SCIREA Journal of Agriculture
http://www.scirea.org/journal/Agriculture
February 3, 2023
Volume 8, Issue 1, February 2023
https://doi.org/10.54647/agriculture210317

Maximizing Photosynthesis and Root Exudates through Regenerative Agriculture to Increase Soil Organic Carbon to Mitigate Climate Change

Andre Frederick Leu
International Director, Regeneration International
ORCID: 0000-0001-9448-8884
Corresponding Author: PO Box 800, Mossman, Queensland, Australia
andreleu.al@gmail.com, +61428459870

Keywords: regenerative agriculture, soil organic carbon, climate change, carbon capture and storage, soil carbon sequestration, root exudates, plant biology, soil microbiome

1. Abstract

To shift from a significant emitter to a major mitigator of greenhouse gas (GHG) emissions, agriculture needs to change from the current dominant paradigm of chemically intensive, industrial/conventional systems to regenerative systems by focusing on plant biology and living soil sciences. Maximizing photosynthesis to capture and convert atmospheric CO_2 into organic molecules to store as soil organic carbon (SOC) would be an effective carbon dioxide removal (CDR) technology to mitigate climate change.

The world reached 420 parts per million (ppm) of CO_2 in the atmosphere in May 2022. The Global Carbon Budget report estimated that atmospheric CO_2 reached an annual average of 417.2 ppm in 2022.

Evidence shows that 430 ppm carbon dioxide equivalents (CO_2eq) to limit warming to 1.5°C and 450 ppm CO_2eq to limit warming to 2°C have been exceeded. Reducing emissions and transitioning to renewable energy is no longer sufficient to stop temperatures from exceeding 2°C, the higher limit of the Paris Agreement. Negative emissions are needed to remove the legacy levels of CO_2. The Intergovernmental Panel on Climate Change (IPCC) stated that without additional sequestration, global mean surface temperature will increase in 2100 between 3.7°C and 4.8°C higher than pre-industrial levels. The IPPC states that CDR is essential in limiting global warming to 1.5°C to achieve net negative emissions. It advocated for CDR technologies such as regenerating natural ecosystems, carbon capture and storage (CCS), and soil carbon sequestration (SCS).

Regenerative agriculture is based on a range of food and farming systems that maximize the photosynthesis of plants to capture CO_2 and use organic matter biomass and root exudates to store it as SOC. It can be applied to all agricultural sectors, including cropping, grazing, and perennial horticulture. Meta-reviews and other published studies have found that transitioning to regenerative agriculture systems can result in more sequestration than emissions from agriculture, turning agriculture from a significant emitter to a major mitigator of GHG emissions.

Scaling up 10% of various best practice regenerative agriculture systems is realistic, achievable, and low-cost. Just a percentage of innovators and early adopters applying best practice regenerative systems to their land holdings can significantly contribute to achieving the negative emissions needed to limit global warming to 1.5°C higher than pre-industrial levels.

2. Introduction

The National Oceanic and Atmospheric Administration (NOAA) measured a monthly average of 420.99 ppm CO_2 at the Mauna Loa observatory in Hawaii on May 2022. The Scripps Institution of Oceanography independently measured a monthly average of 420.78 ppm CO_2. (NOAA 2022)

The Global Carbon Budget report estimated that atmospheric CO_2 reached an annual average of 417.2 ppm in 2022. (Friedlingstein et al. 2022)

401 ppm CO_2 was recorded in 2015 when the United Nations Paris Agreement was adopted as an international treaty on climate change. (Statista, 2022) The goal was to limit global warming to below 2, preferably to 1.5 degrees Celsius, compared to pre-industrial levels. (UNFCCC 2022)

Atmospheric CO_2 levels have increased by about 2.31 ppm per annum since 2015. Emissions increased at around 2 ppm per annum in the decade before the Paris agreement, so the emissions rate is accelerating.

The Intergovernmental Panel on Climate Change (IPCC) Mitigation of Climate Change report stated that greenhouse gas (GHG) concentrations should be limited to 430 ppm carbon dioxide equivalents (CO_2eq) to limit warming to 1.5°C and to 450 ppm CO_2eq to limit warming to 2°C. (IPCC 2014)

According to the report, we have overshot the 1.5°C target. The IPCC estimated that 430 ppm CO_2eq was reached in 2011. (IPCC 2014)

CO_2eq combines carbon dioxide and other major GHGs, such as methane, nitrous oxide, and halocarbons. Their warming potentials are expressed in units equivalent to CO_2. The combination of all these GHGs is used to understand better the levels of gases contributing to global warming, which is why the IPCC uses it. The CO_2eq is usually higher than CO_2 alone. For example, atmospheric CO_2 levels were 391.85 ppm in 2011, compared to 430 ppm CO_2eq. (Statista 2022)

The Global Carbon Budget report stated, "If the current level of emissions persists, there is a 50 percent chance that global warming of 1.5 degrees Celsius (2.7 degrees Fahrenheit) will be exceeded in nine years, the opposite trend needed to reverse climate change." (Friedlingstein et al. 2022)

Observations by the NOAA Global Monitoring Lab in 2021 found that CO_2 alone was responsible for around two-thirds of the total heating influence of all human-produced GHGs. The other GHGs were accountable for a third of the heating potential. (NOAA 2021) Consequently, the 417.2 ppm of CO_2 in 2022 could be as high as 625.80 ppm CO_2eq. The world has already passed the 2°C threshold of 450 ppm CO_2eq.

The IPCC stated that additional mitigation is needed; otherwise, the temperature will overshoot the Paris Agreement targets. "Baseline scenarios, those without additional mitigation, result in global mean surface temperature increases in 2100 from 3.7 °C to 4.8 °C compared to pre-industrial levels." (IPCCC 2014)

According to the IPCC: "Mitigation scenarios in which it is likely that the temperature change caused by anthropogenic GHG emissions can be kept to less than 2 °C relative to pre-industrial levels are characterized by atmospheric concentrations in 2100 of about 450 ppm CO_2eq (high confidence)…."

"Only a limited number of studies have explored scenarios that are more likely than not to bring temperature change back to below 1.5 °C by 2100 relative to pre-industrial levels; these scenarios bring atmospheric concentrations to below 430 ppm CO_2eq by 2100 (high confidence)…" (IPCCC 2014)

The targets have already been overshot, and the emissions rate is accelerating. Reducing emissions and transitioning to renewable energy is no longer sufficient to stop a climate catastrophe.

The IPPC states that the only way to limit global warming to 1.5°C is to achieve net negative emissions by using CDR to draw down CO_2 from the atmosphere. "All pathways that limit global warming to 1.5°C with limited or no overshoot project the use of carbon dioxide removal (CDR) on the order of 100–1000 Gt CO_2 over the 21st century. CDR would be used to compensate for residual emissions and, in most cases, achieve net negative emissions to return global warming to 1.5°C following a peak (high confidence)." (IPCC 2018)

Along with a suite of measures needed to mitigate climate change, the IPCC has advocated for soil carbon sequestration (SCS) as a CDR technology. (IPCC 2018)

This paper hypothesizes that scaling up evidence-based regenerative agricultural systems with high increases of SCS as a CDR technology can significantly contribute to mitigating climate change and assist in limiting global warming to 1.5°C. To achieve the needed levels of CDR, agriculture needs to change from the dominant paradigm of chemically-intensive industrial/conventional systems to those that focus on the sciences of plant biology and living soils to sequester CO_2 from the atmosphere. Maximizing photosynthesis to capture and convert CO_2 into organic molecules to sequester it as soil organic carbon (SOC) would be an effective CDR technology to mitigate climate change.

