PROJECT DRAWDOWN

A DRAWDOWN PRIMER

FARMING OUR WAY OUT OF THE CLIMATE CRISIS

Changing Our Land Use, Agricultural Practices, and Food System Offers Numerous Opportunities to Reduce Greenhouse Gas Emissions, Sequester Atmospheric Carbon, and Help Address Climate Change

DECEMBER 2020

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1

INTRODUCTION

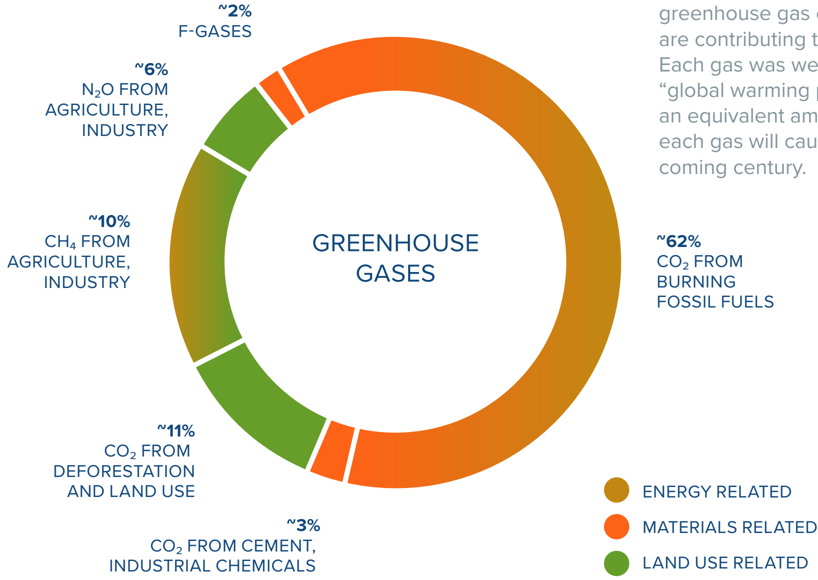
When we think of climate change and greenhouse gas emissions, we usually envision power plants, factories, cars, and smokestacks — not farms and ranches. But it turns out that agriculture and land use, as well as the larger global food system, are among the biggest contributors to climate change. And, as a result, changing these systems, can be an important source of climate solutions.

But how can this be? Isn't climate change caused by burning fossil fuels, that release carbon dioxide (CO_2) into the atmosphere?

There's more to it than that.

First, climate-altering CO_2 emissions are released from land use practices, especially clearing forests and other landscapes to create new agricultural land. Second, humans release other greenhouse gases — not just carbon dioxide — that affect our climate. Most important of these are the emissions of methane (CH_4) and nitrous oxide (N_2O). Methane emissions come largely from industry and agriculture, including from livestock and rice fields. And most of our nitrous oxide emissions also stem from agriculture, especially from fertilizers, manure, and burning crop residues

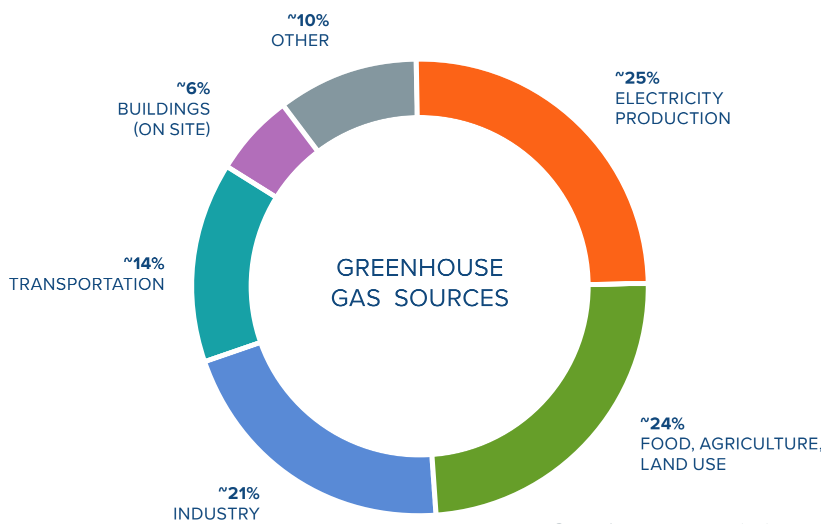
Figure 1.1 — Greenhouse Gas Mixes — CO_2, CH_4, N_2O, and f-gases



Here we show the different greenhouse gas emissions that are contributing to global warming. Each gas was weighted by their "global warming potential" to show an equivalent amount of warming each gas will causing in the coming century.

When we look at all of the contributors to climate change, the CO_2 released from burning fossil fuels — whether in generating electricity, fueling transportation, heating buildings, or powering industry — is responsible for about 62% of today's climate warming. The remaining 38% comes from other sources — including roughly 24% that stem from food, land use, and agricultural practices.[1] See Figure 1.1.

Figure 1.2 — Primary Sources of Greenhouse Gas Emissions



Greenhouse gas emissions come from a variety of secotrs, including electricity, food, agriculture and land use (FALU), industry, transportation, buildings, and other. It is important to note that food, agriculture, and land use is nearly tied with electricity as a leading contributor to climate change.

The food, agriculture, and land use sector (FALU for short) is a major contributor to climate change. And it surprises many people to learn that it essentially ties electricity generation (at ~24% and ~25% of total emissions, respectively) as the top two contributors to climate change today. See Figure 1.2.

> **Imagine that:** Electricity generation and land use and agriculture are *basically equal* in terms of their global impact on climate change. Yet addressing the greenhouse gas emissions from electricity generation and other sectors usually gets far more attention.

For this reason, reducing greenhouse gas emissions from agriculture and land use needs to play a central role in the way we address climate change. After all, roughly a quarter of our greenhouse gas emissions comes from this sector.

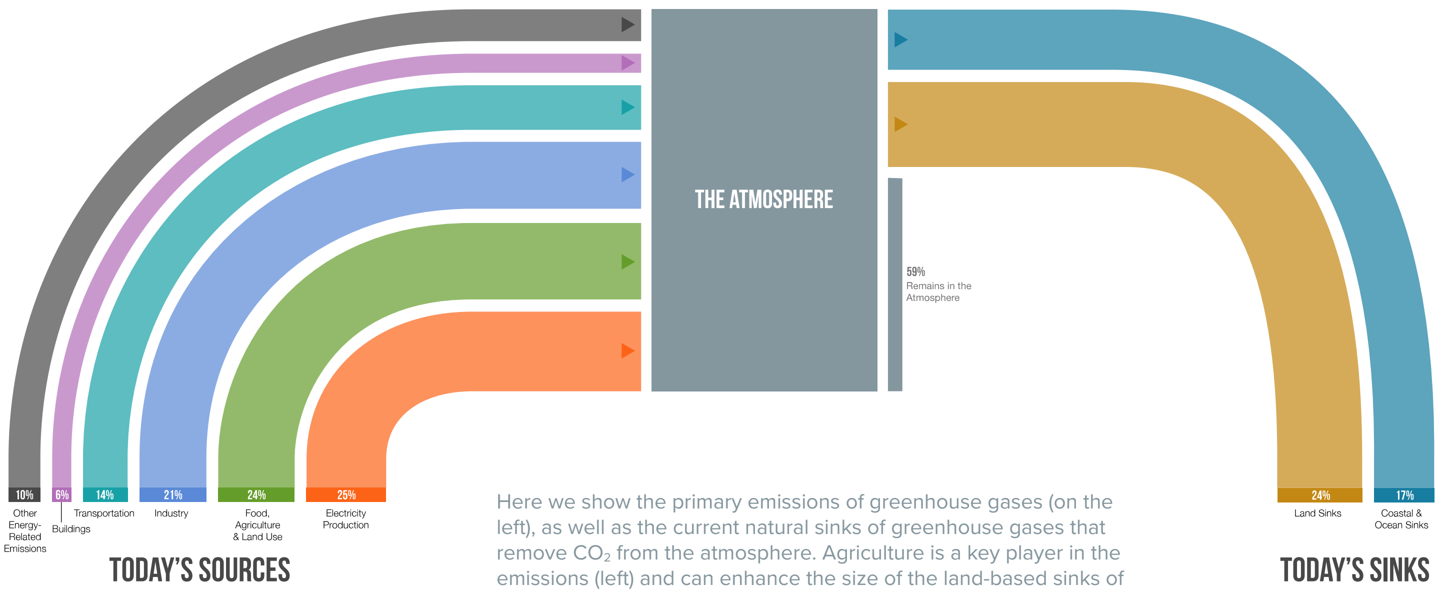
But it turns out that we can go beyond reducing greenhouse gas sources from agriculture and land use. Agricultural lands can also serve as "sinks" to capture and store excess atmospheric carbon dioxide, though their scale and permanence is still somewhat uncertain.

A greenhouse gas "sink" refers to a process that can remove these gases from the atmosphere and store them somewhere else for long periods of time — thereby lowering the levels of greenhouse gases in the atmosphere. Typically, this process refers to the removal of carbon dioxide by land-based ecosystems and the ocean, although some sinks of methane also exist. On land, carbon dioxide is absorbed through photosynthesis, and is later stored in living biomass (as grass or trees, for example) or as organic matter in the soil. Depending on form of biomass or soil organic matter, this carbon can be stored on land, away from the atmosphere, for a season, several years, multiple decades, or several centuries. Ultimately, the carbon that is locked up in biomass or soil organic matter is returned to the atmosphere, through decomposition and microbial respiration.

Perennial root systems. *Photo credit: Jim Richardson*

Nature does a lot of this already. Today, nearly 41% of our greenhouse gases are quickly absorbed by Earth's oceans and land-based ecosystems, leaving about 59% of our greenhouse gas emissions in the atmosphere, which are contributing to climate change. Of the 41% of greenhouse gases that are absorbed, the bulk is carbon dioxide. These "carbon sinks" on land and in the ocean absorb 55% of all carbon dioxide emissions and are part of Earth's natural ecological and biogeochemical processes, not direct human actions.[2] See Figure 1.3.

Figure 1.3 — "Rainbow Diagram" of Emissions and Sinks



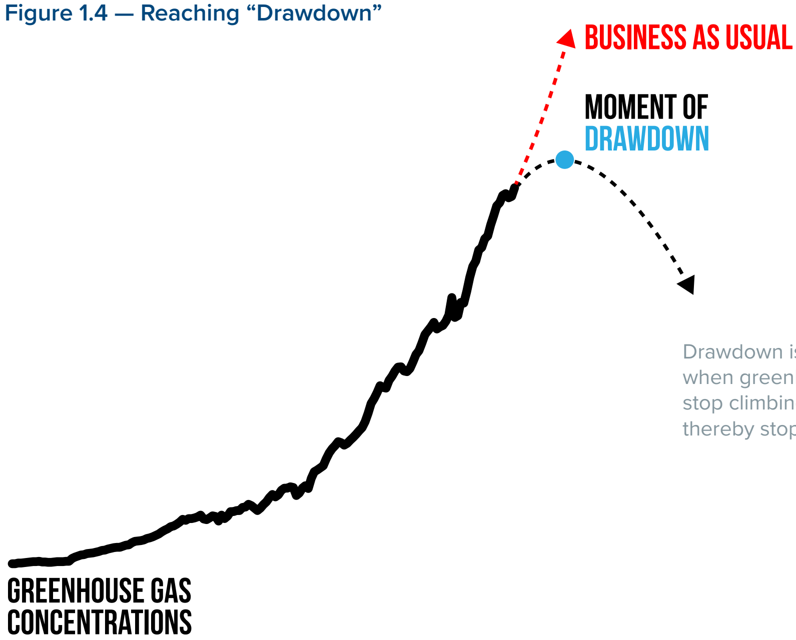
Here we show the primary emissions of greenhouse gases (on the left), as well as the current natural sinks of greenhouse gases that remove CO_2 from the atmosphere. Agriculture is a key player in the emissions (left) and can enhance the size of the land-based sinks of greenhouse gases (right).

If nature can absorb over half of our CO_2 emissions, without any effort on our part, perhaps we can help as well. In particular, if natural ecosystems on land — especially forests — absorb carbon and store it in biomass and soils, then maybe our working lands can too? After all, croplands and pastures cover between 35% and 40% of Earth's ice-free land area, so why aren't we using them to remove carbon dioxide from the atmosphere?

There are many ways to do this on many of our croplands and pastures. By deploying different agricultural practices — usually referred to as "regenerative agriculture" — it is possible to create new carbon sinks.

