CHAPTER 30

MENU ITEM: FOCUS ON REALISTIC OPTIONS TO SEQUESTER CARBON IN AGRICULTURAL SOILS

Some researchers are optimistic about the potential for large-scale sequestration of carbon in agricultural soils. Other researchers are more skeptical. This chapter analyzes both optimistic and more pessimistic claims and concludes that the realistic potential for sequestering carbon in agricultural soils is limited and that efforts should focus on sequestration as a cobenefit of boosting productivity, with a goal to stabilize soil carbon.

The Sequestration Debate

Many strategies for agricultural GHG mitigation have focused less on directly reducing agricultural emissions and more on offsetting them by sequestering more carbon in soils or trees on agricultural land.[265] The 2007 integrated assessment of the IPCC, the so-called AR4, estimated that various forms of carbon sequestration on agricultural land provided 80–90 percent of the global technical and economic potential for agricultural emissions mitigation.[266] The subsequent assessment, the AR5, in 2014 reproduced this figure.[267] The analysis that went into this figure has remarkable staying power: a 2017 paper in *Nature* quantifying estimates of the mitigation potential for soils in agriculture is based on essentially the same modeling analysis that generated the AR4.[268] Today, there is also a major international initiative with the stated goal of increasing global soil carbon by 4 percent per year, which would remove more than 4 Gt of carbon dioxide from the atmosphere each year.[269]

Some of these climate mitigation strategies focus on restoring agricultural land to forests or other natural vegetation. We explore these strategies in Chapter 20 and conclude that some important options exist to reforest both marginal and realistically unimprovable agricultural land, and that restoring drained peatlands should be a priority. Much larger-scale reforestation depends on—and must wait for—a high level of success in implementing the strategies described in this report.

The claim of large potential to store carbon in soils gained wide attention with publication of a paper in *Science* in 2004.[270] As this paper argued, use of land for cropland has undoubtedly led to great carbon loss, which is probably on the order of 25 percent of the carbon within the top meter of soil.[271] Loss rates, however, vary greatly and are probably due in part to management. At least some management practices can undoubtedly increase carbon in soils, such as adding manure, mulch, or more crop residues. There is also no doubt that many grasslands have lost carbon and could store more.

Claims of achievable carbon sequestration rates per hectare vary,[272] but, if all of the world's agricultural lands could sequester 0.5 tons of carbon per year, then the world could achieve something on the order of 2.5 Gt of carbon storage each year (roughly equal to 9 Gt of carbon dioxide, almost 20 percent of annual anthropogenic emissions from all sources).[273] Supporters of such soil carbon sequestration efforts also cite multiple cobenefits, such as aiding productivity and helping soils hold water and resist droughts, which would increase resilience to the rainfall variability likely to result from climate change. Many researchers have continued to make the case for large soil carbon sequestration potential using approaches that are, in effect, based on the physical potential of agricultural soils to store more carbon and the fact that a variety of practices can in theory increase soil carbon.[274]

In response to these claims, a number of other researchers have published articles expressing strong disagreement.[275] Our analysis of these claims leads us generally to side with the doubters. We believe that the realistic potential for soil carbon sequestration is far more limited than has been claimed and that before soil carbon sequestration can be treated as an offset for other emissions, it needs to be used to stabilize current global soil carbon stocks.

The Challenge

There are only two ways to boost soil carbon. One is to add more carbon to soils, and the other is to lose less. Losing less primarily means trying to manage soils so that microorganisms are less effective at consuming carbon and respiring it back into the atmosphere. We agree with the observations of others that carbon sequestration claims based on adding more carbon have frequently double-counted carbon sources, and that there are serious scientific, technical, and economic doubts about the ability to manage soils to starve microorganisms.

