REGENERATIVE GRAZING, CARBON, AND CLIMATE

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GLOSSARY

TERM	DEFINITION
CARBON FOOTPRINT	TOTAL GHG EMISSIONS, CONSIDERING ALL RELEVANT SOURCES AND SINKS
GREENHOUSE GAS EMISSIONS	GASEOUS EMISSIONS OF BOTH NATURAL AND HUMAN-INDUCED ORIGIN WHICH CONTRIBUTE TO INCREASED ENERGY CYCLING WITHIN EARTH'S ATMOSPHERE AND CHANGES IN GLOBAL CLIMATE PATTERNS
MINERAL-ASSOCIATED ORGANIC MATTER (MAOM)	A SOIL CARBON POOL WHICH ACCUMULATES MORE SLOWLY AND IS ASSOCIATED WITH THE MINERAL FRACTIONS OF SOIL. THIS POOL IS LESS VULNERABLE TO TURNOVER AND REACHES A SATURATION POINT WHICH VARIES ACROSS SOIL TYPES AND REGIONS
PARTICULATE ORGANIC MATTER (POM)	A SOIL CARBON POOL WHICH ACCUMULATES RAPIDLY AND POTENTIALLY INDEFINITELY, BUT WHICH IS "VULNERABLE" TO MICROBIAL TURNOVER TO MAKE NUTRIENTS AVAILABLE TO PLANTS
SOIL ORGANIC MATTER	THE PORTION OF SOIL CONSISTING OF FRESH PLANT RESIDUES AND SMALL LIVING SOIL ORGANISMS, DECOMPOSING (ACTIVE) ORGANIC MATTER, AND MINERAL-ASSOCIATED ORGANIC MATTER

INTRODUCTION

Can regenerative agriculture mitigate climate change? Does regenerative grazing sequester more carbon? Arguments abound as to the role of regenerative agriculture—and grazing specifically—as a natural climate solution, each with their own supporting and dissenting evidence. Understanding the way that carbon is introduced to the atmosphere, captured by soils, and stored by soils is critical to defining a position on this topic.

Regenerative grazing is an agricultural practice that uses soil health and adaptive livestock management principles to improve farm profitability, human and ecosystem health, and food system resiliency. Applicable in both annual and perennial forage systems, such grazing builds on ecological principles and the relationship between grasslands and ruminants.[1] It is based on long-standing Indigenous land stewardship of native prairie and savanna. Regenerative grazing typically maintains rest-rotation cycles: short periods of dense grazing followed by long forage rest periods to support vegetative recovery. Regenerative grazing is a component of regenerative agriculture, which emphasizes reduction or elimination of synthetic inputs and tillage; increased diversity of plant, animal, and microbial life; and generation of sufficient revenue to build viable farm businesses and fairly compensate farm labor.

As a result of this focus on ecological outcomes, increasing soil organic matter and the resultant carbon sequestration is considered a key metric of progress towards ecological goals in regenerative agricultural systems. However, capturing ***and keeping*** carbon in soils is a complex process which science is only beginning to fully understand. Further, the ability of carbon capture and permanence in soil to mitigate climate change is a hotly debated topic. This report will review the science of organic matter and carbon cycling in agricultural systems, the basics of climate science, and the critical discourse on the ability of regenerative grazing to serve as a climate mitigator.

CARBON CYCLING IN AGROECOSYSTEMS

The Global Carbon Cycle

Carbon is stored in three places: land, ocean, and atmosphere. Globally, there are about 50,400 billion metric tons of carbon.[2] Of this carbon, about 5% is stored in soil, 1.2% is stored in living organisms like plants and animals, 1.5% is stored in the atmosphere (primarily as carbon dioxide and methane), 15% is stored in fossil fuels, and 77% is stored in oceans.

