieving climate neutrality, given the current worldwide net emissions of about 10 Pg of GWP_{100} CO_2 equivalents/year, by the practices discussed here is currently uncertain. Much additional work is needed to reduce this uncertainty.

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