Building soil carbon with manure, mulch, and crop residues

Farmers can build soil carbon by cutting up parts of trees and shrubs and adding the mulch to soils, by adding manure, and by leaving more crop residues in the soil.[276] Yet in each case, the primary effect is to divert carbon from some other storage location or use to storage in soil. Pruning and mulching trees only shifts carbon from above-ground to below-ground storage—unless the trees were going to be pruned and burned. (As discussed in Chapter 7 on bioenergy, even though trees might eventually grow back, cutting down trees to use them for energy will increase carbon in the atmosphere for decades, and cutting wood to add to soils is likely to do so as well.)[277] Cows produce a given quantity of manure, so using manure on one farm usually means using less in another place. Although some crop residues are burned, most that are not already left on the soils are used for animal feed or household energy, so their use as mulch has both economic and carbon costs because their replacement as fuel or feed also causes emissions.[278]

Available carbon is finite, and any calculation of the sequestration benefits when carbon sources are used as a soil amendment in one location must count the costs of not using that carbon for another purpose or for soil amendment in another location. This calculation is typically ignored by the more optimistic carbon sequestration analyses.

There are some sources of wasted or inefficiently used carbon, such as organic municipal waste now landfilled, that could be added to soils. In China much manure is discharged directly into streams,[279] so diverting this manure onto farm fields would avoid pollution and sequester additional carbon in soils.

Another potential source of soil carbon is crop residues that are currently burned. These arise in some cropping systems including sugarcane harvested by hand, rice straw in much of India, and many cereals in northeastern China.[280] Crop residues are burned for a variety of reasons: to get rid of bulky wastes; to make it easier to harvest some crops, particularly sugarcane; to control pests; and sometimes to improve the pH of soils. The need to burn residues can be reduced by mechanization and pesticide use. For example, in Brazil, the shift to mechanized harvesting of sugarcane has greatly reduced burning of sugarcane leaves and appears to contribute to higher soil carbon compared to burned systems.[281]

The potential soil carbon gains from further residue incorporation are limited, however, if only because only around 10 percent of crop residues are burned.[282] According to FAO estimates for 2016, these residues globally amounted to only 381 Mt of dry matter, which therefore probably contain 190 Mt of carbon. The amount of carbon in residues incorporated into soil probably depends heavily on availability of nitrogen, but may be around 10 percent in nitrogen-rich environments.[283] Therefore, elimination of all residue burning and incorporation of all residues into soils would result in soil absorption of only about 19 Mt of carbon, equivalent to roughly 70 Mt of carbon dioxide per year, or less than 1 percent of likely agricultural production emissions in 2050.

Even increasing these estimates severalfold would create soil carbon gains on cropland of only a small fraction of the more enthusiastic estimates. It would also require overcoming the many practical challenges faced by farmers who burn residues to control pests and reduce soil acidity, and who lack mechanized means to mulch residues.

Crop residues are also commonly targeted as feedstocks for biofuels. We are sympathetic to the use of residues as a soil amendment primarily because of likely benefits for soil fertility, which include not just increased carbon content but other improved soil properties.[284] Yet this use reduces the potential for biofuels even more than we analyze in Chapter 7.

Overall, there is probably some potential to add otherwise underutilized organic material to soils, but the quantities are limited and there are real obstacles.

Reducing carbon losses through changes in tillage practices

In the normal course of farming, crop roots and residues left in the field help replenish carbon released into the atmosphere by soil microbes. Much hope has rested on "no-till" techniques that drill seeds into the ground without turning over the soil. Because the original plowing of grassland or of cut-over forests contributed to the loss of soil carbon, the plausible theory has been that reducing annual soil turnover should expose less of that soil carbon to decomposition by microbes. Many field studies initially appeared to support this view.[285] But in 2007, a scientific debate broke out when some researchers pointed out that past studies focused only on shallow soil measurements, often the top 10–30 centimeters, and that studies measuring soils to a depth of a full meter showed no consistent pattern of change in soil carbon.[286] In effect, analyses measuring carbon only at shallow depths ignored a variety of potential ways in which tillage could transfer more carbon deeper into the soil, so even if no-till practices increase carbon in the top layer of soil, that might be offset by reduced carbon at lower depths.[287] Scientists defending no-till argued in return that the statistical variability in measuring soil carbon changes at depth blocked any solid conclusion that soil carbon gains had not occurred,[288] but the proper inference is that we do not really know.[289] A consensus appears to be emerging that results are highly variable. In some areas, no-till appears to have no effect on soil carbon, and in other areas it appears to have a small effect of perhaps 0.3–0.4 tons of carbon/hectare/year (tC/ha/yr) (assuming continuous use).[290]