3. Discussion

According to the NOAA, more than 90 percent of the warming on Earth over the past 50 years has occurred in the oceans. The ocean's heat energy will warm the planet decades after it is absorbed. Ocean heat is a significant driver of our weather. The oceans and the atmosphere are already about one degree Celsius warmer than at the start of the industrial revolution. (NOAA 2020)

3.1 The need to reduce and sequester emissions

This extra energy is disrupting our weather systems. It is causing weather events to be far more intense. The energy makes winter storms more intense, bringing strong snowstorms and severe floods. Similarly, summer storms, especially hurricanes, tornados, and tropical lows, are far more intense, with deluging destructive rainfall and floods. Droughts and heat waves are more common and result in more crop failures. They are also fueling damaging forest and grass fires, burning out whole communities, and changing regional ecologies due to not allowing time for recovery before the subsequent fires. (IPCC 2018)

The frequency and intensity of these events will only get worse when the world warms to 2ºC, the upper limit of the Paris climate agreement. (IPCC 2018)

According to research published in Nature Geoscience, the last time the world had 380 ppm CO_2 was 3.0–3.5 Million years ago. Temperatures were between 5 to 16 °C warmer, and sea levels were 20 to 30 meters higher. (Rohling et al. 2009)

A paper in Nature Communications shows that sea level rises will cause a vast refugee crisis for 340 million people by 2050. (Kulp and Strauss 2019).

An analysis of heat index levels found that "Even if the Paris Agreement goal of limiting global warming to 2°C is met, the exposure to dangerous Heat Index levels will likely increase by 50–100% across much of the tropics and increase by a factor of 3–10 in many regions throughout the midlatitudes."

The researchers further stated that: "Without emissions reductions more aggressive than those considered possible by our statistical projection, it is likely that by 2100, many people living in tropical regions will be exposed to dangerously high Heat Index values during most days of each typical year, and that the kinds of deadly heat waves that have been rarities in the midlatitudes will become annual occurrences." (Vargas Zeppetello et al. 2022)

The United Nations Paris Agreement proposes net zero CO_2eq by 2050. The increasing rate of emissions shows that it is highly unlikely that this goal will be achieved.

Even if the world transitioned to 100% renewable energy tomorrow, this would not stop the temperature, and sea level rises. The world will continue to heat up because CO_2 lasts between 300 to 1,000 years in the atmosphere. (NASA 2019) The heat in the oceans will continue adversely affect the climate until it slowly dissipates. (NOAA 2020)

The evidence shows this will be too late to stop the enormous damage of catastrophic climate change because, as stated above, the world has already crossed the IPCC threshold for 2°C.

The fact is that we are in a climate emergency now. We must reduce GHG emissions, speed up the transition to renewable energy, stop clearing all forests, regenerate ecosystems, and make a great effort to use the available technologies to sequester CO_2 from the atmosphere.

The IPPC clearly states that the only way to limit global warming to 1.5°C is to achieve net negative emissions by using carbon dioxide removal (CDR) to sequester CO_2 from the atmosphere. It has advocated for regenerating natural ecosystems, carbon capture and storage, and soil carbon sequestration as CDR technologies. (IPCC 2018)

3.2 Soil Carbon Sequestration (SCS) as a CDR Technology

The "4 per 1000" Initiative was launched in Paris on Dec 1, 2015, to change agriculture from a major GHG emitter to a significant mitigator of CO_2 by sequestering it as SOC. The name comes from research by scientists at CIRAD, France, who calculated that an increase in SOC of four parts per thousand per annum in agricultural soils globally would be sufficient to sequester all the annual anthropogenic greenhouse gas emissions. (4 per 1000, 2022)

Multiple scientists, researchers, farmers, governments, and NGOs are working on numerous methodologies and practices to increase SOC levels in agriculture. (Prescott et al. 2021) There have also been pushback, doubts, and criticisms expressed by academics and researchers on the ability of agriculture to achieve enough increases in SOC to mitigate climate change. (Amundson and Biardeau 2018, Lam et al. 2013, van Groenigen et al. 2017, White 2022)

The papers cited by the critics amount to extensive data sets showing that most industrial/conventional agriculture systems decrease SOC or have minimal increases that are insufficient to make a significant difference in mitigating climate change.

There are claims that no-till systems using herbicides are superior to tillage systems and could achieve enough SCS to mitigate climate change. Researchers conducted a meta-analysis of 74 published studies comparing no-till and full-tillage management. They found that no-till can reduce SOC stocks, cause losses in crop yields, and decline in C inputs depending on climate. Yields can also increase with no-till adoption in some instances. C input losses greater than 15% with the adoption of no-till lead to a loss of SOC. (Ogle, Swan and Paustian 2012)

A comprehensive study comparing industrial no-till with an organic agricultural tillage system compared multiple parameters. The organic system found better soil quality, including SOC levels. The results found that systems incorporating high amounts of organic inputs from manure and cover crops can improve soils more than no-tillage systems despite reliance on a minimum level of tillage. (Teasdale, Coffman and Mangum 2007) . The Rodale Institute's 40-Year-Report on their Farming Systems Trial found that the conventional no-till systems had lower SOC than the conventional tillage and much lower than the organic manure tillage system. (Rodale 2022)

Research from Ohio State University compared carbon levels between no-till and tillage fields and found that, in some cases, carbon storage was more significant in the tillage fields. The key is soil depth. They compared the carbon storage between no-till and plowed fields with the plow depth of 20 cm and found that the carbon storage was generally much more significant in no-till fields than in plowed fields. When they examined 30 cm and deeper, they found more carbon stored in plowed fields than in the no-till ones. The researchers concluded that farmers should not measure soil carbon based on surface depth. They recommended going as much as one meter below the soil surface to get a more accurate assessment of SOC. (Christopher, Lal and Mishra 2009)

A review of 120 papers on SOC sequestration by researchers from universities in Illinois, Wisconsin, Iowa, and Ohio compared the difference between the no-till and tilled plots. Their findings did not support SOC sequestration claims of the no-till industry. They found that the no-till subsurface layer often loses more SOC stock over time than is gained in the surface layer. (Olson 2013)

Professor Rattan Lal is a highly regarded soil scientist whose research and review papers on SOC in agriculture are widely cited. He has published articles on the potential of the global scaling up of agricultural systems to sequester CO_2 to offset anthropogenic GHG emissions. His 2004 paper gave a range of 0.4 to 1.2 gigatons of carbon per year, and his 2007 paper showed a range of 0.6 to 1.2 gigatons of carbon per year. (Lal 2004, Lal et al. 2007) The maximum range estimation (1.2 gigatons of carbon per year) equates to 4.4 Gt of CO_2 per year.