Carbon is continuously cycling through these three stores. Fossil fuels are a long-term storage pool for carbon. When they are combusted, they represent addition of "new" carbon to the atmosphere for cycling. Oceans serve as a reservoir for carbon and can provide a buffer to atmospheric changes—an ability further threatened by increasing global temperatures. Plants take up carbon dioxide from the atmosphere through photosynthesis. Some of the carbon remains in the plant, and some is transferred to the soil through plant roots (secreted as root exudates) and plant tissues. Once plant carbon enters the soil it can be consumed by soil organisms (e.g., insects, animals, and microbes).

Soil organisms use the plant carbon for energy to grow. As they do, some carbon dioxide is released back to the atmosphere through respiration, and some returns to the soil through decomposition. As soil organisms die, the carbon stored in their tissues or bodies (e.g., microbial necromass) is returned to the soil.

Like soil organisms, animals consume carbon stored in plants. Some of the carbon remains in their tissues, some is lost as carbon dioxide through respiration, some as methane through enteric fermentation of feed, and some is returned to soil through microbial decomposition of matter in manure.

Soil Carbon

Of the 5% of Earth's carbon which is stored in soil, some is stored close to the soil surface and the remainder is stored in the full soil profile. About 50% of the carbon stored in the first 3 feet of the soil profile is stored in the 2- to 3-foot depth.

Soil carbon exists in two forms: inorganic and organic. About two thirds of soil carbon exists in its organic form. Soil organic carbon is arguably the most well-known form due to its potential as a natural climate solution.[3] Soil organic carbon has become the subject of international conversations about the potential for regenerative agriculture to contribute to climate change mitigation through carbon sequestration.[3–7]

But what is soil carbon sequestration? As carbon is constantly cycling through the three stores, carbon can not only be drawn down out of the atmosphere into soil through plant photosynthesis and biotic decomposition, but can also be emitted back to the atmosphere through microbial respiration. ***Soil carbon sequestration is specifically the capture and persistence of carbon in soils over time.*** Soil carbon sequestration can occur by either increasing inputs or decreasing outputs from soil.

The rate of carbon cycling, or carbon inputs to soil and losses from soil, varies with space and time. The effect of soil carbon sequestration on climate mitigation is dependent on its persistence, or the amount of time carbon remains in the soil before reentering the atmosphere. The ability to capture carbon and keep it in the soil is controlled by a number of complex biological, physical, and chemical factors. We will discuss a few in the context of organic matter, which is the reservoir for carbon in soils.

Organic Matter

As the ability for soils to sequester carbon is dependent on the permanence of carbon that is captured, it is important to find ways of measuring and thinking about organic matter to have a common language and science of soil organic carbon. A useful framework for this purpose includes two pools: particulate organic matter ***(POM or "vulnerable" carbon)*** or mineral-associated organic matter ***(MAOM or "protected" carbon).***[8]

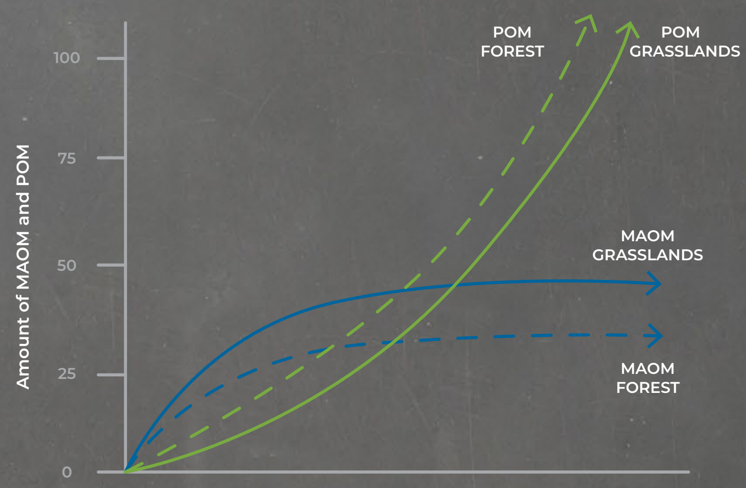
POM is considered vulnerable carbon because it is more available for consumption by microbes, while MAOM can be considered protected carbon due its strong bond with soil particles (e.g., clay). MAOM's association with clay particles makes it difficult for this organic matter to be decomposed, thus protecting the carbon stored in this format. Another way of thinking about POM and MAOM is that POM is the organic matter checking account, while MAOM can be thought of as the organic matter savings account.[9] POM and MAOM exist in differing fractions across ecoregions and land use types, and have very different properties.