In order to stop climate change, we must ultimately achieve "net zero" emissions of greenhouse gases — so they no longer build-up in the atmosphere, warming the planet more and more. In order to keep the planet below 1.5˚C warming, it is thought we need to reach net zero greenhouse gas emissions by 2050. See Figure 1.4.

Figure 1.4 — Reaching "Drawdown"



Drawdown is defined as the moment when greenhouse gas concentrations stop climbing, and start to steadily decline, thereby stopping future climate change.

To do this, we can work on both sides of the street — by first lowering the emissions of greenhouse gases (including from the food, agriculture, and land use sector) and then by enhancing carbon sinks on land and in the ocean (including new carbon sinks in our croplands and pastures).

Interestingly, the food, agriculture, and land use sector is crucial to addressing climate change for two reasons. First, FALU is one of the largest contributors to climate change, with ~24% of greenhouse gas emissions, and significant emissions reductions must be found here. Second, by changing our land use and agricultural practices, we should also be able to create new carbon sinks that can help remove greenhouse gases from the atmosphere.

While reducing greenhouse gas emissions and enhancing carbon sinks can both contribute to stopping climate change, it is important to note the differences of these two approaches.

Reducing emissions — stopping pollution before it even gets into the atmosphere — is an immediate, foolproof, and permanent climate solution. If the greenhouse gases never go into the air, they can't contribute to climate change.

Carbon sinks, by contrast, remove greenhouse gases only after they have been in the atmosphere, usually by slowly removing them (via photosynthesis in the case of agricultural lands) and storing them in temporary reservoirs (grasses, trees, and soil organic matter). That takes time, sometimes decades, and depends on the ultimate size of the carbon reservoirs, leading to the important question of how much carbon can be stored in biomass and in soils? Moreover, there is no guarantee that carbon will be locked up in biomass and soils for long. Future changes in land use and farming practices — because a farm changed hands, for example — could see trees cut and burned, or soils plowed and eroded, releasing the stored carbon back into the atmosphere. In addition, climate change is projected to turn many landscapes from carbon sinks to carbon sources — due to increased droughts, fires, and other disturbances that release carbon from soils and biomass. Indeed this may already be happening in some parts of the world.

Carbon sinks are a very helpful climate solution, but they face the challenges of time delays (how long does it take to remove carbon dioxide?), limited size (how much can biomass and soils hold?), and permanence (how long will the carbon stay locked up?). In addition, it is still challenging and expensive to measure changing levels of biomass and soil carbon over time. Reductions in emissions, on the other hand, do not face the same challenges.

Why Reducing Emissions and Enhancing Carbon Sinks Address Climate Change in Different Ways

To see why reducing emissions and enhancing carbon sinks have very different qualities in terms of addressing climate change, an analogy may be helpful. Let's imagine your home has a bathtub, and it's rapidly overflowing with water, causing damage to your home. Turning off the faucet, that contributes to the problem, is the most immediate and reliable solution. But you also want to use a mop, to help remove the water that has already overflowed. Cutting emissions is like turning off the faucet; it addresses the source of problem. Carbon sinks are like the mop; they can help clean up the mess you already caused. Both are helpful, but they are not substitutable.

In the following sections, we will review the key aspects of how food, agriculture, and land use contribute to climate change, and how this can be addressed by reducing greenhouse gas emissions from this sector, as well as creating new carbon sinks on agricultural lands. Note that this publication focuses primarily on emissions reduction and carbon sequestration. Future Drawdown publications will further explore demand reduction due to diet change and food waste reduction, and the potential to avoid deforestation and restore forest ecosystems.

2

THE CLIMATE IMPACTS OF FOOD, AGRICULTURE, AND LAND USE

The world's food and agricultural systems are having a profound impact on planet Earth.

The world's land cover is dominated by agriculture. Today, about 35% of the world's ice-free land is used for croplands and pastures. (Some estimates are even higher.) No other force has shaped the Earth's surface as much as agriculture. The continued expansion of agricultural land in the tropics is leading to deforestation, especially in the Amazon, West Africa, the Congo, and across Indonesia. By clearing land and habitats, agriculture is the single biggest driver of biodiversity loss worldwide.

Agriculture is also the dominant driver of global water use. Roughly 70% of the world's water withdrawals — water taken from lakes, rivers, and groundwater for human use — is devoted to irrigation and other agricultural uses. In terms of water consumption — water used, but returned to the same watershed — agricultural is responsible for about 85% of global water use. Nothing else comes close.

As a result of the global scale of agriculture, it has reshaped the flow of nutrients across the globe, with major implications for the environment. Our use of chemical fertilizers and animal manures has roughly doubled or tripled the flows of nitrogen and phosphorus across the Earth's surface. Excess nutrients have heavily polluted lakes, rivers, and even coastal oceans in nearly every major agricultural region on the planet. Some of the nitrogen used as fertilizer also ends up as atmospheric pollution, contributing both to local air quality challenges and to global climate change.

While the use of fossil fuels, including oil, coal, and natural gas, electricity production, transportation, industry, and heating are the dominant contributor to climate change, the food, agriculture, and land use (FALU) sector emits roughly 24% of the world's greenhouse gas emissions. See Figure 2.1.

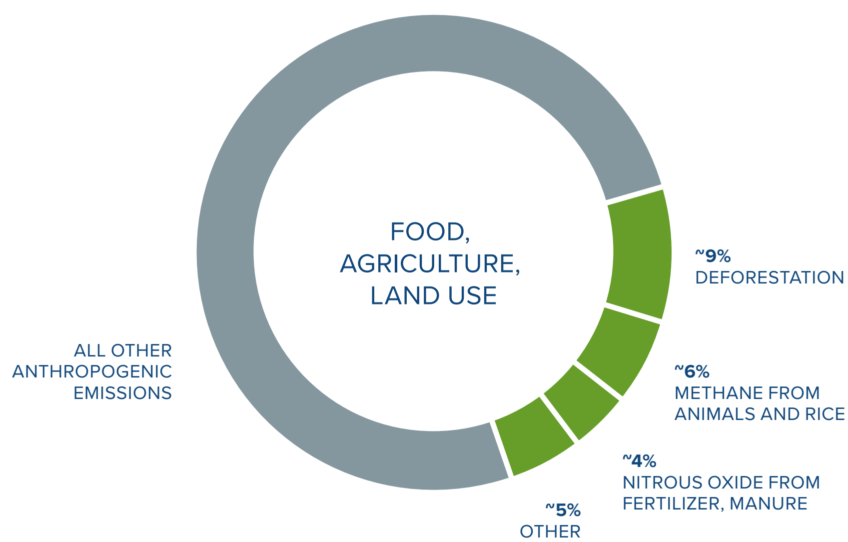
What makes land use and agriculture such big emitters of greenhouse gases?

The largest single source of greenhouse gases from land use and agriculture is **tropical deforestation and other land use** (~9%). Like burning fossil fuels, burning forests (which are also made out of carbon) releases enormous amounts of CO_2 to the atmosphere. Today, most of the world's deforestation is for new agricultural production (soybean fields to grow animal feed, oil palm plantations, and cattle pastures), as well as for timber harvesting and mining.

Methane (CH_4) emissions are the second largest source of greenhouse gases from land use & agriculture. Methane is a powerful greenhouse gas, trapping nearly 28 times the heat of CO_2 on a molecule-for-molecule basis, averaged over 100 years, but it doesn't last in the atmosphere for long. The residence time of methane in the atmosphere is a little over a decade. Most of the methane emissions in FALU come from cattle and sheep (who burp methane), manure piles, rice fields, and biomass burning.

The third largest source of greenhouse gases in this sector stems from nitrous oxide (N_2O) emissions. Nitrous oxide is even more powerful than CO_2 in trapping heat in the atmosphere — approximately 300 times more powerful on a molecule-for-molecule basis, and lasts in the atmosphere for several centuries. Most of the emissions of N_2O in FALU come from overusing fertilizers and manure left on pasture.[3] See Figure 2.2.

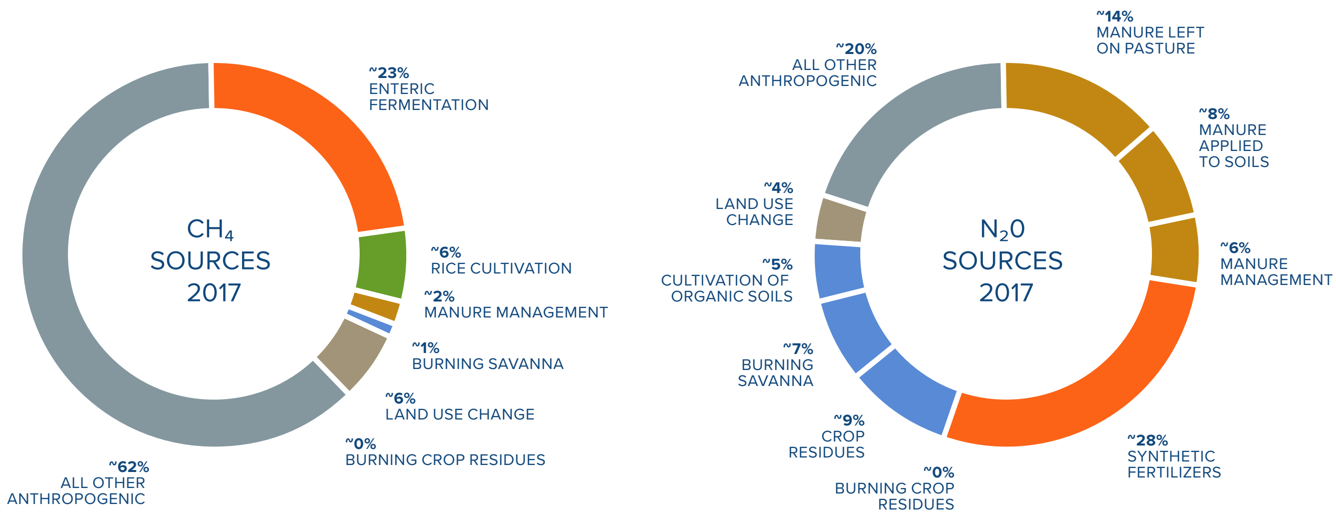
Figure 2.1 — Breakdown of Emissions From Food, Agriculture, and Land Use



It is interesting to note that livestock production is responsible for a large portion of the world's agricultural emissions. In fact, it is even higher than it might seem, given that about a third of all crops are grown for livestock feed, much of the emissions from crop production are actually driven by livestock. Finally, pasture and soybeans for livestock are the main drivers of land use change, another very large source of emissions. It has been estimated that livestock production, including land use change, is the source of ~14-15% of all anthropogenic greenhouse gas emissions, while producing only 10% of the world's food.[4]

In addition to emissions from land use and agricultural practices, other things related to the food system contribute to climate change. For example, the fossil fuels used in farm machinery, making agricultural chemicals, or transporting, refrigerating, and preparing food are important, but are smaller emitters than these other sources.

Figure 2.2 — Breakdown of Methane and Nitrous Oxide Emissions[5]



Methane is 28 times stronger than carbon dioxide and resides in the atmosphere for only 12 years on average. Its largest agricultural sources are enteric fermentation from cattle and other ruminants, and rice cultivation. Thirty-eight percent of methane comes from agriculture, with enteric fermentation by cattle and other ruminants as by far the largest agricultural source, followed by rice cultivation.[6]

Nitrous oxide is 300 times stronger than carbon dioxide and persists for over a century. Though it makes up only 5% of anthropogenic emissions, 80% of all anthropogenic nitrous oxide comes from agriculture. The largest agricultural source is manure, followed by synthetic fertilizers.[7] Given its intense warming power, reducing nitrous oxide is a critical focus for reducing agricultural emissions.

Detailed Breakdown of Greenhouse Gas Emissions From Agriculture

We can examine the individual sources of agricultural greenhouse gas emissions in more detail.