No-till has probably been most widely adopted in Brazil where, in 2012, the practice reached 29 Mha,[291] roughly half of all cultivated land. High adoption rates in Brazil probably reflect the high risk of soil erosion due to intense storms and the discovery of some additional agronomic benefits; for example, reductions in soil acidity. Brazil also widely cultivates glyphosate-resistant soybeans, so farmers can use glyphosate to control weeds without the need for tillage. No-till in Brazil tends to persist year after year. A number of studies have shown that the consistent practice of no-till—at least of recently cleared areas in the Cerrado—has maintained soil carbon levels comparable to those of soils under natural vegetation, while areas under conventional tillage have lost carbon.[292]

Where no-till generates small carbon gains, it still faces many practical challenges.

No-till agriculture is hard to maintain over time. Outside of Brazil, even where no-till is practiced, periodic plowing still commonly occurs to control weeds, deal with soil compaction or meet other agronomic needs.[293] There are virtually no data about how many farms employ truly long-term no-till, meaning no-till practiced for 10 or 20 years, but the data show that continuous no-till even for 10 years is infrequent. For example, in one complicated analysis of Iowa using data from the 1990s, the authors estimated that the probability of no-till persisting for even two consecutive years was only 8 percent, with the vast majority of farmers practicing no-till for a single year.[294] A study by the U.S. Department of Agriculture using more recent data estimated that only 13 percent of cropland in the Upper Mississippi River basin was in no-till for three consecutive years, the maximum period for which data could be assessed.[295] Regular or even occasional plowing probably causes much or all of any soil carbon gains to be lost, although there is some uncertainty because the data are so limited.[296]

Nitrous oxide emissions may increase. There is evidence that if practiced for only a few years, no-till may increase nitrous oxide emissions by temporarily saturating some portion of soils immediately after rainfall, leading to the low oxygen conditions that encourage nitrous oxide formation. This nitrous oxide can cancel out the benefits even of large carbon gains.[297] However, there is also evidence that nitrous oxide emissions decline after 10 years of continuous no-till on those limited areas that practice no-till that consistently. These contrasting results heighten the importance of whether no-till cultivation is practiced persistently.

No-till may reduce yields or increase costs. For many farms, no-till probably decreases yields although effects are variable. No-till appears to result in lower yields on average in wetter climates but to boost yields on average in some drier climates if combined with other practices.[298] Again, a key point is that there is high variability, but the yield consequences of practicing no-till are obviously an obstacle to adoption in many areas. Projections of large potential global carbon gains do not address this issue.

Finally, as discussed in Chapter 13 on soil and water conservation, there can be other challenges to adopting no-till, particularly in developing countries. They include the increased need for herbicides, and sometimes additional labor.

To put these numbers in perspective, if we assume that even one-third of the world's croplands were cropped using no-till—a big assumption given adverse yield and other practicable challenges on much cropland—and if we further assume that no-till is persistent on half of these croplands and that there are no offsetting nitrous oxide emissions—more big assumptions— and that half of these lands sequester carbon at 0.4 tC/ha/yr while the others do not, then the total mitigation would be ~200 $MtCO_2$ per year globally. This level of mitigation would offset only around 2 percent of likely agricultural production emissions in 2050, which would be a small contribution from such expansive efforts and given such optimistic assumptions.