POM (vulnerable carbon) is composed of partially decomposed plant litter (leaves, roots). It is ***cycled more quickly*** (thus more quickly respired by plants and lost as CO2), enabling plant nutrients to be made available via decomposition. This fraction of organic matter is more vulnerable to disturbance (e.g., tillage or overgrazing), but it ***can theoretically accrue carbon indefinitely.***

MAOM (protected carbon) forms when organic matter binds to soil minerals. It is made up of smaller molecules including microbial bodies, or organic matter that has leached directly from plant material or has been transformed by microbes. MAOM's association with minerals makes it the ***most stable (persistent)*** with longer turnover times and the potential to remain in soil for centuries. Its association with minerals also means that the MAOM content of soils ***saturates after some period,*** though this saturation point differs across ecoregions and soil types.

The amount and rate of carbon sequestered in soil depends on both the accumulation of carbon and its persistence. Soil carbon persistence is affected by environmental and management changes. A major pathway for soil carbon loss is soil organic carbon decomposition. Many environmental and biotic factors affect soil carbon decomposition rates, which can range from days (e.g., in wet environments) to millennia (e.g., in dry environments).[10,11] Thus, the role of agricultural soil carbon sequestration in mitigating climate change depends on a thorough understanding of how carbon stabilizes in soil and how this stability will be affected by human or climate disturbance.