Enteric fermentation from ruminant animals. Ruminants are a group of hoofed mammals with a unique digestive system that allows them to meet their dietary needs with grasses and other leaves, which are far too fibrous to serve as a staple to humans. Ruminant livestock include cattle, water buffalo, camels, goats, sheep, llamas, and alpacas. Methane is produced as a waste product from ruminant digestion, and this enteric methane is the source of ~21% of all anthropogenic CH_4 (and ~70% of agricultural CH_4) emissions.[8 9]

Manure. Livestock manure as a source of emissions comes in three categories: manure left on pastures, manure management from partially or fully confined production systems, and manure applied to soils as fertilizer. It is the source of 12% of all agricultural emissions. As a methane source, manure management is minor, emitting only 2% of anthropogenic methane. However, manure is the source of 27% of anthropogenic nitrous oxide emissions (14% from manure left on pastures, 6% from manure applied to soils, and 5% from manure management).[10 11]

Synthetic fertilizers. Synthetic fertilizers are heavily relied on as a source of nitrogen for crop production. However, they offgas as the extremely potent greenhouse gas nitrous oxide, especially when overapplied. Synthetic fertilizers are the source of 28% of anthropogenic N_2O. Overapplication of nitrogen fertilizers is also a major source of water pollution.[12 13]

Rice cultivation. Most of the world's rice is grown in flooded fields. This creates anaerobic (low-oxygen) conditions in the soil, resulting in the production of methane. The amount of methane generated to produce a kilogram of rice is much lower than that for beef, but the amount of rice produced is very large. Rice cultivation is the second largest agricultural source of methane, responsible for 6% of anthropogenic methane emissions.[14 15]

Others. Burning of savannas, the natural decomposition of crop residues (like straw) in the field, tillage of peat-rich soils, and burning of crop residues are the other major sources of agricultural emissions. Together they account for 21% of nitrous oxide emissions and 1% of methane emissions. Note that electricity and fuel use in agriculture are very minor sources of emissions, though they are a major source in the supply chain once food leaves the farm gate.[16 17]

3

REDUCING GREENHOUSE EMISSIONS FROM AGRICULTURE

Because land use and agricultural practices are such big emitters of greenhouse gases, they need to be a big part of our solutions to climate change. The most important things we can do to reduce emissions from land use and agriculture include:

- **Conserving and restoring tropical forests**. The biggest source of greenhouse gases from this sector comes from the clearing of tropical forests. More attention is needed to conserve and restore them, especially in Brazil and Indonesia. Brazil deserves special attention, as dramatic changes in their government could fuel a resurgence in deforestation.
- **New methods of animal agriculture.** Animal agriculture is a major source of methane especially from cattle, sheep, and manure piles. New ways of raising cattle and sheep — including new feed additives (such as seaweeds that appear to lower methane emissions) and new grazing techniques (more on this below) — can help a great deal. Better manure management is needed as well.
- **New methods of rice cultivation.** Rice fields are also a major source of methane emissions, and some techniques may be able to reduce their emissions. More research in genetic and agronomic improvements to rice cultivation is needed.
- **More prudent use of nitrogen fertilizers and manure in farming.** We can reduce nitrous oxide (N_2O) emissions from agriculture by improving the use of chemical fertilizers and manure in the world's croplands. Large areas of the United States, China, and India release nitrous oxide because they are applying far too much fertilizer. Cutting back on fertilizer use can maintain the same crop yields while reducing greenhouse gas emissions and the runoff of nitrogen and phosphorus into local waterways.

We can also implement solutions in the broader food system by reducing the demand for food products and agriculture. Addressing food waste, and our dietary choices, can be very important here:

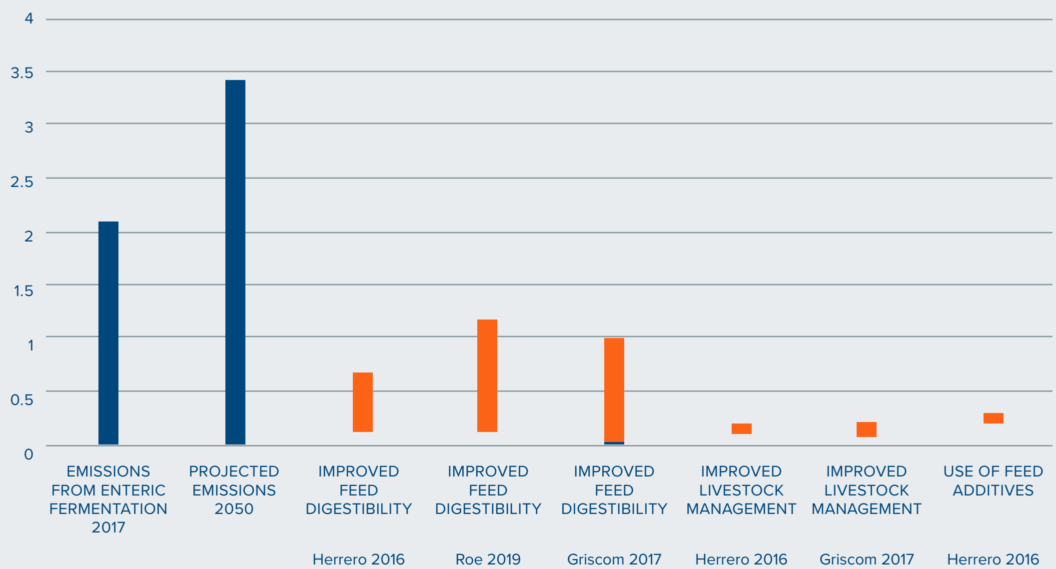
- **Reducing food waste.** It is estimated that about 30 percent of the world's food is lost after harvest, whether in transport, warehouses, markets, homes, schools, businesses, or restaurants. This means that roughly 30% of the land, water, chemicals, and greenhouse gas emissions associated with food production isn't necessary. If we cut food waste, we may be able to cut the resource demands and environmental impacts of agriculture. What's important here is to target the most resource-intensive and polluting food items, especially red meat and dairy products.
- **Eating more plant-rich diets.** We can also reduce the impacts of agriculture on the environment through our dietary choices, especially by reducing the amount of red meat and dairy products we eat. Livestock products all require much more land and resources to produce a kilogram of food or protein than plant-based foods, so shifting towards a more plant-rich diet reduces the area required for agriculture. And animal products have a significantly higher carbon footprint than many plant-based products. While there are ways (see more below) to raise cattle and sheep with fewer greenhouse gas emissions — and even sometimes in ways that sequester more greenhouse gases than they emit — the vast majority of the world's animal agriculture does not yet do this. So, as a first step, cutting our consumption of these can help address climate change.
- **We can intensify agriculture,** to increase the productivity of crops and pastures on the farmland we already have. This approach is intended to spare land, by avoiding future deforestation and other land use change, and may even allow some farmland to be restored to natural ecosystems. Some advocates of intensification encourage increased use of agricultural chemicals, while others encourage an agroecological approach to intensification.[18]

A MORE DETAILED VIEW

Reducing Emissions from Ruminant Livestock

Enteric fermentation from livestock currently emits ~2.1 Gt CO_2-eq of methane per year and is projected to rise to ~3.4 by 2050.[19 20] Methane is a waste product of inefficient ruminant digestion, indicating that not all of their food is being utilized.[21] Thus, many of the approaches to reducing enteric methane focus on improving feeding efficiency or improving feeds themselves. Overall, the potential of enteric fermentation reduction has been estimated to be ~0.4–1.2 Gt CO_2-eq / yr — a ~12–35% reduction of 2050 levels.[22 23 24] See Figure 3.1.

Figure 3.1 — Potential Impact of Enteric Fermentation Reduction Solutions (Enteric Fermentation Source Reduction Gt CO_2-eq/yr 2030)



Improved feed digestibility. High-quality feeds like grains produce less methane in the ruminant digestive system. Energy-dense feeds reduce methane emissions per kilogram of meat or milk produced.[25] This is one reason why ruminants from confined systems have lower lifetime emissions per kilogram than grass-fed ruminants.

Feed additives. Some substances reduce the production of methane by ruminant digestive microbes. These include seaweed, oils, biochar, saponins, probiotics, and methanotrophic microbes. Vaccines against methane-producing ruminant microbes are also under development. Typically any of these approaches provide a 10–20% reduction. Some seaweeds have been shown to have higher methane impacts. It is possible that some additives can have “stackable”, or additive, impacts.[26]

Breeding and management. Low methane production is a heritable trait, and ruminants can be bred for lower methane emissions. Breeding for heightened productivity is responsible for an 60% reduction in the emissions per kilo of meat and milk since the 1960s. Management practices like improving health, increasing conception and number of offspring per birth can all increase the productivity of herds and can reduce their emissions per kilogram.[27]

Improved forage quality. Improving pasture and grazing management improves fodder quality, reducing fiber in fodder grasses and legumes, resulting in decreased enteric methane production.[28]

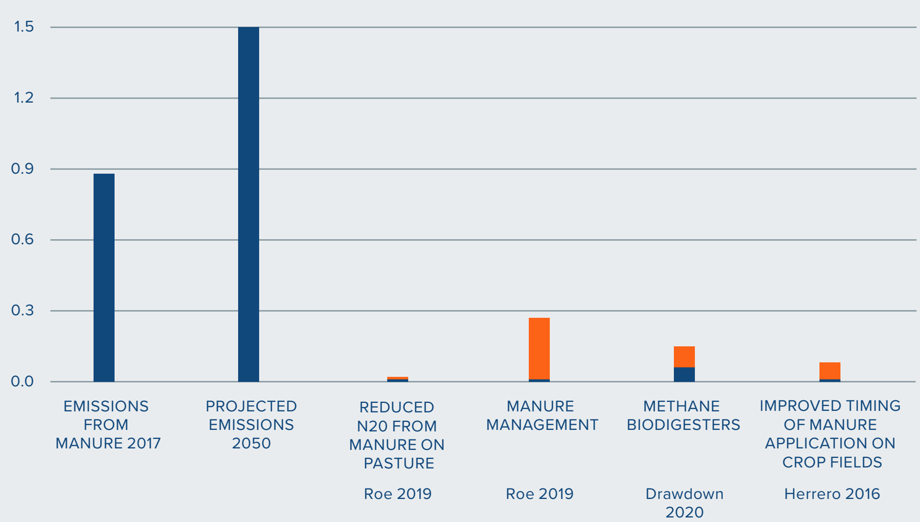
Tree fodder. Ruminants can also consume the leaves of many trees. This has been a component of silvopasture systems for millennia, and is a major component of intensive silvopasture and fodder systems in the tropics today. The tannins found in these leaves reduce enteric methane production.[29] Some herbaceous forages also contain tannins.

A MORE DETAILED VIEW

Reducing Emissions from Manure

Unlike enteric methane, emissions from manure come from all forms of livestock. Manure emits ~0.88 Gt CO_2-eq/yr today and is projected to increase to ~1.5 Gt by 2050.[30] The potential for reducing methane and nitrous oxide emissions from manure is limited, ranging from 0.01-0.26 Gt CO_2-eq/yr.[31 32 33] See Figure 3.2.

Figure 3.2 — Potential Impact of Manure Emissions Reduction Solutions (Methane Source Reduction Gt CO_2-eq/yr)



Manure on Pastures. Manure left on pastures is a large source of anthropogenic nitrous oxide emissions, though it doesn't get nearly as much attention as methane. The potential to reduce these emissions has been estimated at 0.01 Gt CO_2-eq/yr.[34]

Pasture management can help. For example, pasture grasses in the genus *Brachiaria* have been shown to rapidly scavenge nitrogen from ruminant manure and urine, preventing it from offgassing as N_2O.[35] Longleaf plantain reduces N_2O emissions from urine, and reduces methane emissions from manure.[36] Sorghum, rice, fodder beets, and forage rape also share this ability.[37 38 39] The presence of plants, instead of bare soil, has been shown to reduce N_2O emissions.[40] And nitrification inhibitors are sprayed on pastures in some regions.

A recent study also showed that well-managed pastures emit less nitrous oxide than degraded pastures.[41] If this effect is occurs widely, it represents an undersung impact of managed grazing.

Manure on Crop Fields. Manure is applied to crop fields as fertilizer, and in intensive livestock systems it is often applied as a waste disposal technique. As with synthetic fertilizer management, applying manure at the time that crops most need the nutrients can reduce emissions. Avoiding spreading manure on fields when there is a risk of heavy rains also reduces nitrous oxide emissions.[42]

Manure Management. Manure storage from confined livestock is an important source of emissions. Conventional manure management includes storage in constructed lagoons, as a liquid or slurry, and as a solid. Projected impact of improved manure management is 0.1-0.26 Gt CO_2-eq/yr, and comes from a wide range of approaches.[43] Most of these approaches also conserve nitrogen to maximize its use as fertilizer.

