Regenerative agriculture can provide many environmental benefits, but is not a "silver bullet" for climate change mitigation.

Lead Authors: Drs. Jessica Gutknecht and Jacob Jungers, University of Minnesota

Society is faced with the challenge of producing and equally distributing enough food and fiber to support a growing and food insecure global population. This challenge is compounded by the fact that natural resources needed for agriculture are deteriorating and climate change is affecting yields and production stability.[1,2] Much of the US, for example, is already experiencing yield declines and other climate related disruptions to agriculture.[3,4] Agriculture and associated land use changes contribute 25% of global GHG emissions and 10% of emissions in the US.[5,6] This article summarizes the state of science on how agriculture can *mitigate* climate change. It reviews the relative impact and certainty of two mitigation levers - 1) carbon sequestration and 2) greenhouse gas emissions reduction.

"Regenerative agriculture" includes those farming systems that move carbon dioxide out of the atmosphere and into plants and soil. In addition to the potential for removing some carbon dioxide from the atmosphere, these systems improve productivity, environmental quality, soil health, and reduction of impacts from climate disruption.[1,4,7,8] These possibilities have an important context; no carbon sequestration is currently fully reliable or permanent, and even the higher estimates of carbon sequestration in regenerative systems are orders of magnitude smaller than the total amount of greenhouse gas emissions from agricultural systems produced each year. [5,6,9]

This summary highlights the current evidence about the promise of regenerative agriculture for both carbon sequestration and the direct reduction of greenhouse gas emissions. Following this overview are two appendices, A) acknowledgements and references and B) definitions and conversions.

Regenerative agriculture and carbon sequestration rates

- *The Potential:* Regenerative agriculture can sequester carbon at rates ranging from 0.1 to 0.34 US tons per acre per year (Figure 1). The upper end of this range is equivalent to the CO_2 emissions from about 30 gallons of gasoline. Carbon sequestration can be achieved by increasing crop growth and root production, through integrating cover crops into annual agricultural systems, incorporating perennial crops into rotations with common annual crops, to full transition to perennial grain and forage systems. Retiring cropland to perennial cover can offer greater carbon sequestration gains (Figure 1).[10] As discussed below, these carbon sequestration rates are *uncertain and much lower* than emission rates. The same carbon molecules that are sequestered from the atmosphere into plants and soil can lead to other environmental and agronomic benefits, termed stacking benefits. For example, carbon fixed by crops can increase soil health and organic matter, improve fertility, and improve water infiltration capacity and soil aggregation.[11,12] These physical properties convey climate adaptation and economic risk mitigation.[7,13] Other stacking benefits include direct emissions reduction and reduced energy use, but only early evidence is available about this benefit. *Through stacking benefits,* regenerative agriculture is one of the more promising directions for climate adaptation, maybe also providing climate mitigation as well.

- *Unreliability, limitations, and insufficient data*: All estimates of carbon sequestration have a high degree of uncertainty. Even for fully perennial regenerative agriculture, carbon sequestration estimates can vary by an order of magnitude[14], and a fraction of studies, some long term, report no change or even losses in carbon sequestration.[15,16,17] Variability carbon sequestration is driven by many factors including soil type, weather patterns, root growth and depth, the composition and growth of soil biological communities, tillage, and fertilization, where deeper soil might sequester more carbon.[19,20,21] Moreover, regenerative agriculture encompasses many modifications intended to improve sustainability including (but not limited to) perennial crop inclusion, cover cropping, compost application, grazing, organic fertilizer and pest control, and intercropping. Each modification has the potential to directly affect carbon sequestration, and combining modifications can result in unforeseen interactions and complexities. Until these research gaps are filled, an awareness of the variance, limitations, and impermanence of sequestered carbon is important.

Overriding issues include evidence that globally increasing temperatures may lead to soil carbon losses.[18] Sequestration rates, when positive, are not infinite and can slow after 10-20 years of establishment of regenerative agriculture. [6,10] Returning to annual agricultural crops with tillage, or conversion of prairie and forest to agricultural land, also leads to carbon losses.[22,23]

The case for directly reducing emissions in addition to sequestering carbon

Regenerative agriculture is likely to sequester carbon in the short term (10-20 years) and provide stacking benefits. Carbon sequestration acts to pull some existing emissions out of the atmosphere, but to achieve a zero emissions goal we must also directly reduce current greenhouse gas emissions (Figure 2).[6,23,24]