Sequestering carbon on grazing land

Early studies were optimistic about the potential to increase carbon on grazing land, often by reducing the number of grazing animals.[299] Subsequent analyses have shown that the impact of improved rangeland management practices on soil carbon is highly complex, site-specific, and hard to predict.[300] In some grasslands, reduced grazing leads to more soil carbon and in some places it leads to less. Stranger still, truly poor grazing practices that undermine grassland productivity may actually promote carbon sequestration in some savannas by favoring tree growth.[301] Even in New Zealand, where grasslands are intensively managed and carefully studied, there is a high level of scientific uncertainty over the soil carbon effect of different management practices.[302]

In some cases, the claimed gains from improved grassland management probably reflect the ongoing benefits of efforts to restore cropland to grazing land. For example, one paper with careful grassland measurements in the southeastern United States, which has been cited for showing the potential gains of "improved management on grazing lands," studied a site that had recently been converted from cropland to grassland.[303] Newly established grasslands appear capable of building soil carbon quickly, and as Smith (2014) points out, may continue to gain carbon, although in declining amounts, for 100 years.[304] However, like forests, they will eventually reach an equilibrium. Management appears capable of altering the rate at which they gain carbon, but the benefits that should be counted are only the increase in the rate, not the total gain, and this increased rate may not change the ultimate carbon stock the grassland will achieve.

This long-term recovery of carbon stocks is just one of many issues to be considered when assessing claims that improved grazing can result in "climate-neutral" beef, in which soil carbon gains would cancel out emissions from animals.[305] Some studies of European grazing lands directly measured soil carbon, with some reporting these lands gaining carbon and others losing it.[306] A recent large European research project used a form of air monitoring at 15 sites to measure carbon fluxes in and out of soil and vegetation and found net gains of 0.76 tC/ha/yr.[307] That is a large figure, representing perhaps three-quarters of the common estimate of carbon sequestration by grasslands that have been newly reestablished on cropland. It was surprising because science has generally shown that long-established grasslands typically reach an equilibrium in which they stop gaining carbon.[308]

Unfortunately, this argument does not prove that carbon gains were caused by the grazing operation and does not compare the consequences of grazing to the counterfactual of not grazing. Part of the explanation may be that many of these grasslands are still recovering from previous plowing, so the gain would occur whether these lands were grazed or not.[309] In subsequent papers, the European researchers and others explain the results using modeling; they attribute half of the carbon gain to reduced numbers of animals grazing—leaving more biomass to be returned to the soil—and half to climate change and the associated rise of carbon dioxide concentrations, which stimulated more plant growth.[310] Yet if the carbon gains are the result of climate change, they would happen anyway and should not be attributed to grazing operations. In fact, assigning carbon gains to the grazing land ignores the far greater levels of carbon the land would sequester if it were allowed to return to forest, which would be the fate of the vast majority of European grazing lands if they were not grazed.[311]

In addition, moving toward less intensive grazing in Europe, even if it resulted in more carbon gains on European pasture lands, would probably lead to greater aggregate emissions globally if this shift resulted in reduced milk and meat production in Europe. Assuming the same level of global consumption, these efforts would necessitate increased production of milk and meat in regions where farming is less efficient (i.e., lower output and higher emissions per hectare), and would therefore likely trigger pastureland expansion in those regions.

We believe that a paper[312] claiming potential for "carbon-neutral" beef in the United States using only grazing land suffers from similar limitations. The authors estimated that carbon-neutral beef would require twice as much land per cow as the standard alternative using some feedlots, but they did not count the GHG emissions that would occur as more forests and savannas globally are converted to pasture. Even in an ideal situation of globally reduced agricultural land area, more grazing land would reduce the potential to sequester carbon through reforestation.

For reasons we discuss below, we believe that carbon gains on grazing land are possible but that early estimates of high potential cannot be justified.