The Global Carbon Budget 2022 report estimated 40.6 billion tonnes of CO_2 emissions in 2022. This is close to the 40.9 billion tonnes of CO_2 recorded in 2019, the highest annual total ever. (Friedlingstein et al. 2022) This is an exceptional amount that may not be the same every year. Furthermore, a substantial proportion of these emissions are sequestered by the oceans and forests and do not stay in the atmosphere.

A better reference, rather than basing the figures on one exceptional year of emissions is the average of the annual atmospheric CO_2 level increases from 2015, the year of the Paris Accord.

401 ppm CO_2 was recorded in 2015, and the Global Carbon Project estimated that 417.2 ppm was reached in 2022. (Friedlingstein et al. 2022, NOAA 2022, Statista 2022) This would give an average increase of 2.31 ppm annually CO_2 annually.

Using the accepted formula that one ppm CO_2 = 7.76 gigatons (Gt) of CO_2, 2.31 ppm equates to an increase of 17.92 Gt of CO_2 in the atmosphere yearly.

In 2021 the NOAA Global Monitoring Lab found that CO_2 alone was responsible for around two-thirds of the total heating influence of all human-produced greenhouse gases. (NOAA 2022) A reasonable assumption is that 17.92 Gt of CO_2 is two-thirds of CO_2 eq, giving a figure of 26.88 Gt of CO_2 eq.

This means that 26.88 Gt of CO_2 eq per year needs to be sequestered from the atmosphere to stabilize the current level, as per the goal of the '4 per 1000' initiative. The scaling up of agricultural lands based on the highest estimation of Lal et al. would achieve 4.4 gigatons of CO_2eq per year. This shows that our current industrial farming systems cannot achieve the '4 per 1000' goal. (Lal et al. 2007)

More than 26.88 Gt of CO_2 eq must be sequestered to achieve negative emissions to reduce the atmospheric levels of CO_2 to keep the temperature rise to 1.5°C. Negative emissions are essential to stop more CO_2 from heating our already overheated oceans and sequester the legacy atmospheric CO_2 eq.

Amundson and Biardeau presented credible evidence in their paper on why achieving the goal of increasing SOC in the majority of agricultural systems are impossible. For example, they show that only 10% of farmers and ranchers in the USA are involved in programs that may increase SOC. Most landholders have reasons why they will not change their current management practices to ones that increase SOC. (Amundson and Biardeau 2018) A 10%

uptake rate based on Lal et al. extrapolations may result in 0.44 gigatons of CO_2eq sequestered per year, a tiny fraction of what is needed. (Lal et al. 2007)

Several researchers, citing many studies, have stated that it is a waste and/or misuse of time, money, and resources to continue focusing on systems with low increases in SOC. These resources could be better utilized on other priorities. They, along with others, present data showing that the current dominant paradigm of industrial/conventional agriculture systems can never achieve the stated goal of '4 per 1000' or achieve the net negative emissions needed to keep global warming to 1.5°C (Amundson and Biardeau 2018, Lal 2004, Lal et al. 2007, Lam et al. 2013, Olson 2013, van Groenigen et al. 2017, White 2022)

3.3 Regenerative Agriculture

Achieving negative emissions is achievable by focusing the research on scaling up systems with evidenced-based high increases of SOC. A more realistic goal of working with innovators and early adopters, rather than 100% of agriculture, is needed. Rogers first published this concept in 1962 in his book Diffusion of Innovations where he coined the term, early adopters. Rogers' bell curve is still widely used today, as the model for industries to establish new customers or to achieve change management. It starts with the first group of 2.5% of adoptees being innovators, followed by 13.5% of people being early adopters. This amounts to 16% of people who are the first to adopt new practices or products. (Rogers1962) Aiming for changes in agricultural practices with these groups should be achievable, as starting with them is standard practice.

Researchers need to look further than the current industrial/conventional agriculture models, the dominant agricultural paradigm. They must examine emerging systems with documented high increases of SOC, especially the outliers. Outliers are normally avoided or ignored; however, given that the world is in a climate crisis, it is time to critically examine them, replicate them, and improve them through research to scale them up. Adopting a new agricultural paradigm is needed to move away from the intensive chemical approach of industrial agriculture into one that uses the biological sciences, especially plant biology.

Meta-reviews and other published studies have found that transitioning to regenerative agriculture systems can result in more sequestration than emissions from agriculture, turning agriculture from a significant emitter to a major mitigator of GHG emissions. (Gattinger et al. 2012, Aguilera et al. 2013, Leu 2013, Leu 2014, Teague et al. 2016, Prescott et al. 2021)

There are several definitions for regenerative agriculture. As one of the founders of the international regenerative agricultural movement, I will explain regenerative agriculture based on our understanding and intentions when we started the global movement. Hardly anyone had heard of regenerative agriculture before 2015 when we formed Regeneration International to promote this new paradigm in agriculture. We receive articles about it in the news nearly every day now. (Leu 2013)

Regenerative agriculture is based on a range of food and farming systems that maximize the photosynthesis of plants to capture CO_2 and sequester it as SOC. It can be applied to all agricultural sectors, including cropping, grazing, and perennial horticulture. It is being used as an umbrella term for a range of systems such as organic agriculture, agroforestry, agroecology, permaculture, adaptive multi-paddock grazing, silvopasture, syntropic farming, pasture cropping, and other agricultural systems that can increase SOC. It replaces synthetic chemicals with functional biodiversity powered by photosynthesis. (Leu 2021a)

The best systems maximize photosynthesis to increase the capture of CO_2 and store it in the soil as SOC through organic matter biomass and root exudations. (Prescott et al. 2021) Depending on the management system and the species, root exudates can distribute 10% to 40% of the carbon captured by photosynthesis into the soil while the plants grow. (Verma and Verma 2021) The carbon compounds from root exudates penetrate deeper into the soils due to the depths of the roots than above-ground or tilled biomass. Above-ground and tilled biomass can rapidly oxidize into CO_2. Systems with deeper roots are encouraged as their exudates build more durable SOC as deep soil carbon tends to be more stable. (Christopher, Lal and Mishra 2009, Verma and Verma 2021, Leu 2013, Leu 2021b)

The key is ensuring the agricultural systems have photosynthesizing plants for the longest periods possible in their respective climates. This is achieved by using a diversity of correctly managed species to ensure that they can capture the maximum amount of sunlight per hectare as the energy needed to convert CO_2 into the organic molecules that build SOC through the soil microbiome/soil food web. Permanent covers of living plants and limited tillage systems are the preferred methods to increase SOC. (Leu 2021b)

A major issue with papers that criticize using agriculture to sequester CO_2 is that they have focused on data sets from industrial/conventional agricultural systems that decrease SOC or have meager increases. The papers are correct in showing that these agricultural systems are unsuitable for scaling up to achieve the sequestration levels needed to mitigate climate change.

Their extensive data sets show that industrial/conventional agriculture systems are unsuitable for increasing SOC to the levels required to sequester anthropogenic GHGs.