POM/MAOM of Different Environments

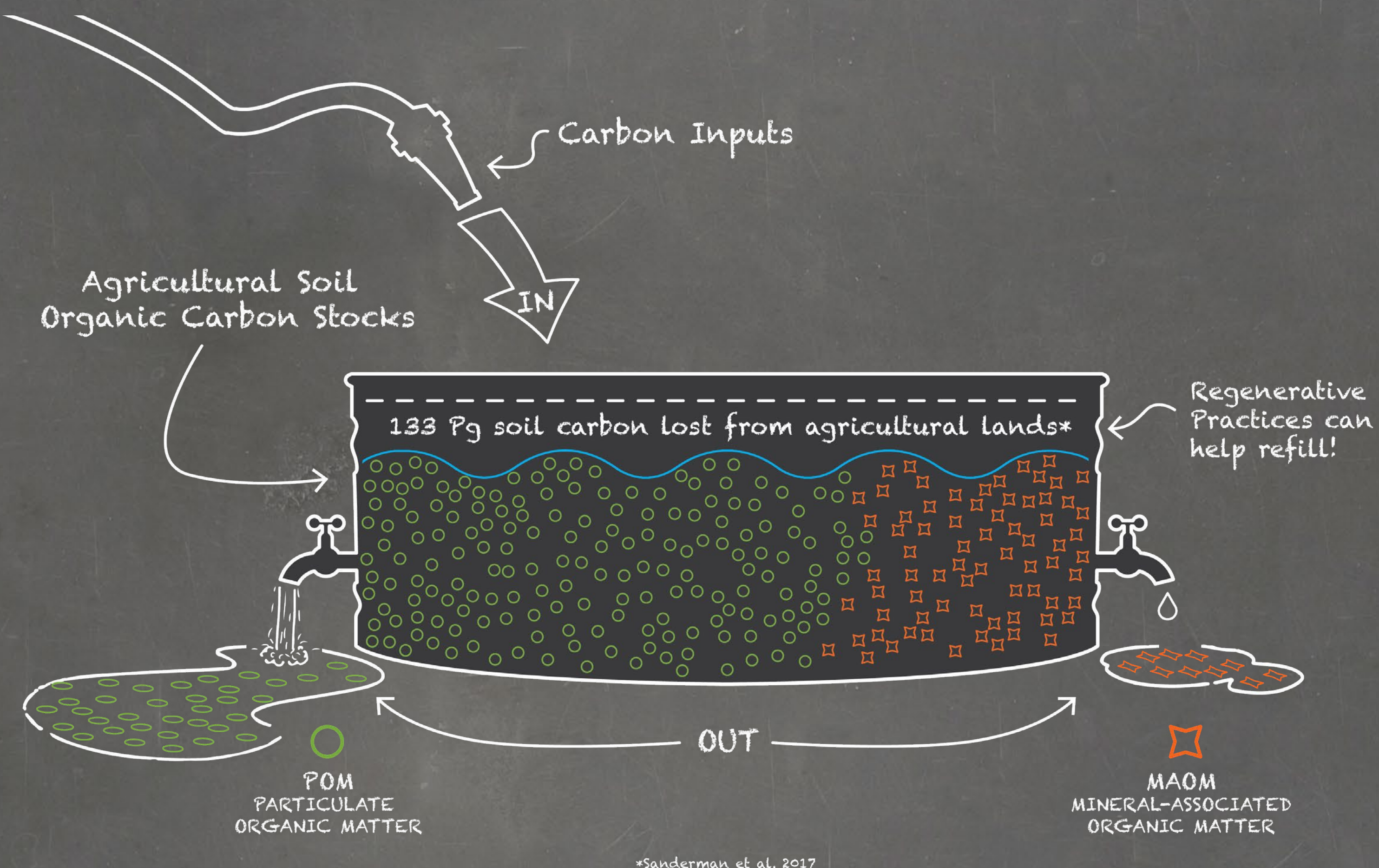


adapted from Figure 4 in Cotrufo et al. 2019

Scientists' theoretical understanding of soil carbon stabilization has increased rapidly in the past few decades. Previously, the chemical recalcitrance—or resistance to decomposition—of plant litter and organic matter was thought to be the primary control over the amount of time that carbon remained in soils.[12]

Today, soil carbon stability is thought to be largely independent of plant litter recalcitrance. ***Recent scientific evidence points to soil organisms and stabilization of carbon on clay mineral particles as the main drivers of soil carbon stabilization and persistence.***[13] Most plant inputs that enter the soil have been processed by microbes, and chemically-labile components (the parts which are quickly broken down and serve as a food source for microbes) of plant litter can be minerally-stabilized.[14]

The oldest soil carbon is found associated with mineral fractions (i.e., MAOM or protected carbon),[15] and the products of microbial transformation of plant litter are more likely than the plant litter compounds themselves to contribute to stable organic matter pools. ***Grassland soils store more of their carbon as MAOM (protected carbon), while forest soils store more of their carbon as POM (vulnerable carbon).***[16] To date, regional estimates of the soil MAOM and POM contents have not yet been published. However, the deep mollisols of the Midwest and the long-term land cover in perennial forages suggest that Midwestern soils may have greater MAOM content and potential for soil carbon stored in this protected form.



CLIMATE CHANGE

Greenhouse Gas Emissions

Gases that trap heat in the atmosphere are called greenhouse gases.[17] These gases are emitted from both natural processes (e.g., microbial respiration in wetlands) and human activities (e.g., fossil fuel combustion).

The primary greenhouse gases are carbon dioxide, methane, and nitrous oxide. About 81% of U.S. greenhouse gas emissions are carbon dioxide, 10% are methane, and 7% are nitrous oxide.[18] Carbon dioxide can live in the atmosphere for thousands of years, while methane lives about 14 years in the atmosphere, and nitrous oxide lives about 114 years in the atmosphere (IPCC). Each gas has a different impact on global climates which is sometimes measured as "global warming potential". In a 100-year time span, methane has an impact on climate that is 25 times greater than the impact of carbon dioxide and nitrous oxide has 298 times the impact of carbon dioxide.[17]

Greenhouse gases play an important role in creating the climate patterns and biota we are familiar with and will continue to play a role in the climate and biota of the future.