Need for additional soil nitrogen

In 2011, Kirkby et al. pointed out that lack of nitrogen presents a major challenge to efforts to sequester carbon.[313] Soil organic matter is sequestered over the long term through microbial activity that requires 1 ton of nitrogen for roughly every 11 tons of carbon. By contrast, plant material on average has only 1 ton of nitrogen for every 100 tons of carbon. To sequester more carbon therefore requires more nitrogen, which Kirkby et al. (2011) calculated at around 80 kg of additional nitrogen for each ton of carbon. This additional nitrogen must be surplus to the amount used by plants.

In a 2017 comment, a number of other academics argued that this need for nitrogen made carbon sequestration an unrealistic climate mitigation strategy in light of both the practical challenges and environmental concerns associated with the additional nitrogen.[314] They calculated that achieving the goal of sequestering 1.2 Gt of carbon per year established by the 4 per 1000 Initiative[315] would require a 75 percent increase in the global application of nitrogen.

A number of academics known as champions for soil carbon sequestration wrote a response that only partially disagreed.[316] They did not challenge the need for vast amounts of nutrients to build soil carbon, and they agreed that trying to supply these nutrients through synthetic fertilizer would be too expensive and environmentally unwise. But they argued that regions with surplus nitrogen and other nutrients could supply the nutrients needed for soil carbon sequestration.

One major implication of this argument is that soil carbon sequestration at scale, sufficient to mitigate climate change, is enormously challenging at this time in sub-Saharan Africa. Much of the region is nutrient-deficient and is still far from being able to provide enough nitrogen even to grow crops. Building soil carbon would require nutrient additions that are high enough both to fully feed crops and to leave a surplus of nutrients to build soil carbon. This limitation does not undercut the importance of boosting soil carbon as part of the larger effort to improve yields and resilience in the region, but it does suggest that building soil carbon in this region to levels that would significantly affect carbon concentrations in the atmosphere is not feasible.

It remains highly uncertain how much even areas with nutrient surpluses could build soil carbon at scale without additional nitrogen applications. Nitrogen is released by soils or applied as fertilizer at particular times and in particular molecular forms. Microbes that turn plant carbon into stable carbon in humus probably cannot always take immediate advantage of all of this available nitrogen before it is lost from the field. A compelling study found that, if nitrogen is not available when carbon is added, soil microbes would break down existing soil organic matter in order to access the nitrogen embedded with it that would allow the microbes to feed on the new carbon source. This process would lead to a loss of soil carbon overall.[317] To build soil carbon by adding crop residues or other carbon sources (i.e., without deliberately adding more nitrogen), this study suggests that nitrogen from earlier fertilization must be freely available in soils or that it must be present in reasonable quantities as part of the added carbon material (as it is in manure or the residues of legumes).

The need for additional nutrients is a fundamental challenge to sequestering soil carbon and has received far less attention in the literature than it deserves. At the very least, it limits the capacity to sequester additional carbon in soils without the additional expense and the risk of further pollution (including GHG emissions) from additions of more nitrogen to the agricultural system.

Carbon gains or reduced losses?

Another important factor that is little discussed is the reasonable probability that the world is actually losing soil carbon today. The main goal (and likely effect) of efforts to sequester soil carbon may be to avoid further losses rather than to generate gains. One issue is that many of the studies claiming soil carbon benefits from different practices do not differentiate between actual soil carbon gains and reduced losses.[318] There are many technical reasons, including the availability of nitrogen, why it might be easier to reduce losses than to build additional carbon.

Current fluxes in agricultural soil carbon vary by region. For example, there are claims of relatively modest soil carbon gains overall in China,[319] conflicting estimates of soil carbon in the United States,[320] and estimates of soil carbon loss in Europe.[321] In general, global nitrogen studies provide the main reason to believe that carbon stocks on cropland are decreasing globally. Because nitrogen is needed to store carbon in soils, a loss of nitrogen from croplands implies that soils are losing carbon. Today, global studies that attempt to account for all inputs and outputs of nitrogen estimate that soils are losing tens of millions of tons of nitrogen.[322] In other words, even after accounting for all nitrogen that is applied to croplands, the amount of nitrogen that is removed by crops or lost to air or water indicates that, on balance, there is a net loss of nitrogen from soils. Although uncertain, if one estimate of nitrogen loss from croplands producing cereals is correct, then global soil carbon losses from these crops alone would account for 50 million tons of CO_2 emissions per year.[323]