A fundamental weakness in their arguments is that they have cherry-picked the studies that support their viewpoints and left out the data sets that show good increases in SOC. The authors have ignored an extensive body of published studies showing that systems that come under the umbrella of regenerative agriculture, such as organic agriculture and adaptive multi-paddock (AMP) grazing, can sequester significant amounts of CO_2 and increase SOC over many decades. (Gattinger et al. 2012, Aguilera et al. 2013, Leu 2013, Leu 2014, Teague et al. 2016)

Many of the examples cited by the critics are industrial farming systems that use synthetic nitrogen fertilizers, which long-term data shows deplete SOC. Researchers analyzed the results of a 50-year agricultural trial. They found that applying synthetic nitrogen fertilizer had resulted in all the carbon residues from the crop disappearing and an average loss of around 10,000 kg of SOC per hectare. It equates to GHG emissions of 36,700 kg of CO_2 per hectare over and above the many thousands of kilograms of crop residue that is converted into CO_2 every year. Multiple researchers have found that the higher the application of synthetic nitrogen fertilizer, the greater the amount of SOC lost as CO_2. (Khan et al. 2007, Mulvaney, Khan, and Ellsworth 2009, Man et al. 2021)

Further research has found that synthetic chemical fertilizers result in a higher percentage of the CO_2 fixed through photosynthesis being used for above-ground biomass growth rather than being excreted by roots as exudates to feed the soil microbiome and increase SOC levels. (Prescott et al. 2021) As stated before root exudates tend to build deeper stable SOC compared to above-ground biomass that readily oxidizes into CO_2.

A substantial body of evidence, starting in 1904, shows how root exudates feed organic carbon compounds to the soil microbiome, thereby increasing SOC. The key is how plants are managed to maximize photosynthesis to capture CO_2 and convert it into numerous organic compounds. (Leu 2021b, Badri and Vivanco 2009, Jones, Nguyen and Finlay 2009, Verma and Verma 2021)

This is now becoming a significant area of research with recent studies adding to the understanding how these regenerative systems work to increase SOC. A paper published at the end of 2022 in Nature Communication is a good example of the benefits of using the biological plant sciences to maximize photosynthesis to capture CO_2, convert it into organic compounds, and maximize root exudations to feed these compounds to the soil microbiome to increase SOC.

The researchers showed that the industrial system of intensive grazing management using chemicals and high stocking densities per hectare decreased plant carbon capture and its transfer through soil food webs and soil respiration components compared to extensive management. (Chomel et al. 2022)

They stated that; "…there is growing awareness of the importance of rhizodeposition as a driver of below-ground energy flow and the structure and functions of soil food webs."

Their results showed that soil CO_2 efflux is relatively less enriched in intensively managed compared to extensively managed grasslands. This was partly due to less root biomass and less SOC input below ground in intensive systems.

The researchers concluded: ".. our results show that there is less plant-derived C transfer to AM fungi and oribatid mites in intensively managed grassland, supporting the idea that intensive management modifies food web structure and decreases the flow of energy through AM fungi." (Chomel et al. 2022)

Researchers compared the soil quality at three Spanish vineyards managed under intensive, regenerative, and minimum impact strategies. They found that the soil carbon stocks were 2.3 and 3.4 times greater in the regenerative and minimal impact vineyards than in the intensive vineyard. (Andrés et al. 2022)

Based on my understanding of regenerative agriculture, I regard both of the systems described by the study authors as regenerative and minimum impact as regenerative, and the intensive system as a standard chemically-intensive industrial agriculture system.

The difference between the intensive and the two regenerative systems is that the intensive system used tillage and herbicides to kill all the ground cover to create bare soil, resulting in soil erosion and oxidation that loses SOC and synthetic nitrogen fertilizers that feed the microbial decomposition of SOC. The two regenerative systems covered the soil with a diversity of perennial and annual ground cover species and did not use synthetic chemical fertilizers. Consequently, the regenerative systems had maximum photosynthesis feeding root exudates to a healthy biodiversity of soil microbiota. The study found that the soil biota is favored by regenerative viticulture. It had 26.2 times more protists, 3.1 times more nematodes, and 29.4 more microarthropods than in the intensive vineyard.

The researchers concluded: "… we found that vineyards managed under regenerative and minimum impact strategies for 5 and 12 years, respectively, after a long history of intensive farming, contain significantly more organic carbon and support significantly more soil invertebrates than a comparable vineyard that is managed intensively." (Andrés et al. 2022)

3.4 Examples of Regenerative Systems

The evidence shows that agriculture needs to change from chemically intensive to biologically diverse. The new paradigm reduces and ultimately avoids the use of synthetic chemicals. Plant biology and living soil science must be at the forefront of this research.

A general rule is that the soil is covered with the maximum amount of living plants for as long as possible in the growing season. Dead plants and bare soil do not photosynthesize, so the most productive regenerative systems avoid killing plants as weeds with herbicides and excessive tillage. Instead, plants are managed as ground covers and cover crops to build soil fertility by maximizing root exudates. Various strategies are used to manage weeds and use them as cover crops to build fertility. Grazing is one of the most widespread management tools in these regenerative systems. (Leu 2021b, Teague et al. 2016)

3.4.1 AMP/Regenerative Grazing

Ruminant livestock systems are a significant source of agriculture's anthropogenic greenhouse gases. The United Nations Food and Agriculture Organization's (FAO) research showed that cattle, buffaloes, goats, and sheep for meat and milk generated 5.8 gigatons of CO_2 eq in 2010. (FAO 2010) The production is divided between high-intensity confined animal feeding operations and extensive pasture-based grazing systems on 3.36 billion hectares of permanent pastures. (FAOSTAT 2015) Governments such as New Zealand are proposing taxing ruminant production as a way of reducing production to reduce methane output. (BBC 2022)

A meta-review published in the Journal of Soil and Water Conservation found that transitioning to regeneratively managed ruminant grazing systems can result in more sequestration than emissions, turning ruminant agriculture from a significant emitter to a major mitigator of GHG emissions. The researchers stated: "Our assessment shows that globally, GHG emissions from domestic ruminants represent 11.6% (1.58 Gt C y–1) of total anthropogenic emissions while cropping and soil-associated emissions contribute 13.7% (1.86 Gt C y–1). The primary source is soil erosion (1 Gt C y–1)… Permanent cover of forage plants is highly effective in reducing soil erosion, and ruminants consuming only grazed forages under appropriate management result in more C sequestration than emissions." (Teague et al. 2016)

Most studies looking at the emissions from livestock systems do not factor in the SOC sequestration levels that can result from different livestock management systems. Researchers doing life cycle analysis comparing different livestock management systems found that converting to a regenerative grazing method called adaptive multi-paddock (AMP) grazing resulted in significant levels of SOC sequestration and became net carbon negative. "In our study, the highest SOC stock occurred upon converting to MP [Multi-paddock] grazing, indicates that among the three different grazing practices we analyzed, MP has the highest carbon sequestration rate. Combined with its potential to significantly lower GHG emissions, we conclude that MP serves as the best carbon mitigation option." (Tong et al. 2015)