Climate Change

Carbon dioxide emissions have risen dramatically since the start of the industrial revolution, due in large part to the combustion of fossil fuels. Prior to the industrial revolution, significant quantities of carbon were lost through the conversion of forests and grasslands to agricultural land and intensive tillage practices. Increasing concentrations of greenhouse gases in the atmosphere lead to increasing frequency and severity of extreme weather events (e.g., hurricanes, flooding, fires, and drought), generally increasing global temperature, and decreased precipitation in some parts of the world.

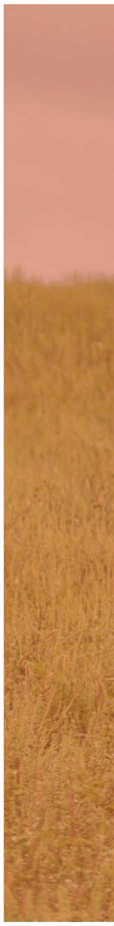
To document these changes, climate scientists sample air samples from gas bubbles in long-held ice stores at the arctic poles and measure their concentrations of greenhouse gas emissions. These measurements provide a snapshot in time of the greenhouse gas emissions in a given time period.

While average global temperature has always fluctuated by about 5 degrees Celsius, current greenhouse gas emission trajectories threaten to exceed the maximum average fluctuation in the last several hundred thousand years of measurements we have been able to attain. The implications of this increase, particularly without any abatement in sight, have significant potential consequences for human wellbeing around the world.

Mitigating Climate Change

What does it mean to mitigate climate change? ***Mitigating climate change refers to curbing or reducing greenhouse gas emissions such that global increases in average temperature are halted or reversed.*** This can be achieved by reducing emissions from industrial and agricultural processes, by the implementation of carbon capture technologies, and by natural climate solutions aimed at increasing carbon sequestration in working and wild lands—both above- and below-ground.

Several intergovernmental accords have been drawn to lead the global effort towards reducing greenhouse gas emissions. The first was the Kyoto Protocol, which was proposed at the 1997 United Nations Framework Convention on Climate Change (UNFCCC) meeting. This protocol put the onus on industrialized countries to commit to emissions reduction targets. It did not take effect until 2005. The second intergovernmental accord, the Paris Agreement originally signed in 2015, builds on the Kyoto Protocol by involving less industrialized countries in the process of reducing global greenhouse gas emissions. The Paris Agreement[19] specifies a commitment to limiting greenhouse gas emissions such that average global temperature does not exceed 2 degrees Celsius based upon historical average global temperatures and a desire to limit the risk of increasing frequency and severity of extreme weather events on Earth's habitability for humans.



CAN REGENERATIVE AGRICULTURE MITIGATE CLIMATE CHANGE?

Arguments abound as to whether soil carbon sequestered through regenerative agriculture and grazing can mitigate[20] or even reverse climate change.[21] Here we present a review of the supporting and dissenting arguments for the contribution of regenerative agriculture to climate change mitigation efforts.

The Potential for Regenerative Agriculture to Mitigate Climate Change

Soils have tremendous potential to sequester carbon, though the amount and permanence of stored carbon is highly variable, and the science is still developing. Global soils currently store about 2,400 billion metric tons of organic carbon down to a 2-m depth, which is more than the amount stored in vegetation and atmosphere combined. Over time, ***about 133,000 billion metric tons of soil have been lost due to erosion*** from agricultural management practices including deforestation to convert forests to agricultural land, intensive tillage use[7] and overgrazing. With great loss also comes great potential; a 2018 report introduced the concept of “natural climate solutions” into the mainstream climate change discourse.[3,4]

Natural climate solutions represent opportunities to mitigate climate change by ***sequestering carbon both above and belowground in working and wild lands.*** The authors estimate that by implementing a suite of practices including everything from cover cropping to grazing optimization, reforestation, and wetland restoration, we can ***potentially mitigate the equivalent of about 21% of the net annual U.S. greenhouse gas emissions*** in 2016. Most of that potential represents carbon sequestered in trees and other plant biomass, while 29% comes from increased soil carbon sequestration, and 7% represents emissions avoided by preventing land conversion from grassland or forest. Maximizing this potential to achieve the international goal of limiting global warming to 2 degrees Celsius requires an “all of the above” approach, as advocated by the authors. In addition to potential climate change mitigation, the authors cite the co-benefits of increased soil carbon as additional impetus for incentivizing these options (e.g., increased water infiltration and storage, reduced reactive nitrogen emissions, and increased wildlife habitat). These co-benefits, particularly increased water infiltration and storage, are increasingly important for adapting to inevitable climate change impacts.