Manure management can be improved by cooling manure, covering during storage, separating liquids and solids, aeration, and applying chemical additives and nitrification inhibitors. Manure emissions can be reduced via composting, which produces a useful fertilizer, or used in anaerobic digestors, which produce biogas for electricity or cooking.[44]

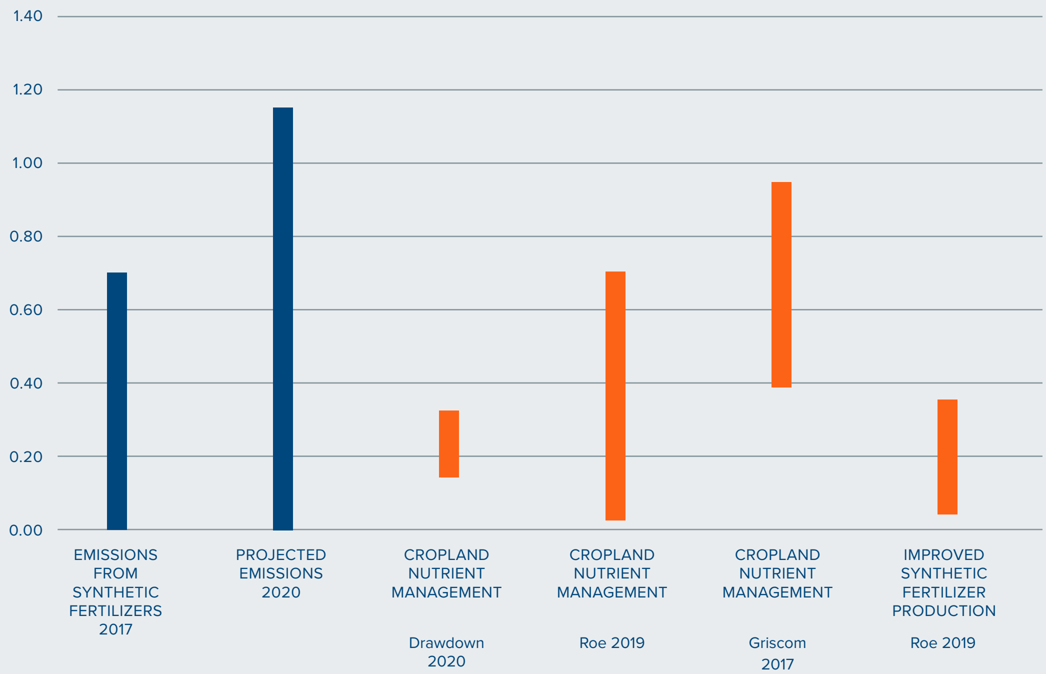
Cattle grazing on Brachiaria at the ILRI campus in Nairobi Kenya. *Photo credit: ILRI/Collins Mutai*

A MORE DETAILED VIEW

Reducing Emissions from Fertilizers

Emissions from overuse and inappropriate use of synthetic fertilizers are a major source of nitrous oxide. Approaches to reducing emissions include better management of synthetic fertilizers and use of alternative nitrogen sources. Estimates of the potential of these solutions range from 0.03-1.07 Gt CO_2-eq/yr, compared with emissions of 0.70 in 2017 and projected to 1.16 in 2050[45 46 47 48] (see Figure 3.3). The only approaches for which global estimates are available are related to synthetic fertilizers, though green manures and other approaches reduce or replace the use of these products.

Figure 3.3 — Potential Impact of Reduced Synthetic Fertilizer Emissions (Synthetic Fertilizer Source Reduction Gt CO_2-eq/yr)



Nutrient management for synthetic fertilizers. This solution reduces nitrous oxide emissions from overapplying fertilizers or applying them at the wrong time. The nitrogen in synthetic fertilizer not quickly taken up by plants can off-gas as nitrous oxide, or wash into watersheds, where it causes serious pollution problems. Improved nutrient management approach seeks to reduce emissions, water quality issues, and the waste of fertilizer. Note that these principles also apply to organic fertilizers including manure and compost.

Compost and manure as nitrogen sources. Other sources of nitrogen can replace synthetic fertilizers, but also have their own emissions challenges. Manure and compost can be applied to fields, but also release some greenhouse gases themselves.

Nitrogen-fixing plants as nitrogen sources. Green manures are nitrogen-fixing annual cover crops that are tilled into the soil to make nitrogen available for the crops planted later. Herbaceous legumes like clovers are sown in pastures both for their protein as fodder and for their fertilizing effect. Nitrogen fixing trees are widely used in tropical agroforestry systems as sources of fertility and fodder. Nitrogen-fixing plants do emit some nitrous oxide.[49]

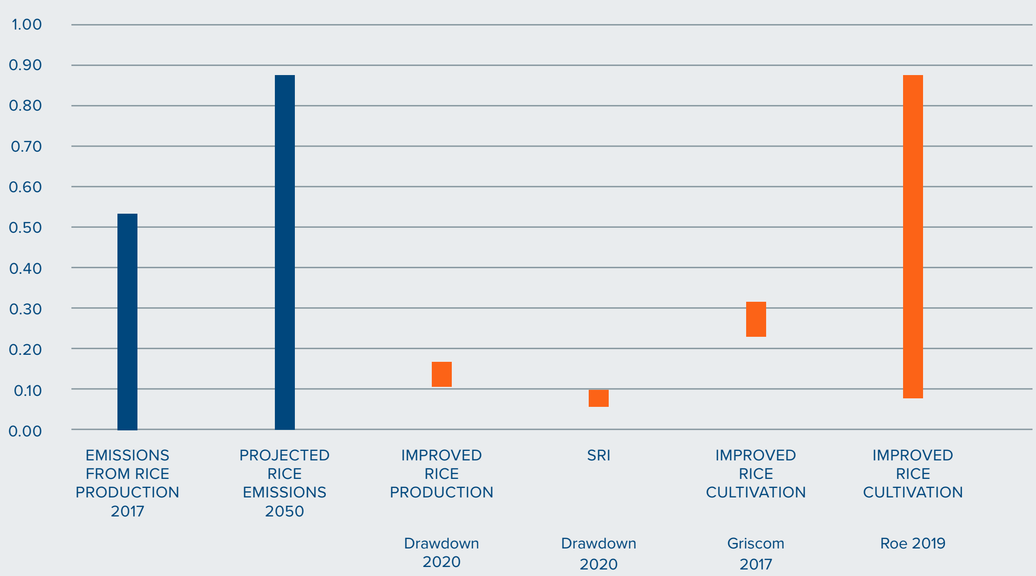
Crop-livestock integration. Integrating livestock with crops is a traditional practice, still widespread in some parts of the world. Animals don't create new nutrients, of course, but they can transport them where needed and transform them into a readily usable fertilizer product.[50]

A MORE DETAILED VIEW

Reducing Emissions from Rice Cultivation

Rice production is a major source of methane, produced in anaerobic conditions in flooded rice fields. A number of approaches can reduce these emissions. Estimates on the emissions reduction potential of these approaches range from 0.08 to 0.87 Gt CO_2-eq, while current production is 0.53 and projected to increase to 0.87 by 2050.[51 52 53 54] See Figure 3.4.

Figure 3.4 — Potential Impact of Rice Emissions Reduction Solutions (Rice Emissions Reduction Gt CO_2-eq/yr)



Low-methane rice. Numerous practices are being deployed to reduce methane in rice production. Water management can reduce water use and methane emissions, by draining fields in mid-season or by alternating wet and dry periods. Nutrient management can reduce methane yields, and reducing tillage stabilizes soils and reduces methane emissions.

System of Rice Intensification (SRI). SRI is a rice production system that began in Madagascar in the 1980s and has spread rapidly. SRI focuses on several elements: planting individual seedlings, more widely spaced; intermittent watering instead of continuous flooding; compost application; and the use of a rotary hoe to control weeds.

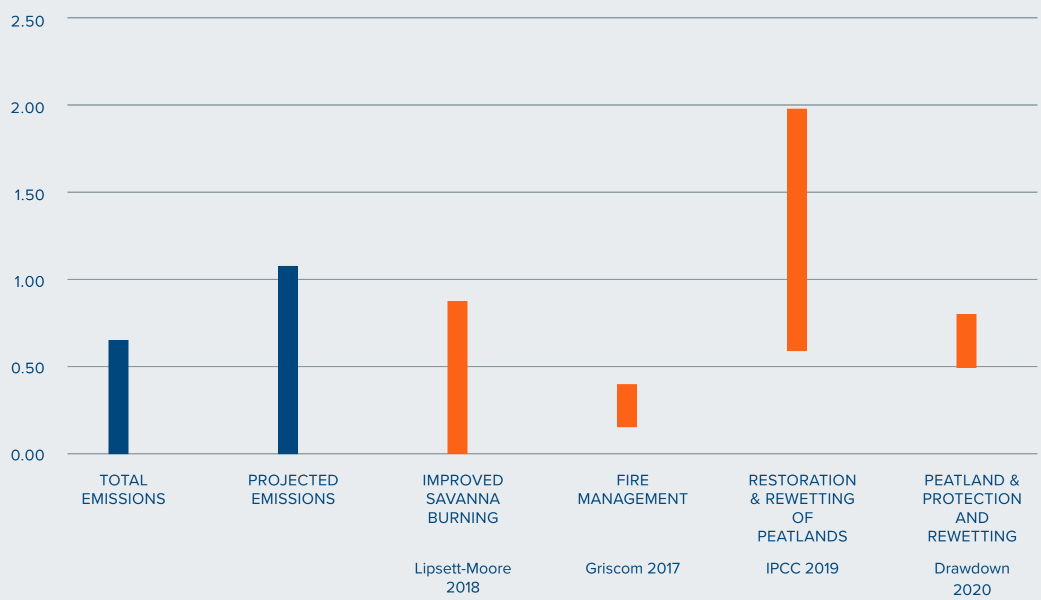
System of Rice Intensification farming in Chattisgarh, India. *Photo credit: Jacob*

A MORE DETAILED VIEW

Reducing Emissions from Other Agricultural Activities

This category includes emissions from decomposition and burning of crop residues, farming on drained peatland soils, and burning of savannas. There are solutions for each of these emissions sources. Current emissions from these sources is 0.67 Gt CO_2-eq, projected to rise to 1.09 by 2050.[55] Emissions reduction potential is estimated at 1.6-3.3 Gt CO_2-eq, though much of that is from biosequestration from restored peatlands.[56 57 58 59] See Figure 3.5.

Figure 3.5 — Potential Impact of Other Emission Reduction Solutions (Reduction of Other Agricultural Sources Gt CO_2-eq/yr)



Reducing savanna burning. Shifting savanna burning from the late to early dry season reduces the intensity of fires and their emissions. Efforts in Australia have demonstrated that controlled burns in the early dry season can greatly reduce methane and nitrous oxide emissions from savanna burning. The potential impact of improved savanna burning is estimated at 0.89 Gt CO_2-eq/yr.[60]

Reducing emissions from cultivation of peat and other organic soils. Peatland soils contain 30% of the world's soil carbon on only 3% of the land. Clearing peatlands for agriculture has tremendous greenhouse gas emissions. When peatlands are drained and converted to agriculture, methane emissions are substantial. Rewetting and restoring peatlands can reduce this source and get peatlands back to sequestering carbon. Estimates of the global potential of peatland restoration range from 0.51-2.00 Gt CO_2-eq/yr.[61 62]

4

CREATING CARBON SINKS ON WORKING LANDS

Reducing greenhouse gas emissions from land use and agriculture will have to play a central role in addressing climate change. After all, roughly a quarter of the world's greenhouse gas emissions comes from this sector.

But it turns out that our land use and agricultural practices can address climate change in other ways as well. In particular, we can create or enhance new "sinks" of carbon (especially carbon dioxide, but also for some methane) on our working lands — especially managed forests, croplands, and pastures. Such sinks can remove greenhouse gases from the atmosphere — gases that have already been emitted.

Nature does a lot of this already. Roughly 55% of our carbon dioxide emissions are quickly absorbed by Earth's oceans and forests, leaving only ~45% of our CO_2 emissions in the atmosphere. If nature didn't do this, warming from CO_2 emissions would be much, much worse.

If nature can absorb over half of our CO_2 emissions, perhaps we can change our agricultural and land use practices so that working lands can also be a carbon sink, augmenting nature's sinks? If so, this goes beyond reducing greenhouse gas emissions in the food, agriculture, and land use sector; it can remove greenhouse gases already in the atmosphere.

In fact it is widely held that our working lands — whether managed or replanted forests, croplands, or pastures — can serve as a powerful sink of excess atmospheric carbon dioxide. A great many advocates, farmers, and scholars are excited by the potential for these carbon sinks in addressing climate change. However, there are still many open questions about carbon sinks on working lands. We consider these below.