Ton for ton, reducing the global loss of carbon is just as important for mitigating climate change as increasing global sinks, but standard global climate assessments do not assume any ongoing soil carbon losses on existing cropland, aside from peatlands. Because of the uncertainty, our model does not assume such losses either.[324] However, if these nitrogen budgeting studies are correct, then our projected emissions—and the projections of other modelers—are too optimistic. Additional management practices will be needed just to maintain soil carbon levels and reduce emissions to bring them into line with current projections.

Complexity of the soil carbon issue

Despite the complexity of the issues presented, our discussion still fails to communicate the full degree of uncertainty about nearly all features of soil carbon.

Accuracy of soil carbon measurements. Whether analyses are based on accurate measurements is itself a major issue. Today, it is commonly agreed that soil carbon measurements need to be taken at a depth of a full meter and adjusted to take account of the different density of soils at different depths to generate proper carbon content measurements. But vast quantities of soil data have not been collected in accordance with these practices. As a result, some meta-analyses exclude much data and end up relying on limited sources and still need to adjust for some inadequacies.[325] Many others simply rely on data measured to limited depth.[326]

Another big issue, rarely explicitly addressed, is how to define soil carbon. Much plant residue remains, at least for some time, in small pieces that will decompose as microbes turn it into more stable material. If some of this material is measured as soil carbon, there can be the appearance of large gains. At least one study that carefully considered this issue had to exclude much global soil carbon data because they not been gathered in ways that excluded larger residue particles.[327]

In addition, determining soil carbon changes over a few years is challenging because the amount of change is small by comparison with the total stock of carbon in the soil. Soils are heterogeneous and tillage practices can result in different surface configurations. Even when measurements are taken by scientists renowned for their care, different measurement techniques can result in dramatically different estimates.[328]

Accumulation and retention of soil carbon. The processes that affect accumulation and retention of carbon in soil are also enormously complex. In 2013, a large group of prominent soil scientists published an article, "The Knowns, Known Unknowns and Unknowns of Sequestration of Soil Organic Carbon," whose dominant lesson was the scope of the known unknowns.[329] Although adding carbon and nitrogen are inherently critical to building soil carbon, in some cases each is known to decrease soil carbon by "priming" microorganisms to become more active and consume more of the previously stored carbon. As summarized in this study, it generally appears that soil carbon can more easily be sequestered in clay soils, but some studies show no correlation. Soil erosion could have a large effect on the global storage of carbon, but, because eroded soils may bury carbon elsewhere, researchers disagree about whether erosion, on average, leads to more or less carbon storage globally.

In addition to all the other challenges discussed above, these complexities suggest that carbon gains are likely to be site-specific. Most conclusions to date carry with them a significant level of uncertainty, and carrying out a strategy to boost soil carbon will be hard to implement and harder still to verify.

Summary of the Challenge

Since a prominent 2004 *Science* paper,[330] researchers estimating soil carbon sequestration potential have continued to emphasize the simple fact that many of the world's agricultural soils can technically store more carbon than they do today and that practices exist to enhance their carbon levels.[331] We believe that analysis is too simple because the ability of soils to store carbon is only one factor and generally not the principal limiting factor of sequestering more carbon in soils. (Banks have additional shelf space to store more money, and there are "practices" for making money, but that does not mean it is easy for the world to become richer.) The technical capacity of soils to store more carbon does not by itself resolve the technical, practical, and economic challenges of getting the carbon into the soil and keeping it there.

At best, studies estimating large soil carbon gains focus on technical potential, which is itself complex, and do not deal with the practical and economic challenges. To summarize, these challenges include the differential yield effects; the need to count only additional carbon and biomass (or to count only net gains if diverting this biomass from another use); the need for more nitrogen; the multiple practical challenges facing farmers who try to change tillage, crop rotations, and manure- and residue-management practices; and the fact that even short-term gains can quickly be lost through changes in management due to changing markets and farm conditions.