Livestock production systems which employ regenerative grazing principles have documented soil carbon sequestration. For example, a study of southeastern agricultural systems from degraded row crop production cropland to management-intensive grazing showed a range of sequestration rates from 2.9 to 9.0 Mg C per hectare per year, with the most recently converted farm having the greatest sequestration rate and the earliest converted farm having the reduced sequestration rate. Similarly, A more recent study reported about 13% greater soil carbon and nitrogen stocks in southeastern U.S. pastures managed using regenerative grazing principles than in neighboring pastures managed under continuous grazing.[22]

Together, sequestration rates like these have the potential to reduce carbon footprints; in one example, a beef finishing system that employed regenerative grazing principles in the Midwest was estimated as a carbon sink when an estimated carbon sequestration rate of up to 3 Mg C per hectare per year was applied to its carbon footprint for this stage in the beef life cycle (−6.7 lb carbon dioxide-equivalents per lb of carcass weight).[23] In another example, a southeastern U.S. multi-species production system managed using regenerative grazing principles was reported as having a long-term average carbon sequestration rate of 2.2 Mg of carbon per hectare per year, which translated into an 80% reduction in the carbon footprint of total animal protein produced by the system.[24] Yet another system which estimated carbon footprints for Midwest beef production demonstrated a 15% reduction in the carbon footprint of beef produced in systems that employed management-intensive grazing when assuming more modest sequestration rates of 0.12 Mg C per hectare per year during the cow-calf phase and 0.4 Mg C per hectare per year during the finishing stage.[25]

It is worth noting that soil carbon sequestration alone is not the sole mechanism for reducing carbon emissions from systems employing regenerative grazing principles. In addition to carbon sequestered in pasture and cropland soils, regenerative grazing may also support a reduction in carbon emissions through a variety of pathways, including decreased fossil fuel usage and decreased fertilizer usage. As a result, several reports have proposed soil carbon sequestration through adoption of regenerative agriculture principles as climate change mitigation tools.[2,3] Together, these data indicate large potential for rebuilding soil carbon stocks and thus contributing to carbon drawdown and climate change mitigation efforts.

The Challenges for Regenerative Agriculture as a Climate Change Mitigator

The potential for regenerative agriculture to contribute to climate change mitigation is not without its criticisms. As demonstrated earlier, soil carbon sequestration is a complex, non-linear process influenced by environmental conditions and current and historic management. ***While carbon may be sequestered into soil, permanence is not guaranteed, and the science of soil carbon sequestration is still in its infancy.***

Organizations such as the World Resources Institute consider arguments for regenerative grazing as a climate mitigator to be overblown and have taken a staunch stance against not only grazing, but also regenerative agriculture as a climate mitigation option.[26–28] Their primary criticisms are centered around biophysical and economic limits to widespread implementation of regenerative agricultural practices.