Where is Carbon Stored on a Working Landscape?

Carbon sinks on land are driven by plants through the process of photosynthesis. This remarkable process captures atmospheric carbon dioxide, releases oxygen back to the atmosphere, and builds complex carbon compounds within plants — including sugars, lignins, and cellulose.

Carbon is stored in living plants, but when the plant dies, those carbon atoms persist in the landscape — traveling through dead plants, animals, microbes, and organic compounds in the soil. When evaluating carbon sinks on land, we consider carbon that is stored in three major carbon pools:

Biomass Carbon. The carbon found inside living plants is divided between *aboveground biomass (AGB)* — made up of wood, leaves, and grasses — and *belowground biomass (BGB)* in roots. The bulk of the world's biomass carbon is stored in wood, which is why maintaining and planting tree cover plays such an important role in creating biomass-based carbon sinks.

Fazenda da Toca, a 5,700-acre farm managed by Pedro Diniz in Itirapina, Brazil.
Photo credit: Pedro Paulo F. S. Diniz

Detritus Carbon. In natural systems, when plants die or shed biomass (losing leaves and fine roots each year), the resulting dead biomass is called detritus.

In agricultural lands, we need to separate harvested and grazed plant biomass from crop residues. In the case of annual crops and cover crops, all non-harvested plant matter breaks down, whether it is tilled into the soil or left on the surface as residue. For perennial crops, long-lived woody parts and roots store carbon for their lifetime, but yearly leaf-drop and dieback of fine roots become detritus carbon. In pastures, carbon is removed by grazing, and added by manure. Farming practices can also work-in off-site carbon sources in the form of compost, manure, and other inputs.

Soil Organic Carbon (SOC) is the largest pool of carbon on land and is largely made up of decomposed plant matter and microbes. As plant detritus and crop residues break down, some of their carbon is released as carbon dioxide by microscopic animals and microbes (as respiration). The remainder is converted into soil organic matter, sometimes called humus by gardeners and farmers. Plants also exude some of the sugars created through photosynthesis through their roots to feed beneficial organisms like microbes and mycorrhizal fungi, adding to the build-up of soil organic carbon.

Soil organic carbon comes in many different forms, and each has a certain lifetime in the soil. Some SOC breaks down quickly. This happens when microbes release the carbon back to the atmosphere as carbon dioxide through respiration. Other forms of SOC are much harder to break down, and it may take decades or centuries for microbes to break down these compounds.. And some forms of SOC are extremely long-lived, where organic carbon is tightly bound to soil particles, making this soil carbon essentially “semi-permanent”. It is estimated that the mean residence time (period of carbon storage) of soil organic carbon, when bound to mineral particles in the soil, is centuries or even millennia in some cases.[63] Shorter-lived forms of carbon may only persist from a few days up to around a year.

Soil organic carbon is an especially important player in creating carbon sinks on working lands. The levels of soil organic carbon are ultimately controlled by two process — *inputs* of organic materials to the soil (from plant detritus, crop residues, plant exudates, or additional organic carbon added by farmers) and *losses* of organic matter (from microbial respiration as soil organic matter breaks down, the leaching of organic carbon compounds to groundwater, or losses from soil erosion). By changing our farming practices, we can alter the inputs and losses of organic matter in the soil, thereby increasing or decreasing soil carbon levels.

When Does Soil Carbon Accumulation Slowdown?

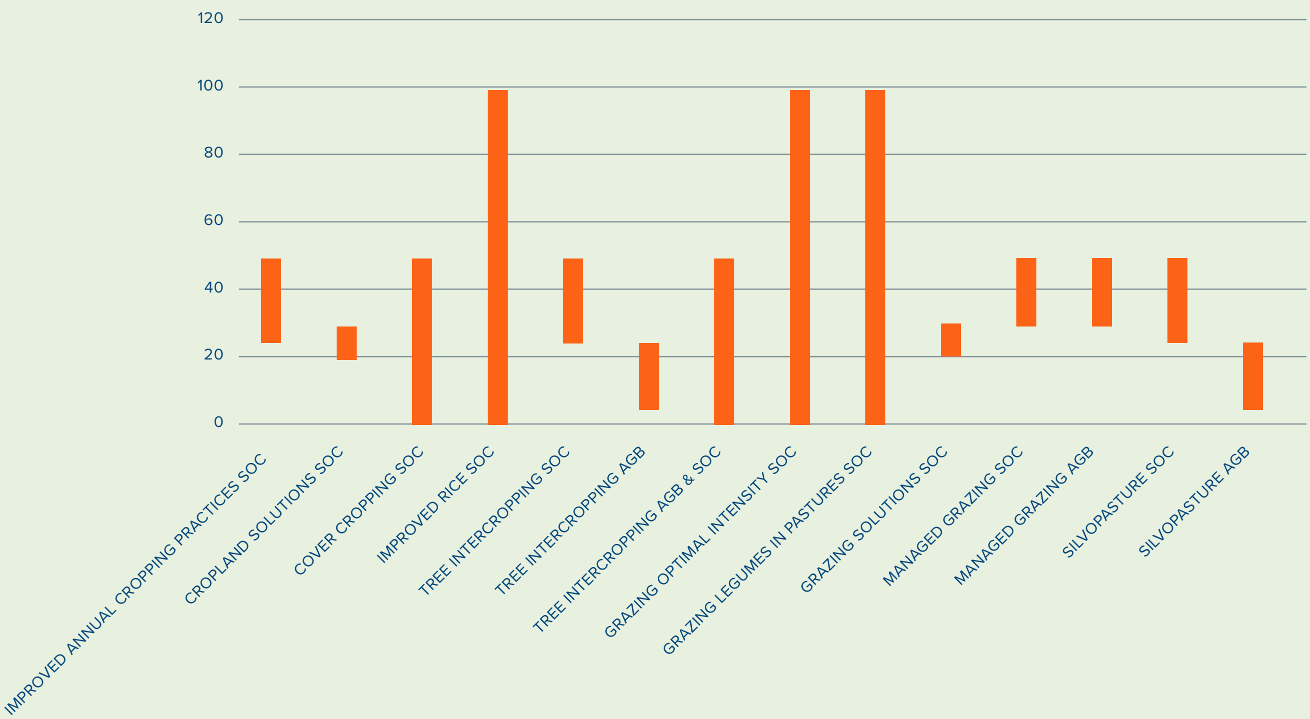
Given enough time, the carbon balance of a landscape comes to approximate equilibrium, where carbon inputs are roughly balanced by carbon outputs. Specifically, the carbon absorbed by photosynthesis is balanced by losses of carbon from decomposing plant matter and soil organic matter, and losses of soil organic carbon from erosion and leaching. When this equilibrium is reached, the levels of carbon in biomass, detritus, and soils reflect this balance of carbon inputs and losses.

While these carbon inputs and losses can approach equilibrium fairly quickly, usually over the course of several years to a few decades, some forms of biomass (in long-lived trees) and soil organic carbon (especially “semi-permanent” organic matter tightly bound to soil particles) can continue to build up slowly — sometimes for centuries or more.

This leads to the issue of “saturation” of carbon stocks on the landscape. While it is unlikely that any landscape has ever completely “saturated” their carbon stocks in biomass and soils, many *asymptotically* reach a saturated-like state in a few decades or less. That is, the build-up of carbon in biomass and soils is very rapid at first — for several years to a couple of decades — but then slows dramatically as most of the biomass and soil carbon pools reach a near equilibrium state. Only the slow build-up of long-lived biomass (very large and old trees) and semi-permanent soil organic matter (a small fraction of the carbon in soils) will continue after this. Rather than saying soils are “saturated”, which is not technically correct, we prefer the term “**slowdown**” — to denote this slowing in carbon accumulation on the landscape.[64]

How long does it take for carbon sequestration to reach this “slowdown” state? Figure 4.1 shows estimates for various practices for both aboveground biomass and in soils.[65 66 67] For improved annual cropping systems, it is projected at between 20–50 years. In tree intercropping systems, soil estimates range from 20–50 years, and biomass carbon between 5–50 years. In managed grazing, estimates range from 20–100 years. For silvopasture, soil carbon estimates run from 25–50 years, and biomass from 5–25 years. See Figure 4.1.

Figure 4.1 — Years to Soil Carbon “Slowdown” (Years to Saturation)



There may be some ways to partially overcome these limits. Farmers and ranchers can continue to adopt practices over time that increase the carbon sequestration potential. For example, they may begin with cover crops, then add compost application, then incorporate agroforestry elements, and finally add perennial crops.[68] There may be ways to work around carbon “slowdown” in mature landscapes as well. For example, aboveground biomass in agroforestry systems can be harvested and used in long-lived wood products, and then replanted, resetting the clock on biomass carbon. Moreover, adding biochar to soils may also increase their total soil carbon storage capacity over time.[69]

But, fundamentally, carbon sequestration rates decrease as biomass and soils asymptotically reach this “slowdown”, and a dynamic equilibrium between carbon inputs and losses, and estimates of agricultural carbon sinks must take this into account.

What Farming Practices Sequester Carbon?

To create a carbon sink on our working landscapes, we need to increase the deployment of practices that lead to the build-up of new carbon — whether in biomass or soils — over time. That carbon is usually "sequestered" in long-lived trees or by building-up high levels of organic matter in the soil.

How can we create carbon sinks through land use and agriculture? Here are some ways this has put into practice:

- **Restoring forests and planting large areas of trees**. This one is pretty simple. Burning and cutting down trees releases CO_2; replanting and restoring them absorbs CO_2. We can even restore forests to their natural ranges, some not seen in millennia, and increase the forest cover of the planet. (But we must be careful to not indiscriminately plant trees where they could be ecologically disruptive, especially in grasslands and semi-arid ecosystems.)

- **Using "regenerative" annual cropping techniques so croplands accumulate biomass, increase plant cover, and rebuild soil.** Here we employ techniques from "regenerative annual cropping", which aims to go beyond maintaining the ecological health of the landscape and soil fertility to actively restoring and improving soil fertility and ecosystem health. Such farming practices start accumulating significant amounts of organic matter, rebuild the soil, and sequester carbon from the atmosphere.

  On croplands, these practices include no-till cultivation (which, unfortunately, is often linked to heavy herbicide application), cover cropping, compost application, and other practices from the organic and sustainable agriculture pantheon.

- **Perennialize agriculture through increased adoption of agroforestry systems and perennial crops.** Agroforestry systems integrate trees into the production of crops and livestock and incorporate tree intercropping (integrating trees with annual crops), silvopasture (trees in grazing systems like pasture and rangeland) and multistrata systems (multi-layered farming approaches like shade coffee). Perennial crops, including tropical tree staples, and the perennial grains which are under development, offer another way to perennialize agriculture.

- **Managing grazing lands with "regenerative agriculture" techniques so they accumulate soil carbon.** We can implement grazing practices that stimulate grass productivity and root growth, so that pastures accumulate so much soil organic matter they can offset the emissions of grazing animals. This can be achieved by adjusting stocking rates or employing more complex Adaptive Multi-Paddock (AMP) grazing systems. Sometimes compost is added to the landscape as well, stimulating even more carbon sequestration, but more research is needed to see how this can be scaled up and sustained over time.

  One of the challenges of using regenerative grazing techniques as a carbon sink is the need to overcome the methane emissions of cattle or other ruminants that burp significant amounts of and continue to do so their entire lives. The build-up of soil organic carbon can potentially offset these methane emissions for a time, but if the build-up of soil carbon eventually slows down, as scientists believe it inevitably almost always will, it will become challenging to continue to offset the cattle methane emissions. Some grazing approaches offer some hope by partially reducing emissions from ruminants, as discussed in the previous section.

An important feature of these carbon sequestering agricultural practices is that they often produce other benefits, especially to farm productivity and resilience. For example, the use of trees, buffer strips, and cover crops on the landscape can reduce soil erosion and help retain nutrients on the landscape. And the build-up of soil organic matter dramatically improves the soil's ability to retain nutrients and moisture (especially during a dry spell).