The Opportunity

Despite the challenges and uncertainties, it is obvious that some types of farming tend to result in more soil carbon than others (even if only because they lead to smaller losses) and that increased soil organic carbon has important agronomic benefits in addition to mitigating climate change. In many systems, it will be worthwhile to continue to push no-till farming forward to help reduce soil erosion and improve water retention. Except in rice systems, where retaining rice straw increases methane, it makes sense to try to retain on the land those crop residues that are currently burned or removed. Doing so would necessitate replacing crop residues used as livestock feeds with more nutritious fodders, which would benefit livestock production where farmers are able to generate those fodders (although that may require some additional land).

On the whole, however, we believe that the realistic potential to sequester carbon is to be found in approaches such as those described below that can plausibly generate economic gains independently and that do not sacrifice carbon storage in another location.

Boost crop and pasture productivity

Measures that increase cropland and pasture productivity (Course 2) have the potential to help build soil carbon. Increasing yields will also increase crop residues and root growth, which can contribute to boosting or maintaining soil carbon. Efforts to boost crop yields are responsible for the soil carbon gains on cropland in China (at least in the top soil layers) as discussed above, and they have either modestly boosted or reduced the losses of soil organic carbon in the United States.

The same is true for grazing land. In Brazil, for example, there is consistent evidence that soil carbon is higher under productively managed pasture than degraded pasture.[332] China has made extensive efforts to restore the productivity of overgrazed land and, although the performance is variable, the evidence is strong that many grazing lands have simultaneously sequestered more carbon.[333] There is some evidence that introducing legumes into grasslands can increase soil carbon through root effects to levels beyond those achievable with improvements in fertilization.[334] A new meta-analysis found small gains from largely unspecified "improved grazing" practices on existing grazing land.[335]

A more recent global modeling study suggests that optimizing grazing globally has the *technical* potential to sequester the equivalent of up to 0.6 Gt of carbon dioxide per year[336]—around 40 percent of the IPCC's 2007 estimate of carbon sequestration *economic* potential on grazing land.[337] Because achieving this potential would require improvements in grazing practices on billions of hectares of land, including the introduction of legumes (which presents problems because legumes are often selectively grazed by animals), it should be used mainly as a theoretical estimate. Yet it does highlight that increasing productivity can increase soil carbon.

Agroforestry

Agroforestry, discussed in more depth in Chapter 13, may provide a means of boosting soil carbon by increasing carbon uptake. Unlike annual crops, trees can grow year-round and therefore take advantage even of the drier season. They can also often tap into groundwater that annual crops cannot reach. Although farmers commonly clear trees to provide more light for their annual crops, trees can sometimes boost productivity. In tropical areas, shade from trees can be less of a problem than in temperate systems because sunlight is abundant, some crops need some shading, trees can increase humidity or add nutrients, and some trees lose their leaves during the growing seasons of some crops.

Trees, of course, also store carbon in vegetation. Although this chapter has focused on soil carbon because we deal elsewhere with reforesting agricultural land, agroforestry can provide opportunities to build vegetative carbon without reducing food production.

Despite potential benefits, we believe the practical potential of agroforestry at this time is too uncertain to estimate. Agroforestry can refer broadly to any form of agriculture incorporating the cultivation and conservation of trees. It can include any form of tree-based crops, such as rubber or cocoa. Growth in the agroforestry sector is obviously limited by demand for the outputs and, although converting annual crops to tree crops would sequester carbon, the annual crops would need to be replaced by cultivation elsewhere.