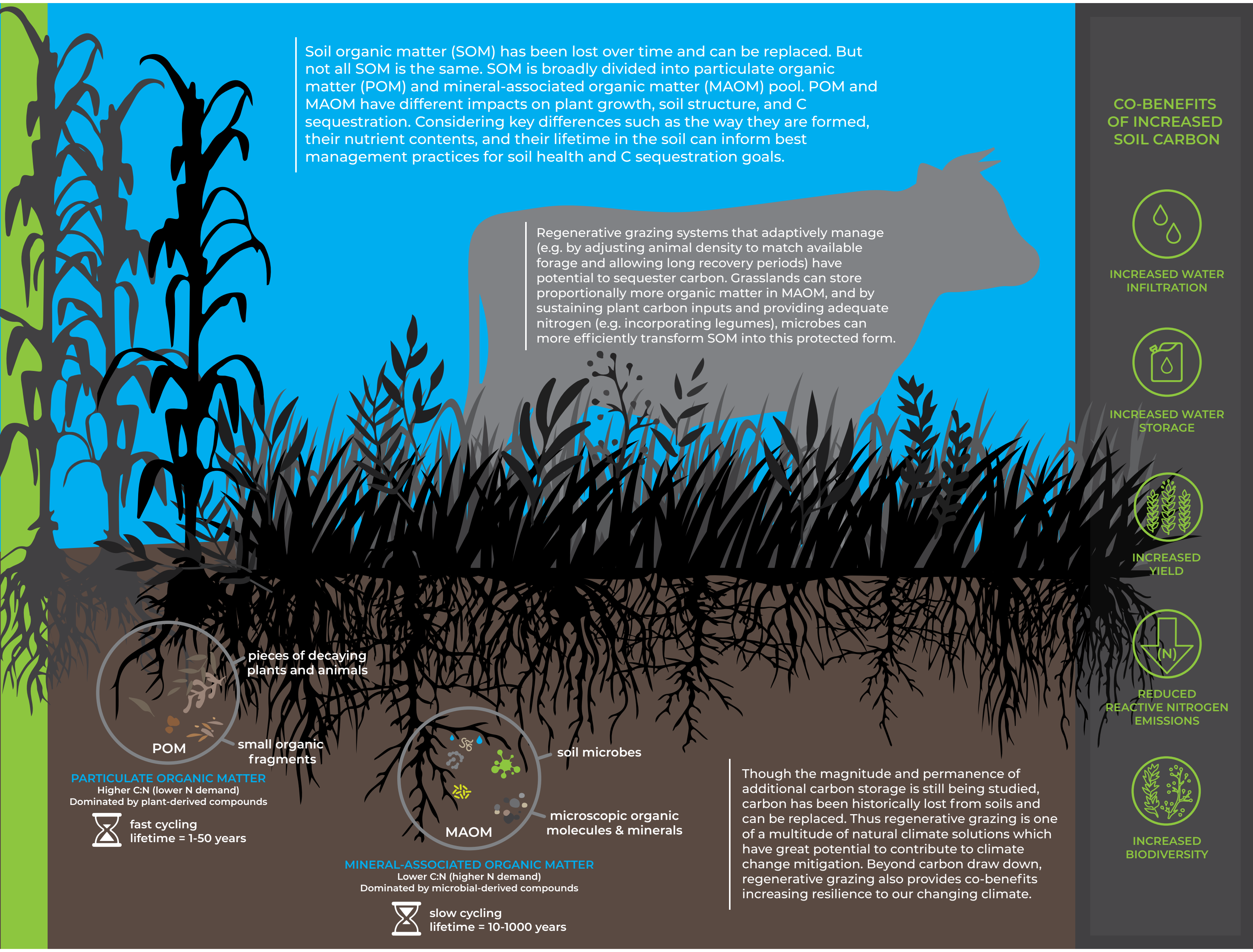
First, detractors cite biophysical limits to carbon sequestration. While degraded lands may rapidly accrue carbon, the rate of sequestration decreases over time. Beyond the tapering of carbon sequestration rates, the impact of regenerative agriculture on climate change mitigation is only as large as the proportion of land use it occupies. Currently, regenerative agriculture is estimated to account for only 4% of global agricultural lands, and critics argue that this proportion of land would have to grow rapidly. ***An increase in land managed using regenerative agriculture principles requires producers to not only rapidly adopt new management practices which fall under this paradigm, but to also maintain agricultural land under regenerative management*** to avoid re-release of carbon to the atmosphere in the future.