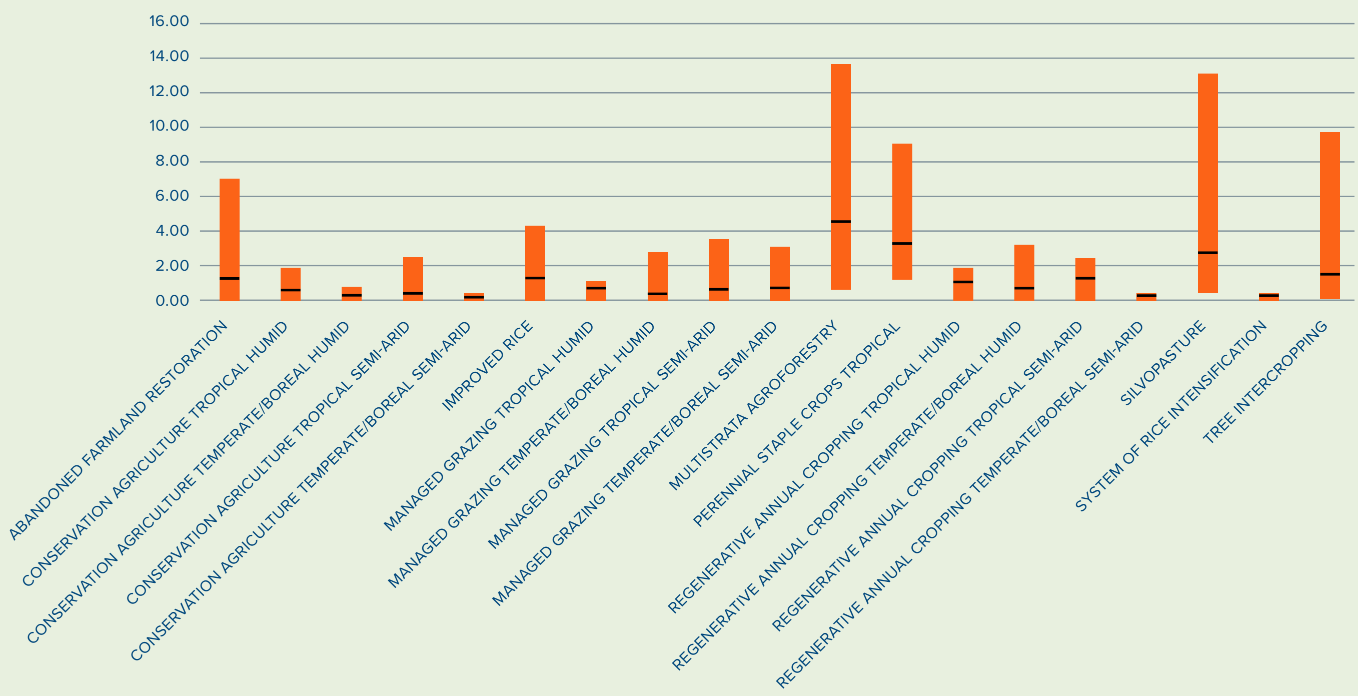
How Do Different Farming Practices Sequester Carbon?

While a great many agriculture practices can sequester carbon, they differ in their ability to do so.

Generally speaking, practices like agroforestry and perennial cropping systems that incorporate woody plants show higher sequestration rates.

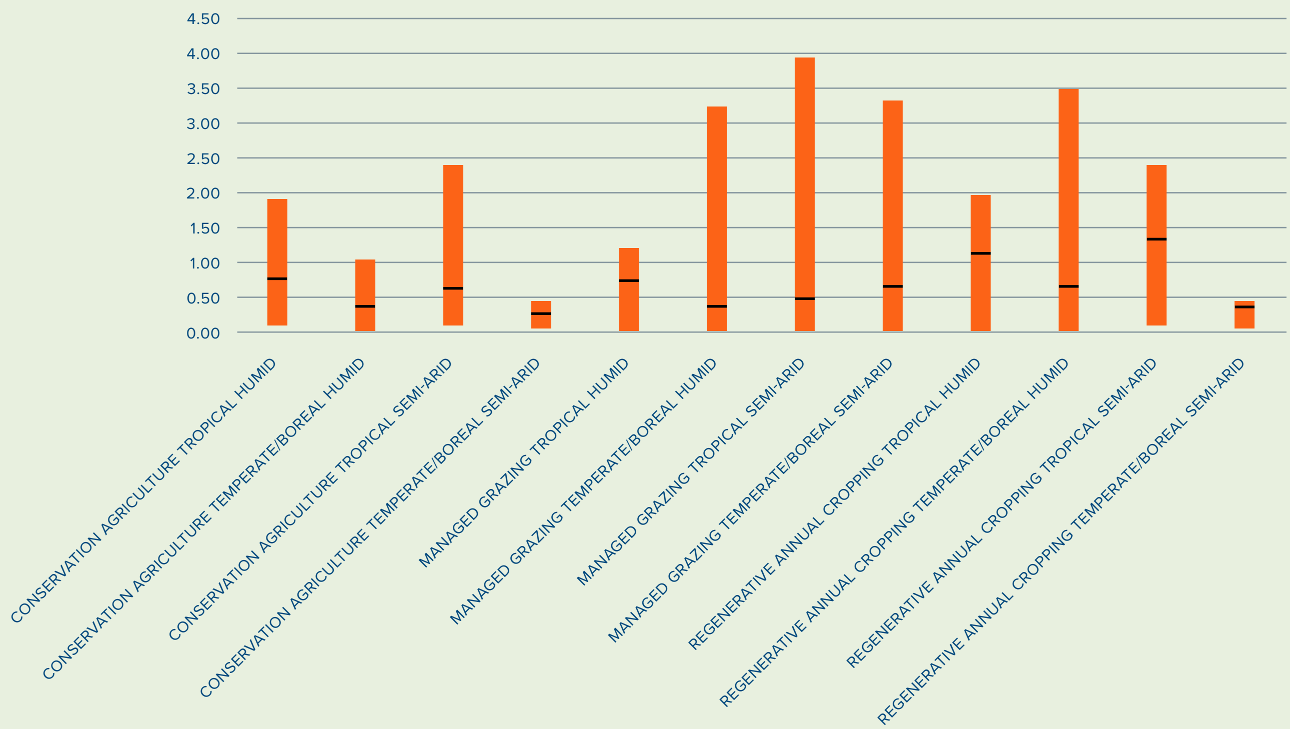
Figure 4.2 shows the range of sequestration rates, as estimated in Project Drawdown's agricultural biosequestration solutions research.[70]

Figure 4.2 — Ranges of Reported Sequestration Rates and Mean Values (Sequestration Rate Variations by Climate t/ha/yr)



The same practice also may show different sequestration rates in different climates. In colder regions, more carbon typically ends up in soil than in biomass, and it is held for a longer time in the soil as decomposition rates are slower in colder areas. In the tropics and subtropics, carbon is more likely to be held in aboveground biomass and doesn't last as long in soils. Overall, drier climates have lower sequestration rates.[71] Figure 4.3 shows how many sequestration rates vary across different climates.[72]

Figure 4.3 — Ranges of Reported Sequestration Rates and Mean Values by Climate Type (Sequestration Rate Variation by Climate t/ha/yr)



In some cases there is a very wide range reported for the same practice. This may reflect very different versions of the practice — for example, some tree intercropping systems have much higher densities of trees than others. In the case of managed grazing, there are wide variations in practice, which range from adjusting stocking rates to complex Adaptive Multi-Paddock (AMP) grazing systems. Several studies have found that sequestration rates for AMP grazing are 10 times higher than those for ordinary managed grazing, but this is not consistent across all AMP grazing operations, and there are many complexities that seem to affect sequestration in grazing systems including the mix of warm- versus cool-season grasses, rainfall and soil texture, and grazing intensity.[73 74 75]

Don’t Overlook Agroforestry

Much of the attention on “regenerative agriculture” and carbon sequestration has revolved around improved annual cropping systems, managed grazing, and limited forms of crop-livestock integration. But the potential benefits of agroforestry practices, which integrate trees into working landscapes, are often neglected.

Project Drawdown has found that these systems are already widespread, especially in the tropics.[76] In fact, tree intercropping is much more widespread than regenerative annual cropping, and silvopasture is more widely practiced than managed grazing. These practices also have higher sequestration rates than regenerative annual cropping and managed grazing. There is also much more scientific certainty about their benefits: silvopasture sequestration rates are known to be much higher than managed grazing, and there is much less controversy over the per-hectare impacts, for example.[77 78]

Many of the definitions of regenerative agriculture, including those used in certification systems and by some major food companies, minimize these powerful agroforestry practices. That downplays the essential contributions of tropical farmers to mitigating climate change. It also misses the potential benefits of increasing tree cover on farmland in cold regions, even though agroforestry is widespread in temperate China and Europe.[79]

Coppiced edible leaf mulberry under nitrogen fixing acacia canopy. *Photo credit: Eric Toensmeier*

Sequestering Carbon Requires Nutrients and Water

Organic matter, whether in living plants or soil compounds, is made from carbon and wide variety of other elements. The most limiting of which are nitrogen and phosphorus, the primary components of agricultural fertilizer. These elements are often extremely limited in many soils, especially degraded soils where soil carbon has already been lost.

This means that carbon sequestration in biomass and soils may become limited by the availability of nitrogen and phosphorus on the landscape. **For example, for every billion metric tons of CO_2 that is sequestered, 25 million metric tons of nitrogen is required. That's the equivalent of about 19% of global synthetic fertilizer production today.**[80]

Water is of critical importance to photosynthesis, and water availability is projected to become ever more uncertain with climate change. Scarcity of water, nitrogen, and other nutrients like phosphorus thus may constrain the size of agricultural carbon sinks to less than their technical potential.[81]

Field stubble burning when the harvest is complete. Farmer spreads fertilizers in the field.
Nile riverbank, Aswan, Egypt, February 2018. *Photo credit: iStock/Socha*

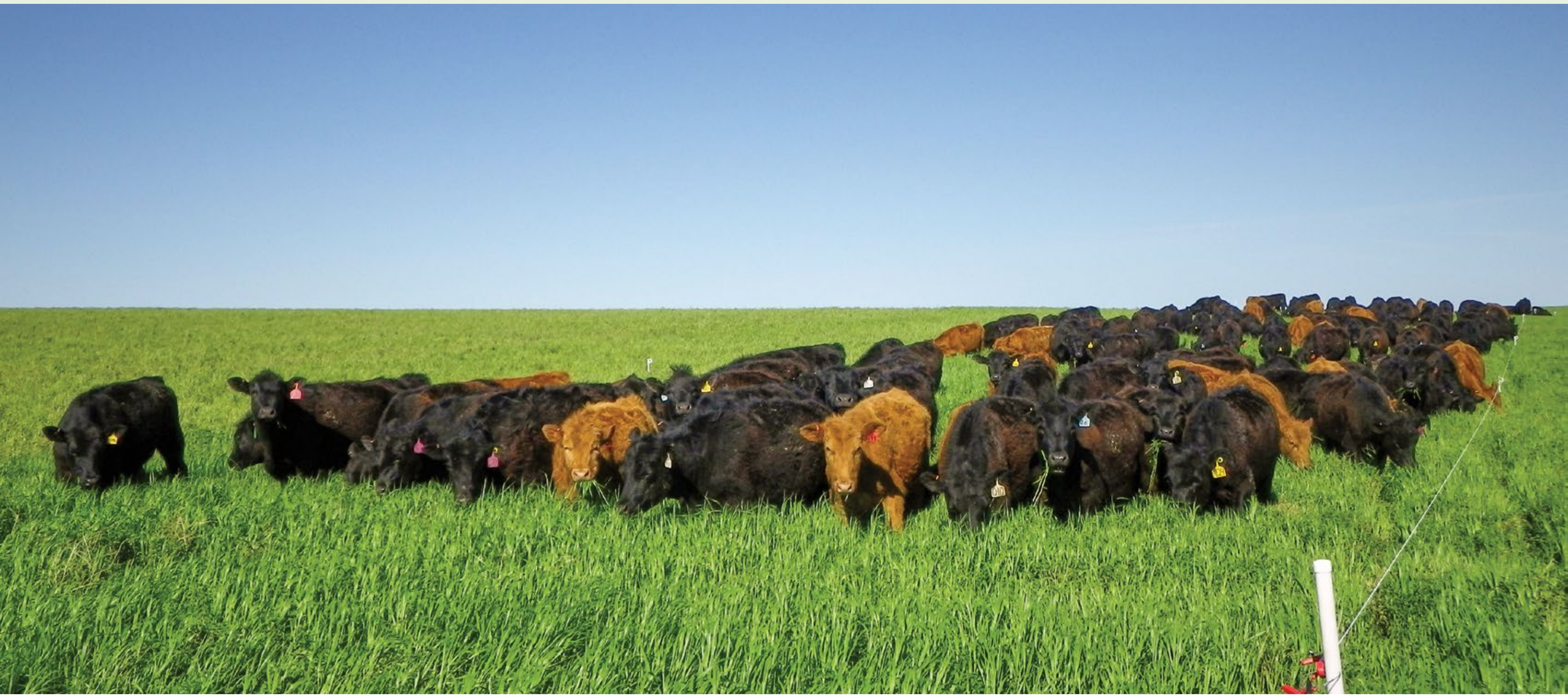
Soil Methane Sinks

Some microorganisms (methanotrophs) in soils have the ability to consume limited amounts of methane, helping to remove some of this powerful greenhouse gas from the atmosphere.[82] But this “methane sink” is very small compared to the methane emissions coming from agriculture as a whole.