In a later study, the researchers found similar results and recommended the widespread adoption of regenerative agriculture systems that include AMP grazing, not just for the increasing SOC; they found considerable ecological and biodiversity benefits. "Incorporating forages and ruminants into regeneratively managed agroecosystems can elevate soil organic C, improve soil ecological function by minimizing the damage of tillage and inorganic fertilizers and biocides, and enhance biodiversity and wildlife habitat. We conclude that to ensure long-term sustainability and ecological resilience of agroecosystems, agricultural production should be guided by policies and regenerative management protocols that include ruminant grazing." (Teague et al. 2016)

Research has shown that changing systems can achieve very rapid increases in SOC. Tong and colleagues found that: "After converting from HC [heavy continuous grazing] to MP [adaptive multi-paddock grazing], the C sequestration rate was estimated as a much higher value of 1765 kg·C·ha−1·year−1, which is consistent with the finding of Soussana et al., who reported a C sequestration rate of 2400 ± 700 kg·C·ha−1·year−1. This is because when poor management lowered SOC stock over the time, a transition to an improved practice such as MP will increase SOC stock at a higher rate." (Tong et al. 2015)

Earlier research by Teague and colleagues showed that changing livestock systems can significantly increase SOC. "… improved AMP grazing management can result in an average SOC sequestration rate of 11 t CO_2 equiv ha–1 y–1…" (Teague et al. 2011) 11 tons of CO_2 eq per hectare per year is much higher than the levels achieved by most agricultural systems. It is an example of SOC sequestration rates needed to achieve the goal of the '4 per 1000' and the net negative emissions required to keep global warming to 1.5°C

Researchers using regenerative grazing practices in the southeastern United States achieved 8.0 Mg ha−1 yr−1 of SOC. , which means that these grazing systems have sequestered 29.36 metric tons of CO_2 eq per hectare per year. Very significantly, the authors give other examples from research around the world that have achieved similar levels of SOC sequestration through regenerative grazing levels, so the results of this research paper are not an isolated outlier.(Machmuller et al. 2015)

3.4.2 Pasture Cropping

Pasture cropping is an innovative regenerative agriculture system where the crop is planted in a perennial pasture instead of bare soil. There is no need to plow out the pasture species or kill them with herbicides before planting the cash crop.

Colin Seis in Australia first developed this. The principle is based on the ecological fact that annual plants grow in perennial systems. The key is to adapt this principle to the appropriate management systems for specific crops and climates. Pasture cropping can be used on permanent pastures and arable cropping lands. (Winona 2022)

Neils Olsen further innovated pasture cropping. He developed equipment that combines cultivation, mulching, aeration, and mixed species seeding into narrow tilled strips in the perennial pasture in one pass. The field is grazed down or mulched before planting to reduce competition with the cash crop.

Pasture cropping is an excellent system for increasing SOC. Olsen was paid for sequestering 11 tons of CO_2 eq per hectare per year under the Australian government's Carbon Farming Scheme in 2019. He was paid for 13 tons of CO_2 eq per hectare in 2020. (Soil Kee 2019) He was the first farmer to be paid for sequestering soil carbon under the Australian government-regulated system. (Emissions Reduction Fund 2022)

3.4.3 BEAM

BEAM (Biologically Enhanced Agricultural Management), developed by Dr. David Johnson of New Mexico State University, produces compost with a high diversity of soil microorganisms. The BEAM system aligns well with research by Prescott et al. and Andrés et al. 2022 showing how organic carbon-based inputs such as composts encourage higher proportions of root exudates than synthetic water-soluble chemical fertilizers.(Prescott et al. 2021, Andrés et al. 2022) Multiple crops grown with BEAM have achieved very high sequestration levels and yields. Research published by Johnson and colleagues shows: "… a 4.5-year agricultural field study promoted annual average capture and storage of 10.27 metric tons' soil C ha-1 year -1 while increasing soil macro-, meso- and micro-nutrient availability offering a robust, cost-effective carbon sequestration mechanism within a more productive and long-term sustainable agriculture management approach." (Johnson, Ellington and Eaton 2015)

These figures mean that BEAM can sequester 37,700 kgs (37.7 tons) of CO_2 per hectare per year. BEAM can be used in all soil-based food production systems, including annual crops, permanent crops, and grazing systems, including arid and semi-arid regions.

3.4.4 The future of systems with high increases in SOC

The above examples of increases in SOC are much higher than the levels quoted in most of the published literature. (Lal 2004, Lal et al. 2007, Lam et al. 2013, van Groenigen et al. 2017, White 2022)

Consequently, some authors and researchers express skepticism about their credibility. The material and methods used in the above examples are published and can be replicated. They are evidenced based systems. Just dismissing them based on an opinion is the opposite of science. The only way to prove or disprove these results is to replicate the material and methods and see the results. Until this is done, these published results are valid.

The fact is; that there is an urgent need to turn agriculture from a significant source of GHGs to a major mitigator. Agriculture needs to contribute to the suite of the solutions necessary to achieve negative emissions to avoid $2^{o}C$ or greater warming and all the associated problems.

The above examples of regenerative agricultural systems and other outliers have the most potential. They should be the focus of future research and replicated to see their accuracy in different climates and soil types. The results should be scaled up to sequester CO_2 if they are positive. Further research should be prioritized to improve these systems.

3.5 Carbon Capture and Storage

Carbon capture and storage (CCS) is promoted as a CDR technology for reducing GHG emissions. A report from the IPCC stated that CCS is essential to reach net zero by 2050. (IPCC 2022)

A review of all the major carbon capture projects found that over 70 percent of the projects were used for enhanced oil recovery. Oil and gas companies use the captured CO_2 to pump more oil and gas out of depleted wells, producing more GHG emissions. The study reviewed the 13 large-scale CCS projects currently in existence worldwide. It found that seven underperformed, and one was questionable. Nearly 90% of the proposed CCS capacity in the power sector failed at the implementation stage or was suspended early. Only two projects in the gas processing sector demonstrated some success. (Robertson and Mousavian 2022)

The report clearly shows that billions of dollars have been invested into this sector with very few results. The carbon capture sector is still a net emitter of GHGs. Billions more dollars are being budgeted for industrial CCS projects. In proportion to CCS, very few dollars are spent on implementing regenerative agriculture, which has much greater CDR potential and much lower implementation costs.

4. 'Back-of-the-envelope' Calculations for Achieving Negative Emissions

The exercises below are 'back-of-the-envelope' calculations. They are not proposed to offer scientific proof. These types of back-of-the-envelope analyses help conceptualize the potential of a strategy or methodology when testing a hypothesis.

4.1 Global Agricultural Land Figures

The United Nations Food and Agriculture Organization (FAO) estimated that the total land used to produce food and fiber is 4,911,622,700 Hectares.