In some analyses, the term *agroforestry* is applied to any trees found on farms. Using this broad definition, one recent study estimated that growth of trees on farms globally sequestered an average of 0.75 Gt CO_2e each year between 2000 and 2010, predominantly on parcels of land that are mixed combinations of forest and agriculture.[338] Findings like this must be considered in the light of numerous data and mapping challenges. We believe that this paper is probably counting as agroforestry what is primarily reforestation of abandoned agricultural land.[339]

The potential true net carbon gains from agroforestry are those that result from incorporating trees and shrubs into existing productive systems without loss of yield, such as productive silvopastoral systems discussed in Chapter 11, and park systems in the Sahel in Chapter 13. Agricultural landscapes also often include land that is producing little or no food, such as some (but not all) field borders. Some studies focusing on such opportunities have estimated meaningful opportunities for carbon gains.[340] As we discuss in Chapter 13, much of the true technical potential to expand agroforestry remains unclear and unexplored but we believe it has more potential than realized today.

Possibility for new scientific breakthroughs

Driving much of the interest in soil carbon is the basic fact that microbial decomposition of organic materials in soils and dead vegetation returns tens of gigatons of carbon to the atmosphere each year, while the amount of this carbon that is instead retained in soils varies greatly from one location to another. If changed land-management practices could retain even a small fraction of the carbon that microbes are now respiring, then the climate-mitigation impact could be significant. The conditions that influence the level of carbon retention turn out to be far more complex than thought only a decade ago. They depend significantly on soil structure and on a variety of biological and ecosystem conditions.[341] In forests, for example, research has shown that the presence or absence of one group of fungi has a major effect on levels of carbon storage.[342] New research could generate new mechanisms for increasing carbon storage. One research initiative, for instance, aims to breed plants whose roots produce more suberin, an organic compound highly resistant to breakdown.[343] The potential importance of soil carbon storage warrants research into the fundamental science of soil carbon storage and creative ways of increasing it.

Recommended Strategies

The challenges and uncertainties involved in boosting soil carbon do not imply a complete lack of opportunities to improve soil management, but the uncertainties are too high to project how much. We also believe the best evidence indicates that agricultural soils are losing carbon today, and those losses are not commonly commonly counted as agricultural emissions. However, losses form nonpeatland soils are too uncertain to be reflected in our 2050 baseline. Although new science may change this impres-sion in the future, we believe that the reasonable goal in the short and medium term should be to maintain global soil carbon. We therefore believe that improvements are necessary, but we count them only as maintaining global soil carbon, and we assume that such improvements occur in our baseline and all our mitigation scenarios.

The effort that societies can and will put into solving the food and climate challenge is not unlimited, and it should focus on the most promising options. In the case of carbon storage, we know that deforestation and other land-use changes are obvious targets. We could reduce gigatons of emissions by avoiding conversion of forests and other native landscapes and producing the food we need on existing agricultural land. Only 26 Mha of drained peatlands generate more than a gigaton of emissions, and we know those emissions can be stopped by rewetting the land. Based on these and the other promising opportunities we identify in this report, we do not believe that carbon sequestration in soils should receive much effort for climate mitigation purposes alone.

Instead, we believe that such efforts should follow a no-regrets strategy that focuses on boosting soil carbon either as a cobenefit of other actions taken for different purposes or when boosting soil carbon is critical to meeting other objectives. Such efforts include improving cropland and grazing land productivity, and appropriate development of agroforestry. No-till potentially offers other benefits, including yield gains in dry climates, reduced soil erosion, and other beneficial soil properties when practiced over the long-term. Where it is practicable to achieve truly continuous no-till beyond 10 years, reductions in nitrous oxide and yield advantages also appear achievable. Alternative animal feeds to replace crop residues will benefit livestock productivity, and any emissions reductions or soil carbon gains would be additional.[344]

In Chapter 13, we also highlight the urgent need to rebuild degraded soils in sub-Saharan Africa. This task does not represent an easy source of climate benefits—it is hard—but improving soils will be critical if Africa is to feed itself, reduce poverty, and reduce clearing of forests and savannas. Overall, we believe there are many potential opportunities for such synergies, and they should be the focus of efforts to sequester more carbon in soils.