Converting natural ecosystems to cropland or grazing land typically reduces their CH_4 sink capacity by roughly two-thirds, and it can take more than 100 years to recover.[83] Converting forests to grazing land changes soils from a CH_4 sink to a source.[84] And conventional grazing practices can also shift natural grassland soils from a CH_4 sink to a source.[85]

Improved land use practices can sometimes enhance the methane sink. For example, afforestation of pastures has been shown to increase the CH_4 sink.[86] This offers the intriguing potential that agroforestry systems like silvopasture may help to increase soil CH_4 sinks. Improved grazing and rangeland / pasture management practices can increase CH_4 sinks in grasslands, in some cases even doubling the size of the annual sink.[87] Increasing the use of high organic matter amendments like compost, and increased retention of crop residues, can increase the methane sink in croplands. And studies have found that biochar addition to flooded rice soils can also increase the power of the CH_4 sink.[88]

While methane sinks can be improved, it is very important to note that landscapes only have a very limited ability to absorb and consume methane — even as agriculture sources (especially livestock and manures) are leading methane emitters to the atmosphere. In fact, global grassland soils can only capture up to ~15% of the emissions coming from grazing ruminants each year.[89]



Herd of cattle grazing on Brown’s Ranch in North Dakota. *Photo credit: Paul Brown / Brown's Ranch*

Overcoming Methane Emissions from Cattle is a Challenge

There is a notion going around in parts of the regenerative agriculture community that methane from cattle in managed grazing systems is not of concern — that it is consumed by the soil methane sink, that grazed animals produce less than feedlot animals, or that atmospheric methane is coming from some other source. But there's no scientific evidence to back up these notions, and in fact there is strong evidence and near-universal agreement from scientists that it is incorrect.

To begin, cattle on pasture actually emit more methane per kilo or meat or milk produced than feedlot animals.[90 91 92] That's why switching more ruminants to feed concentrates is one option for reducing enteric methane. Improving fodder quality can also reduce enteric methane emissions, but in most cases emissions per kilo are still higher than ruminants fed on concentrates.[93]

The soil methane sink does have a rather modest capacity to absorb methane. Globally, grassland methane sinks absorb as much as ~15% of annual global enteric methane emissions, leaving ~85% as a potent greenhouse gas source.[94] Moreover, in the absence of cattle, this methane sink would be absorbing other anthropogenic methane emissions.

Accounting for these methane emissions is critical to addressing climate change in agriculture. And regenerative agriculture systems that claim to be a climate solution must address this point. Fortunately, there are cases where per-hectare soil carbon sequestration rates from managed grazing systems were found to be higher than their methane emissions.[95 96] Unfortunately, such high rates of soil carbon sequestration may only continue for a period of years to decades. Once soil carbon sequestration slows down, these managed grazing lands will become net sources of greenhouse gases once again.[97]

Note the conversion of pasture and rangeland to silvopasture can greatly increase annual carbon sequestration rates. It also offers the opportunity to add additional long-term carbon sinks by harvesting timber and other long-lived wood products, which stores carbon in the product while allowing new trees to be planted, starting active carbon sequestration once again.[98]

Silvopasture. *Photo credit: Eric Toensmeier*

Soil Inorganic Carbon

Much of the focus on agricultural carbon sequestration has been on soil *organic* carbon, but soil inorganic carbon (SIC) is also significant. Soil inorganic carbon persists in soils (and groundwater) for much longer than organic carbon. And the world's drylands, which are disproportionately low in organic carbon, store some 95% of the world's SIC (Lal 2019a, Lal 2019b).[99 100] Researchers are beginning to explore how sustainable land management practices in drylands help to increase SIC levels. Practices to increase SIC include managed grazing, agroforestry, and applying rock powders.[101 102 103]

Dryland restoration in Mali. *Source: TREEAID flickr.com/photos/53871588@N05/*

5

HOW MUCH CARBON CAN WE SEQUESTER? AND FOR HOW LONG?

There is increasing interest in sequestering carbon on agricultural lands, but with that interest has come some extraordinary claims and a great deal of confusion. A handful of individuals and organizations have claimed that agricultural practices could, all by themselves, completely stop climate change. That's not true, as we demonstrate below, but there are still many questions about how much of a role agricultural carbon sequestration can play in addressing climate change.

To understand how much carbon might realistically be sequestered on agricultural lands, we can start with the basics. First, how much land can be used? Second, how much can each hectare of land sequester?

How Much Land Can We Use?

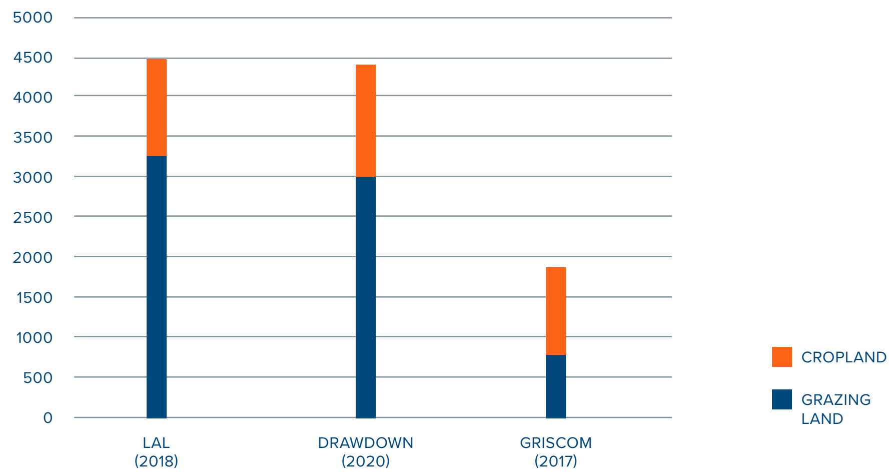
There is limited land available for agricultural carbon sequestration.

First of all, we should not convert natural ecosystems — whether forests, grasslands, or other systems — to agricultural land for the purposes of carbon sequestration. Nearly all natural ecosystems contain more carbon than their agricultural counterparts, and no carbon farming techniques are likely to make up for this loss.[104]

Instead, we should be focusing on lands already in agricultural production, or former agricultural lands that have been degraded and abandoned. Figure 5.1 shows different estimates of the area available for agricultural sequestration.[105] [106] [107]

Figure 5.1 — Area Available for Agricultural Carbon Sequestration (MHa Available for Ag Biosequestration)

Note that the estimate from Griscom (2017) is lower than the other two, as they used more conservative figures for the area of grassland that is amenable to carbon sequestration through improved grazing and pasture management.



How Much Carbon Can Be Stored?

No one is entirely sure how most carbon might be sequestered in agricultural biomass and soils. But there are some ways we can potentially estimate it.

(a) Restoring Soils to Their "Natural" Carbon Levels. One approach is to consider the biomass and soil carbon that has been lost from natural landscapes since the dawn of agriculture. We can use that amount of "lost carbon" as a possible ceiling of what could be recaptured. Generally speaking, the levels of carbon found in natural ecosystems are considered the maximum potential for agricultural lands, given that cropland and grazing land have lost so much of their original carbon. Unfortunately, much of that land is seriously degraded, and some of it is under pavement and cities, and is highly unlikely to return to high-carbon landscapes in the foreseeable future.[108]

Agricultural lands have lost substantial carbon, both in soils and aboveground biomass. Most have lost between 25–75% of their SOC, as well as most or all of their carbon in aboveground biomass, as a result of clearing forests for crop and livestock production.[109] Overall, it is estimated that, since the dawn of agriculture, we have lost approximately 1,177 Gt-CO_2-eq from the world's landscapes. Over half of these losses have come in the last century and a half.[110] While it may be possible to replace much of this carbon, getting even two-thirds of the original soil carbon back is considered the best "attainable" potential in most cases.[111, 112]

Based on this logic, and using hundreds of thousands of soil carbon measurements of natural and agricultural landscapes — with measurements taken across different climate zones, topographic regimes, and soil types — scientists estimate that global soil carbon restoration could sequester up to roughly 294–331 Gt-CO_2-eq, with an upper limit of ~489 Gt-CO2-eq.[113]

(b) Look Across the Published Data. Another approach is to look at the world's available lands, assign a range of values from data on the carbon impact of different farming practices to them, and determine the overall sequestration impact. These estimates include many but not all practices, and further data on sequestration rates, global adoption potential, and variations between and within practices and climates. Using this technique, Lal (2016) estimates that cropland soils might sequester up to ~228 Gt-CO_2-eq.[114] Our work at Project Drawdown estimates a global impact of ~132–206 Gt-CO_2-eq.[115]

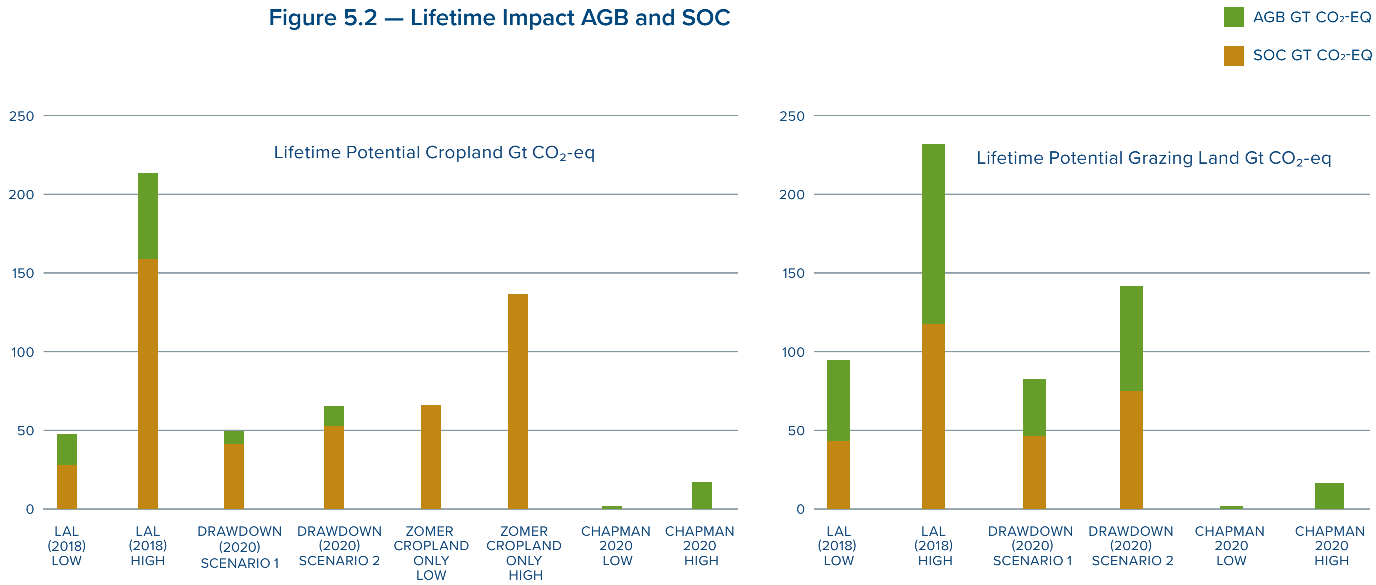
Metepantli living terrace edges. *Photo credit: Eric Toensmeier*

(c) Don't Extrapolate from Just a Few Datapoints. Unfortunately, some estimates have taken just a few, exceptionally high, sequestration rates from some limited experiments and applied them to all the world's cropland and/or grassland. This is not statistically robust and fails to account for the natural variation in carbon uptake across climate, topographic, and soil zones. Moreover, basing estimates on high "outlier" data points can greatly overestimate sequestration potential. An individual rate may be so high as a result of an exceptional farmer or rancher, something unusual about their soil or land use history, or testing in a year with especially favorable conditions. Many times, exceptionally high rates of carbon sequestration may be seen in the first few years of changing practices, but those amounts usually drop significantly over time. Nevertheless, it is of vital importance to follow up on reports of unusually high impacts, as these practices may offer game-changing insights.