This is divided into: Arable/Crop land: 1,396,374,300 Hectares

Permanent pastures: 3,358,567,600 Hectares
Permanent crops: 153,733,800 Hectares (FAOSTAT 2015)

4.2 Regenerative/AMP Grazing Calculations

Permanent pastures represent 68% of agricultural lands To explain the significance of Machmuller's figures: 8.0 Mg ha−1 yr−1 = 8,000 kgs of carbon stored in the soil per hectare per year. Soil Organic Carbon x 3.67 = CO_2, which means that these grazing systems have sequestered 29,360 kgs (29.36 metric tons) of CO_2/ha/yr. (Machmuller et al. 2015)

If these regenerative grazing practices were implemented by early adopter pastoralists on the world's permanent pastures: they would sequester 98.6 Gt CO_2/yr. (29.36t CO_2/ha/yr X 3,358,567,600 ha = 98,607,544,736t CO_2/ha/yr)

If this system was deployed on 10% of the world's grazing lands, they could sequester 9.86 Gt of CO_2 per year.

4.3 Pasture Cropping Calculations

The significance of Olsen's pasture cropping system is that if applied to permanent pastures and arable/croplands, would sequester 63.8 Gt of CO_2 per year. (Permanent pastures and arable/croplands 4,911,622,700 ha x 13t CO_2/ha/yr = 63,851,095,100t of CO_2/ha/yr)

If early adopter farmers and ranchers deployed this system on 10% of all permanent pastures and arable/croplands, it could sequester 6.38 Gt of CO_2 per year.

4.4 BEAM Calculations

BEAM sequestered 10.27 metric tons of soil C ha-1 year -1 in a 4.5-year field trial. A basic calculation shows the potential of scaling up this simple compost technology across global agricultural lands. Soil Organic Carbon x 3.67 = CO_2, meaning that 10.27 metric tons of soil carbon = 37.7 metric tons of CO_2 per hectare per year.

If BEAM were extrapolated globally across agricultural lands, it would sequester 185 Gt of CO_2/yr. (37.7 t CO_2/ha/yr X 4,911,622,700 ha = 185,168,175,790t CO_2/ha/yr). 10% of agricultural land to BEAM could sequester 18.5 Gt of CO_2 per year.

4.5 Potential Sequestration

If this system were deployed by a small percentage of innovators and early adopter farmers and ranchers on global agricultural lands, it could sequester 18.5 Gt of CO_2 per year.

A simple back-of-the-envelope calculation shows that converting:

- 10% of the world's permanent pastures to best practice regenerative grazing systems, such as Machmuller et al., could sequester 9.86 Gt of CO_2 per year;
- 10% of the world's permanent pastures and arable/croplands to pasture cropping could sequester 6.38 Gt of CO_2eq per year; and
- 10% of agricultural land to BEAM could sequester 18.5 Gt of CO_2 per year.

Combined, they could sequester 34.74 Gt of CO_2 per year. This is more than the current anthropogenic emissions of 26.88 Gt of CO_2 eq per year and would achieve negative emissions.

Combining these regenerative systems is not double or triple counting. Many permanent pastures are not suitable for cropping and can only be used for grazing. Pasture cropping can be used in most arable and grazing systems where is sufficient soil moisture in the rainy season to grow an annual crop. BEAM can be used in all systems. The different systems give flexibility and more options for adoption by landholders. Furthermore, according to Rogers's bell curve, a 10% adoption rate amongst different farmer/rancher groups is a more realistic goal, especially for working with innovators and early adopters who total 16% of each group.

4.6 Limitation of the 'back-of-the-envelope' calculation

A major limitation of 'back-of-the-envelope' calculations is that while the levels of SOC sequestration achieved by the three regenerative systems are evidenced-based, the extrapolations are theoretical and have margins of error. The fact is; all the papers producing figures on the potential scaling up of agriculture at a large scale or globally to sequester CO_2 extrapolate data and all of them, including this paper, are subject to assumptions and error margins.(Lal 2004, Lal et al. 2007, Gattinger et al. 2012, Lam et al. 2013, Olson 2013, Aguilera et al. 2013, Leu 2013, Teague et al. 2016, van Groenigen et al. 2017, Amundson and Biardeau 2018, White 2022) However, they are useful tools in assessing the viability of SCS to mitigate climate change. In reality, the actual amounts will be variable because best practice systems rarely scale up evenly and result in variable numbers.

The systems quoted in this paper are three outliers; however, other regenerative agricultural systems have the potential to draw down large quantities of CO_2 if scaled up on global landscape scales. Many emerging systems, especially perennial agroforestry systems, have the potential to achieve higher increases in SOC. Even if the results were half that of the back-of-the-envelope calculation, the outcome would be impressive and a massive contribution to the needed negative emissions.

5. Conclusion

There is no need to change 100% of agriculture. Just a percentage of innovators and early adopters applying best practice regenerative systems to their land holdings can significantly contribute to achieving the negative emissions needed to limit global warming to 1.5°C.

Reducing emissions and transitioning to renewable energy is no longer sufficient to stop a climate catastrophe. The IPCC states that the only way to limit global warming to 1.5°C is to achieve net negative emissions using CDR. This requires sequestering CO_2eq from the atmosphere.

The IPCC recommended SCS and CCS among the CDR technologies needed to achieve negative emissions.

A large body of published research shows that the current dominant paradigm of chemically intensive, industrial/conventional systems cannot achieve the levels of sequestration needed to attain significant negative emissions, especially the stated goal of the ‘4 per 1000’ initiative of drawing down all the annual anthropogenic greenhouse gas emissions.

Research shows that most current CCS systems are net emitters or have underperformed in sequestering CO_2 despite billions of dollars being spent on them.

Scaling up 10% of various best practice regenerative agriculture systems is realistic, achievable, and low-cost compared to expensive high-tech concepts like CCS.

The evidence shows that agriculture needs to change from chemical to biologically intensive. The emphasis must be based on living soil and biological plant sciences to maximize photosynthesis to capture CO_2 and convert it into organic compounds and then maximize root exudations to feed these compounds to the soil microbiome to increase SOC.

Using a proportion of the billions of dollars proposed for industrial CCS systems to transition a small percentage of global agricultural production to evidence-based, best-practice, regenerative approaches could sequester enough CO_2 and store it as SOC to mitigate climate change and assist in achieving the much-needed negative emissions to limit global warming to 1.5°C higher than pre-industrial levels.

References

[1] "4 per 1000” Initiative, 2022, https://4p1000.org/?lang=en Accessed August 31, 2022

[2] Aguilera E, Lassaletta L, Gattinger A and Gimeno BS, 2013. Managing soil carbon for climate change mitigation and adaptation in Mediterranean cropping systems: A meta-analysis. Agriculture Ecosystems and Environment 168:25-36.

[3] Andrés, P.; Doblas-Miranda, E.; Silva-Sánchez, A.; Mattana, S.; Font, F. Physical, Chemical, and Biological Indicators of Soil Quality in Mediterranean Vineyards under Contrasting Farming Schemes. Agronomy 2022, 12, 2643. https://doi.org/10.3390/agronomy12112643

[4] Amundson R and Biardeau L 2018 Opinion: Soil carbon sequestration is an elusive climate mitigation tool, Proceedings of the National Academy of Sciences, USA 115:11652–11656.