Second, soil carbon sequestration requires that carbon added to the soil remains there long-term. Considerable uncertainty exists around soil sampling and soil carbon quantification methods (e.g., soil depth sampling, accounting for expansion and contraction of the soil profile, etc.), carbon accounting (e.g., is carbon storage associated with conversion of row crop land to pasture offset by conversion of pasture to cropland elsewhere? Does this new method require additional nitrogen that introduces nitrous oxide, a more potent greenhouse gas, into the atmosphere, thus raising total climate impact?), and soil carbon permanence in agricultural lands. For example, some studies have demonstrated tradeoffs between increases in shallow soil depths at the expense of carbon losses in deeper depths, meaning that the net change is zero and no carbon is sequestered. While advances have been made in our understanding of the POM and MAOM soil organic matter fractions and their contribution to short- and long-term carbon storage, we still have more to learn about how to achieve greater MAOM storage when accounting for different soil types, management approaches, historical management practices, plant available nutrient needs, and local climates.

Third, carbon sequestration requires some amount of nitrogen to feed microbes in the soil which control organic matter dynamics. The addition of nitrogen to soil is associated with its own greenhouse gas emissions as described above. Whether this is nitrogen from synthetic fertilizers or manure nitrogen, some nitrous oxide emissions will be emitted from manure storage and/or the decomposition of manure piles on the pasture or grazing land surface.

Finally, detractors point to the challenges to adoption for farmers. These challenges and uncertainties are nontrivial, as they are not only ecological, but also social, political, and physical.[29] Barriers include land access, behavioral and cultural change, lack of regenerative supply chain infrastructure, and a need for policy reform.

These critiques are not without their rebuttals.[30] For example, as most soils are already in nitrogen surplus, regenerative agricultural practices such as cover crops which scavenge excess nitrogen and other practices which build soil organic matter enable more efficient nitrogen cycling, thus potentially reducing the need for synthetic nitrogen fertilizers (and their associated greenhouse gas emissions). ***In short, there is scientific support for the potential for regenerative agriculture to serve as one of a suite of natural climate solutions for mitigating climate change, though there is considerable uncertainty around the magnitude and permanence of the impacts of these solutions.*** Disputes about magnitude aside, climate change mitigation requires an "all of the above" approach and natural climate solutions can be concurrently implemented with efforts to reduce fossil fuel emissions.



Regenerative Grazing and Soil Carbon Sequestration: What Else do We Have to Learn?

Regenerative grazing is defined by the Pasture Project as "a suite of practices which harness the power of grazing livestock to rebuild soil health". These practices include adaptive grazing, which is the use of high stocking durations with frequent moves, thus providing long rest periods for paddocks.

While the magnitude and feasibility of regenerative agriculture as a climate mitigation tool continues to be debated, we know that grazing practices which enable plants to rest, thus developing more extensive root systems to contribute carbon to the soil and support the growth of microbes which serve as a form of carbon storage are essential to the ability for grazing to sequester carbon. Such practices fall under a number of grazing regimes including management intensive grazing, adaptive multipaddock grazing, and deferred grazing. We also know that grasslands store more of their carbon belowground in MAOM form than forests, and that perennial plants contribute to the development of extensive root systems which lead to increased soil organic matter formation and thus the potential for greater long-term carbon storage.

There is still much for us to learn! The science on the influence of management practices across soil types and climates influences the proportion of soil carbon stored as POM versus MAOM, though it is clear that regenerative grazing plays an important role in building soil organic matter and associated nutrient retention. Beyond the science of soil carbon sequestration, ***we must both identify the social, political, and physical limits to adoption of regenerative agriculture and pathways for overcoming them.***

While considerable uncertainty surrounds the ability of regenerative grazing alone to mitigate climate change, what is certain is that well-planned grazing which incorporates perennial plants and allocates time for the plant to rest contributes to increased soil organic matter and soil carbon storage. This makes regenerative grazing one of a multitude of natural climate solutions which have great potential to contribute to climate change mitigation. Beyond carbon drawdown, ***regenerative grazing has the potential to improve ecosystem function and provide a plethora of other ecosystem services*** including water filtration, improved nutrient and water cycling, increased habitat for wildlife, and more.

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