Figure 5.2 compares estimates of the cumulative carbon sequestration potential for the world's croplands and grazing lands, according to multiple estimates. The results range from 66–445 Gt-CO_2-eq. Estimates for lifetime cropland sequestration range from 48–213 Gt-CO_2-eq, versus 84–232 Gt-CO_2-eq for grazing land (note that there is more than twice as much grazing land as cropland).[116 117 118] See Figure 5.2.

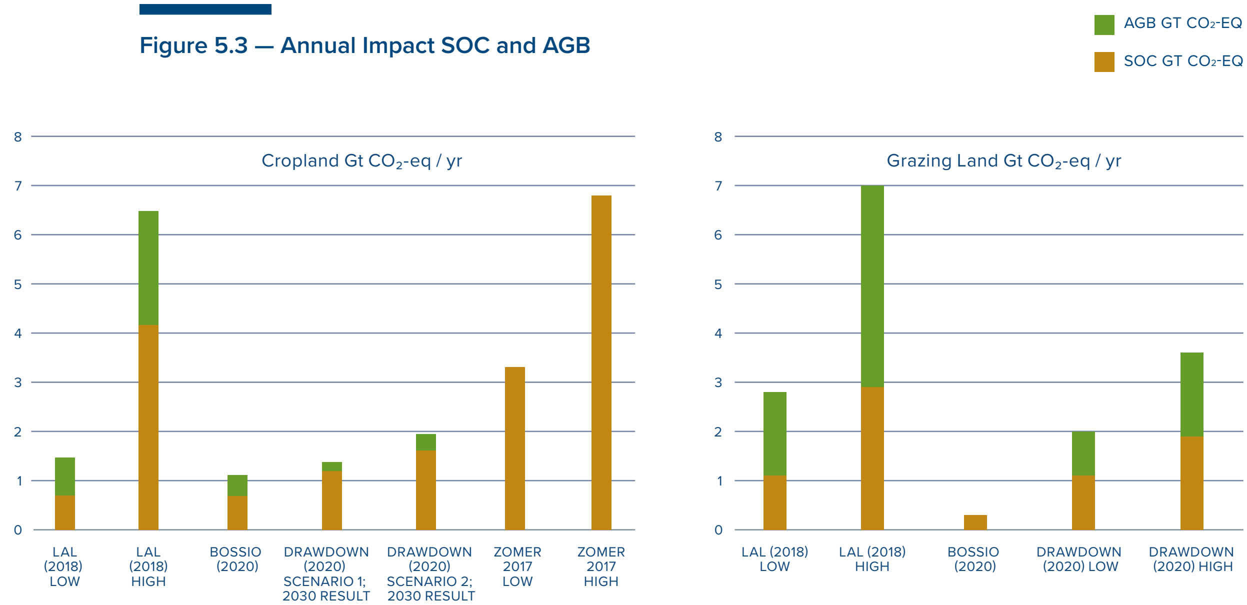
To put these numbers in perspective, the world's current greenhouse gas emissions are equivalent to roughly 52 Gt-CO_2-eq per year. These lifetime estimates for carbon uptake on agricultural lands range between 1.3 to 8.5 times higher — meaning that they could only sequester enough to offset 2 to 5 years emissions. While extremely helpful, it is certainly not enough to stop climate change in the long run. But combined with emissions reductions, it can be a powerful tool to help address climate change.

Figure 5.2 — Lifetime Impact AGB and SOC



On an annual basis, the estimated potential global carbon sequestration rate ranges from 2.6–13.6 Gt-CO_2-eq / yr (see Figure 5.3). The potential sequestration rate for cropland is 1.1–6.6 Gt-CO_2-eq / yr, of which aboveground biomass contributes 14–53%. For grazing lands, the sequestration potential is estimated at 0.4–7.0 Gt-CO_2-eq / yr, with aboveground biomass accounting for 46–61% (see Figure 5.3).[119 120 121 122 123]

Figure 5.3 — Annual Impact SOC and AGB



How Long Can Agricultural Landscapes Hold Carbon?

Once croplands and pastures sequester carbon, taking it out of the atmosphere and helping address climate change, important questions remain.

First, we must ask ***how long*** **can agricultural lands naturally hold on to biomass and soil carbon, keeping it out of the atmosphere?**

Carbon in biomass is stored for the lifespan of the plant tissues in question. Grasses and forbs, for example, generally live for a season up to a few decades. In forests, the leaves and fine roots of trees are typically shed annually, but the woody biomass stores carbon through the entire life of a tree — whether decades or centuries. As a result, any long-term carbon storage in biomass is largely limited to the lifetime of trees.

Soils can also hold organic matter across a wide range of timescales, from a season, through years and decades, to centuries. Different forms of SOC have different natural lifetimes, depending on how resistant the organic carbon in question is to decay. Altogether, the levels of soil carbon are likely to persist as long as the improved management practices are followed, but it is highly vulnerable to future changes in land use and natural disturbances including those from climate change.[124]

Once the practices that sequestered carbon are discontinued, the carbon that was gained can be quickly emitted back to the atmosphere — especially carbon that is not bound to mineral particles.[125 126] Without maintenance of carbon-friendly practices, soil carbon is re-emitted to the atmosphere more quickly than it was sequestered.[127] Soil organic carbon can be lost through a return to tillage, poor grazing practices, and other practices that cause degradation of agroecosystem carbon.[128]

That's why we also need to ask ***what practices need to be kept in place*** **to ensure that biomass and soil carbon isn't lost in future disturbances — whether future changes in land use practices or changing climatic conditions.** From a policy perspective, it is extremely important to consider how any potential "carbon credits" for soil carbon sequestration are managed for long periods of time, where changing land use practices and climate could release much of that carbon back into the atmosphere. **We need to be mindful of the risks associated with the lack of permanence in agricultural carbon stocks.**

It is also important to note that some of the carbon held in biomass and soils can also be lost even under the best continued farming practices. Carbon in biomass can be lost in fires, harvested for fiber or fuel, or otherwise lost.[129] Moreover, climate change could cause the loss of sequestered carbon in both soils and biomass.[130] There is no single response of biomass and soil organic carbon to projected climate change — in some regions it is projected to increase, while in others it will likely decrease, sometimes dramatically.[131] And climate-fueled disasters — especially fires, droughts, and floods — can all quickly release carbon, as seen in recent fires in Australia and the Amazon Basin.

6

CONCLUSION: WE MUST CHANGE AGRICULTURE TO HELP ADDRESS CLIMATE CHANGE

The world's food system, agricultural practices, and land use are a significant contributor to climate change — together emitting roughly a quarter of our current greenhouse gas emissions. Most of these emissions come from land use (especially deforestation), methane emissions (mostly from cattle), and nitrous oxide emissions (primarily from fertilizer overuse and manure). To help address climate change, we must reduce these emissions, first and foremost. In this primer, we have outlined a wide variety of ways to reduce agricultural emissions, which together present highly actionable steps towards addressing this part of the climate change problem.

Moreover, our land use and agricultural practices can be changed — using "regenerative" style techniques, and others — to create temporary carbon sinks on land. These carbon sinks work by sequestering carbon within biomass and soils, significantly raising the level of these carbon stocks above their present-day values. While the potential for these types of sinks is substantial, there are challenges facing them too. In particular, we must be aware of the limits on the potential size of biomass and soil carbon stocks, and their tendency to slowdown carbon accumulation after several years or decades — whereas emissions reductions can continue indefinitely. And we must recognize the need to manage carbon sinks well into the future to avoid releasing the carbon back into the atmosphere if the practices that sequestered it are discontinued or if natural disasters like droughts or fires create a disturbance. In addition, if grazing animals are used in the regenerative farming practice, the system must carefully address how it, on net, can overcome the methane emissions from livestock, even as soil stocks eventually slow their rates of carbon accumulation. Finally, it is much more challenging to measure and predict soil carbon sequestration than emissions reductions.

While the potential for regenerative agriculture to sequester carbon has been, at times, overpromised and overestimated, it does indeed have impressive capacity and an essential role as part of a broader program to cut emissions and promote carbon sinks.

Addressing climate change in the food, agriculture, and land use sector can use two parallel, and complimentary, sets of tools — reducing the primary emissions from agricultural practices *and* enhancing carbon sinks on agricultural lands. **This means that — in theory — improving land use and our food system can dramatically reduce a quarter of the world's greenhouse gas emissions and remove significant amounts of already-emitted carbon dioxide from the atmosphere.**

We strongly endorse approaches that focus *both* on immediate emissions reductions from the FALU sector *and* long-term investments in regenerative agriculture that can advance farming practices, significantly improve local environmental conditions and soil resilience, and create substantial carbon sinks that can also help address climate change.

It is important to be aware of the key differences between emissions reductions and sequestration strategies (Table 6.1). For example, emissions reduction takes place immediately, while carbon sequestration often takes several years or decades to kick in. In addition, carbon sequestration often continues for several decades until soils and biomass slow their rates of sequestration, whereas emissions reductions can continue indefinitely. Most important: emissions reductions are irreversible, but carbon sequestered in soils and biomass can be quickly returned to the atmosphere if regenerative farming practices are ceased or due to natural disasters including those caused by climate change. Finally, emissions reductions and carbon stored in aboveground biomass are fairly easily measured, predicted, and quantified, while soil carbon sequestration presents many challenges for prediction as well as economically viable measurement and monitoring.

Table 6.1 — Emissions Reduction vs. Biosequestration Impacts

	TIMELINE OF IMPACT	LIFETIME OF IMPACT	REVERSIBILITY OF IMPACT	EASE OF MEASUREMENT	POTENTIAL ANNUAL IMPACT GT CO_2-EQ/YR
Emissions reduction	Immediate	Can continue forever	Irreversible	Relatively simple	1.3–4.2
Biosequestration: Soils	Delayed (may take several years to begin)	Measured in decades	Can be reversed through return to poor farming practices or climate disasters	Very challenging to predict and measure	1.0–7.1
Biosequestration: Aboveground Biomass	Delayed (may take several years to begin)	Measured in decades	Can be reversed through return to poor farming practices or climate disasters	Relatively simple	1.1–6.4

While these approaches have different pros and cons, we strongly endorse a portfolio of climate solutions in FALU — including efforts to reduce food waste, change diets, reduce the primary emissions from agriculture, land use, and regenerative-style agricultural practices that improve soils, create healthier landscapes, waterways, and sequester carbon. An "all of the above" approach, finding potential synergies among solutions is worth pursuing. Any single solution, as exciting as they may be, is unlikely to be nearly as effective as pursuing a more complete set.

Pursuing these solutions will require substantial changes in policy, business practice, capital, and behavior, of course. But most of these would generate *incredible* economic and social co-benefits, and would be very smart things to do. Reducing food waste, protecting rainforests, promoting healthier diets, reducing the overuse of fertilizers and manure on farm fields, and promoting regenerative agricultural practices could significantly contribute to improving the health, economic, and local environmental benefits of the food system — and help address climate change at the same time.

Without a doubt, taken together, these solutions represent an *enormous* opportunity to help address climate change. But it does **not** replace the work we need to do in other sectors — especially electricity, industry, transportation, and buildings. Massive efforts to phase out fossil-fuels and other emissions in these areas are needed too.

Looking across FALU and other sectors, key priorities for climate action include:

- **Replace carbon-based electricity with renewables** as quickly as possible, and **shift as many transportation and building systems to electricity** as soon as we can.
- **Reimagine the production and use of greenhouse-gas intensive materials,** including concrete, steel, and refrigerants.
- **Reinvent our agricultural practices and food system** so that they increase food security and reduce greenhouse gas emissions.
- **Restore natural ecosystems and practice regenerative agriculture,** so that we create new carbon sinks — as well as healthy landscapes, clean waterways, and more wildlife habitats.

There is no *single* answer to addressing climate change. No silver bullets exist. But a silver buckshot does.

If we look at the whole landscape of climate solutions, we can see numerous opportunities to work together — across economic sectors, geographic locations, and local-to-national scales — to reduce emissions, create carbon sinks, restore healthy ecosystems, create jobs and local economic benefits, improve human well-being, and stop global warming.

It *can* be done. The only question is: Will we?

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