[5] Badri DV, Vivanco JM 2009, "Regulation and function of root exudates". Plant, Cell & Environment. 32 (6): 666–81. doi:10.1111/j.1365-3040.2009.01926.x

[6] BBC 2022, https://www.bbc.com/news/business-61741352 (accessed Oct 2, 2022)

[7] Christopher S. F, Lal R and Mishra, U, 2009. Long-term no-till effects on carbon sequestration in the Midwestern U.S. Soil Science Society of America Journal, 73: 207-216.

[8] Chomel M, Lavallee J M, Alvarez-Segura N, Baggs E M, Caruso T, de Castro F, Emmerson MC, Magilton M, de Vries F T, Johnson D & Bardgett R D 2022, Intensive grassland management disrupts below-ground multi-trophic resource transfer in response to drought, Nature Communications, November 2022

[9] Emissions Reduction Fund, Case Studies 2022, Australian Government Clean Energy Regulator, Soil Carbon https://www.cleanenergyregulator.gov.au/Infohub/case-studies/emissions-reduction-fund-case-studies#Soil-carbon Accessed Sept 4, 2022

[10] FAO 2010, Global Livestock Environmental Assessment Model (GLEAM), https://www.fao.org/gleam/results/en/ Accessed September 1, 2022

[11] FAOSTAT 2015, United Nation's Food and Agriculture Organization, FAOSTAT data on land use, retrieved December 4, 2015

[12] Friedlingstein, P., O'Sullivan, M., Jones, M. W., Andrew, R. M., Gregor, L., Hauck, J., Le Quéré, C., Luijkx, I. T., Olsen, A., Peters, G. P., Peters, W., Pongratz, J., Schwingshackl, C., Sitch, S., Canadell, J. G., Ciais, P., Jackson, R. B., Alin, S. R., Alkama, R., Arneth, A., Arora, V. K., Bates, N. R., Becker, M., Bellouin, N., Bittig, H. C., Bopp, L., Chevallier, F., Chini, L. P., Cronin, M., Evans, W., Falk, S., Feely, R. A., Gasser, T., Gehlen, M., Gkritzalis, T., Gloege, L., Grassi, G., Gruber, N., Gürses, Ö., Harris, I., Hefner, M., Houghton, R. A., Hurtt, G. C., Iida, Y., Ilyina, T., Jain, A. K., Jersild, A., Kadono, K., Kato, E., Kennedy, D., Klein Goldewijk, K., Knauer, J., Korsbakken, J. I., Landschützer, P., Lefèvre, N., Lindsay, K., Liu, J., Liu, Z., Marland, G., Mayot, N., McGrath, M. J., Metzl, N., Monacci, N. M., Munro, D. R., Nakaoka, S.-I., Niwa, Y., O'Brien, K., Ono, T., Palmer, P. I., Pan, N., Pierrot, D., Pocock, K., Poulter, B., Resplandy, L., Robertson, E., Rödenbeck, C., Rodriguez, C., Rosan, T. M., Schwinger, J., Séférian, R., Shutler, J. D., Skjelvan, I., Steinhoff, T., Sun, Q., Sutton, A. J., Sweeney, C., Takao, S., Tanhua, T., Tans, P. P., Tian, X., Tian, H., Tilbrook, B., Tsujino, H., Tubiello, F., van der Werf, G. R., Walker, A. P., Wanninkhof, R., Whitehead, C., Willstrand Wranne, A., Wright, R., Yuan, W., Yue, C., Yue, X., Zaehle, S., Zeng, J., and Zheng, B.: Global Carbon Budget 2022, Earth Syst. Sci. Data, 14, 4811–4900, https://doi.org/10.5194/essd-14-4811-2022, 2022.

[13] Gattinger A, Muller A, Haeni M, Skinner C, Fliessbach A, Buchmann N, Mäder P, Stolze M, Smith P, El-Hage Scialabba N and Niggli U, 2012. Enhanced top soil carbon stocks under organic farming. Proceedings of the National Academy of Sciences 109:18226-18231.

[14] IPCC, 2014: Summary for Policymakers. In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

[15] IPCC, 2018: Summary for Policymakers. In: Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 3-24. https://doi.org/10.1017/9781009157940.001.

[16] IPCC 2022, Climate Change 2022 Mitigation of Climate Change, Working Group III Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Summary for Policymakers, Eds Priyadarshi R. Shukla et al. ISBN 978-92-9169-160-9
https://www.ipcc.ch/report/ar6/wg3/downloads/report/IPCC_AR6_WGIII_SPM.pdf accessed Aug27,2022

[17] Johnson D, Ellington J and Eaton W, 2015, Development of soil microbial communities for promoting sustainability in agriculture and a global carbon fix, PeerJ PrePrints | http://dx.doi.org/10.7287/peerj.preprints.789v1 | CC-BY 4.0 Open Access | rec: 13 Jan 2015, publ: 13 Jan 2015

[18] Jones DL, Nguyen C, Findlay RD 2009, "Carbon flow in the rhizosphere: carbon trading at the soil–root interface". Plant and Soil. 321 (1–2): 5–39. doi:10.1007/s11104-009-9925-0

[19] Khan, S.A., R.L. Mulvaney, T.R. Ellsworth, and C.W. Boast. 2007. The myth of nitrogen fertilization for soil carbon sequestration. Journal of Environmental Quality 36:1821-1832. \

[20] Kulp SA & Strauss BH 2019, New elevation data triple estimates of global vulnerability to sea-level rise and coastal flooding, Nature Communications, (2019)10:4844, https://doi.org/10.1038/s41467-019-12808-z, www.nature.com/naturecommunications

[21] Lal R 2004 Soil Carbon Sequestration Impacts on Global Climate Change and Food Security, Environmental Science, 11 June 2004

[22] Lal R, Follett RF, Stewart BA and Kimble JM 2007, Soil Carbon Sequestration to Mitigate Climate Change and Advance Food Security. Soil Science, 172, 943-956.

[23] Lam SK, Chen D, Mosier AR and Roush R 2013, The potential for carbon sequestration in Australian agricultural soils is technically and economically limited. Sci. Rep. 3, 2179; (2013).

[24] Leu A 2013, Commentary V: Mitigating climate change with soil organic matter in organic production systems. TRADE AND ENVIRONMENT REVIEW, 2013, WAKE UP BEFORE IT IS TOO LATE, Ed. Ulrich Hoffman, UNCTAD/DITC/TED/2012/3 UNITED NATIONS PUBLICATION ISSN 1810-5432

[25] Leu A 2014, THE POTENTIAL FOR MITIGATION AND ADAPTATION TO CLIMATE CHANGE WITH SOIL ORGANIC MATTER INCREASES IN ORGANIC PRODUCTION SYSTEMS . Acta Horticulturae. 1018, 75-82

[26] Leu A 2021a, Our Global Regeneration Revolution: Organic 3.0 to Regenerative and Organic Agriculture https://regenerationinternational.org/2021/07/12/our-global-regeneration-revolution-organic-3-0-to-regenerative-and-organic-agriculture/

[27] Leu A 2021b, GROWING LIFE, REGENERATING FARMING AND RANCHING, Acres USA, Greeley Colorado, USA, December 2021

[28] Machmuller MB, Kramer MG, Cyle TK, Hill N, Hancock D & Thompson A, 2015. Emerging land use practices rapidly increase soil organic matter, Nature Communications 6, Article number: 6995 doi:10.1038/ncomms7995, Received 21 June 2014 Accepted 20 March 2015 Published 30 April 2015

[29] Mulvaney, R.L., S.A., Khan, and T.R. Ellsworth. 2009. Synthetic nitrogen fertilizers deplete soil nitrogen: A global dilemma for sustainable cereal production. Journal of Environmental Quality 38:2295-2314.

[30] Man, M., B. Deen, K.E. Dunfield, C.Wagner-Riddle, and M.J. Simpson. 2021.Altered soil organic matter composition and degradation after a decade of nitrogen fertilization in a temperate agroecosystem. Agriculture, Ecosystems & Environment 310:107305.

[31] NASA 2019, The Atmosphere: Getting a Handle on Carbon Dioxide, https://climate.nasa.gov/news/2915/the-atmosphere-getting-a-handle-on-carbon-dioxide, Accessed Aug 28, 2022

[32] NOAA 2017, National Oceanic and Atmospheric Administration (US) https://www.climate.gov/news-features/climate-qa/how-much-will-earth-warm-if-carbon-dioxide-doubles-pre-industrial-levels, Accessed Aug 28, 2022

[33] NOAA 2021, Climate Change: Atmospheric Carbon Dioxide, https://www.climate.gov/news-features/understanding-climate/climate-change-atmospheric-carbon-dioxide, Accessed Aug 28, 2022

[34] NOAA 2020, Climate Change: Ocean Heat Content, https://www.climate.gov/news-features/understanding-climate/climate-change-ocean-heat-content, Accessed Aug 28, 2022

[35] NOAA 2022, Carbon dioxide now more than 50% higher than pre-industrial levels, https://www.noaa.gov/news-release/carbon-dioxide-now-more-than-50-higher-than-pre-industrial-levels?fbclid=IwAR3_PAk4AmI4czOO5ikK_CAGca94LMwQwIEfG9lo3ZWi72BeR6KaX05hHSw, Accessed Aug 27, 2022

[36] Ogle SM, Swan A and Paustian K. 2012, No-till management impacts on crop productivity, carbon input and soil carbon sequestration, Agriculture, Ecosystems &Environment, Volume 149, 1 March 2012, Pages 37-49 https://doi.org/10.1016/j.agee.2011.12.010

[37] Olson K R 2013, Soil organic carbon sequestration, storage, retention and loss in U.S. croplands: Issues paper for protocol development. Geoderma, 2013; 195-196: 201 DOI: 10.1016/j.geoderma.2012.12.004

[38] Prescott C E, Rui Y, Cotrufo M F, and Grayston SAJ 2021, Managing plant surplus carbon to generate soil organic matter in regenerative agriculture, Journal of Soil and Water Conservation, Nov/Dec 2021, Vol.76, No 6.

[39] Robertson B and Mousavian M 2022, The Carbon Capture Crux - Lessons Learned, The Institute for Energy Economics and Financial Analysis (IEEFA) https://ieefa.org/resources/carbon-capture-remains-risky-investment-achieving-decarbonisation, Accessed Sept 4, 2022

[40] Rodale 2022, Farming Systems Trial 40-YEAR REPORT, Rodale Institute, https://rodaleinstitute.org/science/farming-systems-trial, Accessed December 8, 2022

[41] Rogers, Everett M. (1962). Diffusion of innovations (1st ed.). New York: Free Press of Glencoe.

[42] Rohling EJ, K. Grant, M. Bolshaw, A. P. Roberts, M. Siddall, Ch. Hemleben and M. Kucera (2009) Antarctic temperature and global sea level closely coupled over the past five glacial cycles, Nature Geoscience, advance online publication, www.nature.com/naturegeoscience

[43] Soil Kee 2019, World first at the Soilkee farm, with first carbon credits issued to a soil carbon project under the Emissions Reduction Fund and the Paris Agreement, https://soilkee.com.au/gallery/20190314-soilkee%20media%20release%20.pdf Accessed Sept 4, 2022

[44] Statista, 2022 https://www.statista.com/statistics/1091926/atmospheric-concentration-of-co2-historic/ Accessed Aug 27

[45] Teague, W.R., S.L. Dowhower, S.A. Baker, N. Haile, P.B. DeLaune, and D.M. Conover. 2011. Grazing management impacts on vegetation, soil biota and soil chemical, physical and hydrological properties in tall grass prairie. Agriculture Ecosystems and Environment 141:310-22.

[46] Teague W R, Apfelbaum S, Lal R, Kreuter U P, Rowntree J, Davies C A, Conser R, Rasmussen M, Hatfield J, Wang T, Wang F and Byck P, 2016,The role of ruminants in reducing agriculture's carbon footprint in North America, Journal of Soil and Water Conservation March 2016, 71 (2) 156-164; DOI: https://doi.org/10.2489/jswc.71.2.156

[47] Teague, W.R., F. Provenza, U.P. Kreuter, T. Steffens, and M. Barnes. 2013. Multi-paddock grazing on rangelands: Why the perceptual dichotomy between research results and rancher experience? Journal of Environmental Management 128:699-717.

[48] Teasdale JR, Coffman CB and Mangum RW (2007). Potential long-term benefits of no-tillage and organic cropping systems for grain production and soil improvement. Agronomy Journal, Sept–Oct, 99 (5): 1297-1305.

[49] Tong W, Teague W R, Park C S and Bevers S, 2015, GHG Mitigation Potential of Different Grazing Strategies in the United States Southern Great Plains, Sustainability 2015, 7, 13500-13521; doi:10.3390/su71013500, ISSN 2071-1050, www.mdpi.com/journal/sustainability The role of ruminants in reducing agriculture's carbon footprint in North America

[50] UNFCCC 2022, The Paris Agreement, https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement, Accessed Aug 28

[51] van Groenigen JW, van Kessel C, Hungate BA, Oenema O, Powlson DS and van Groenigen KJ 2017, Sequestering Soil Organic Carbon: A Nitrogen Dilemma, Environmental Science and Technology. 2017

[52] Vargas Zeppetello LR, Adrian E, Raftery AE and Battisti DS 2022, Probabilistic projections of increased heat stress driven by climate change, Communications Earth & Environment, (2022)3:183 | https://doi.org/10.1038/s43247-022-00524-4 www.nature.com/commsenv

[53] Verma S and Verma A 2021, Plant Root Exudate Analysis, in PHYTOMICROBIOME INTERACTIONS AND SUSTAINABLE AGRICULTURE, Editor(s):Verma A, Saini JK, Hesham A and Singh HB, John Wiley & Sons Ltd 2021, Print ISBN:9781119644620, Online ISBN:9781119644798

[54] Winona 2022, What is Pasture Cropping, https://winona.net.au/pasture-cropping/, Accessed September 4, 2022

[55] White RE 2022, The Role of Soil Carbon Sequestration as a Climate Change Mitigation Strategy: An Australian Case Study. Soil Systems. 2022, 6,46.