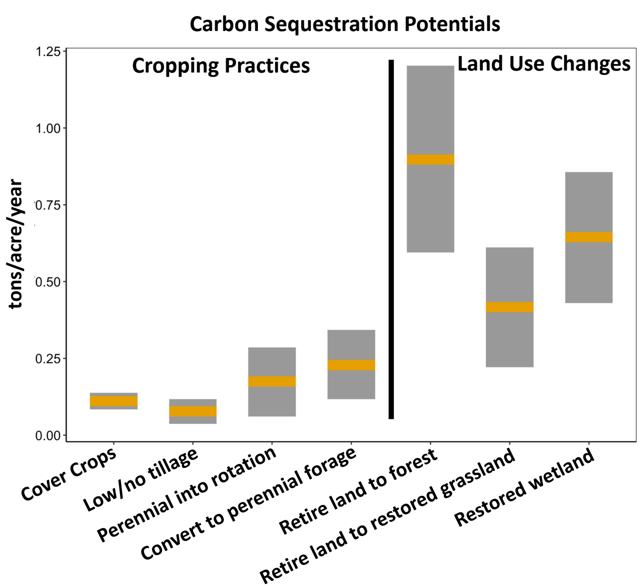

Figure 1. Carbon Sequestration potentials (MPCA 2019)

Perennial regenerative agriculture can sequester up to 0.34 US tons of carbon per acre per year (Figure 1). Using Minnesota as a case study, if half of the 20 million acres of Minnesota cropland were dedicated to regenerative systems or land retirement, 3.4 million or 14.8 million tons of carbon respectively would be sequestered per year for 10-20 years (Figure 2). At the same time, *35-40 million tons of agricultural greenhouse gas emissions annually produced in Minnesota*.[9] Carbon sequestration alone is unlikely to bring us to zero emissions.[24]

Approximately 12% of the total emissions in Minnesota come from nitrous oxide, and approximately 13% are from methane, two very potent greenhouse gases (see appendix 2). Agriculture is the predominant source of both of these emissions.[9] Efficient and effective nitrogen use, which potentially can be achieved with Regenerative perennial crops that are effective at taking up nitrogen fertilizer[26], could reduce nitrous oxide emissions.[6] Similarly, sustainable protein production can reduce methane emissions.[6] Regenerative agriculture potential to reduce fossil fuel and other emissions as well. Because of the limited data available about these possibilities, there is both a need for research and a need for exploring other emissions reduction strategies.

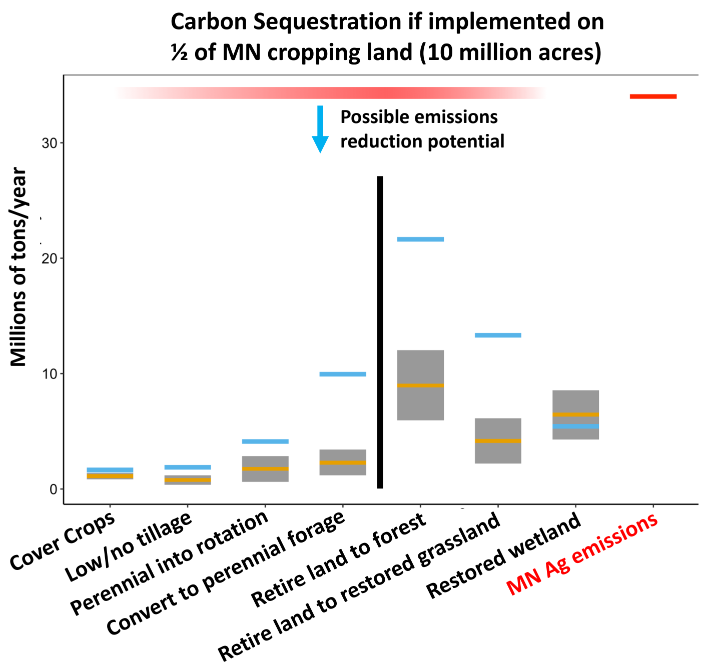

Figure 2. C sequestration and emissions reduction potential scaled to 1/2 of MN cropland. Yellow lines = average C sequestration based on literature review. Gray areas are the range, within 95% confidence, of the average. Blue lines represent the sequestration + emissions reduction potential across the cropping system life cycle. The red line represents the 13-year average MN total emissions from agriculture

Needs for research

- A more detailed understanding of the potentially stacking benefits of clean water, emissions reduction, and climate adaptation from regenerative agriculture.[11,25,2,6]
- An understanding of the variance, limitations, and change in rates over decadal time periods of carbon sequestration rates and totals.[22,24]
- An understanding about how different environmental variables such as local climate, soil type, or soil depth intersect with management to influence carbon sequestration.
- The emissions reduction potential of regenerative agriculture from a systems perspective, including input costs and fertilizer use efficiencies, regionalized supply chains and life cycle assessment. This includes assessing emissions reduction per product produced and delivered to consumers (food, feed, or bioenergy).
- Methane emissions sources, amounts, and pathways to reduction.[6,27,28]

Summary Points

- Regenerative agriculture is likely to result in positive but unreliable carbon sequestration potentials, with the highest rates in the first 10-20 years and that only last as long as the regenerative agricultural practice is maintained.
- The carbon sequestration potentials of regenerative agriculture are small compared to annual agricultural related GHG emissions. Significant land use change or direct emissions reduction are required to achieve emissions reduction goals.
- Regenerative systems are likely to improve climate adaptation and resiliency.
- Regenerative systems have potential to directly reduce emissions.
- Several areas of research are needed, including quantifying emissions reduction potentials of regenerative agriculture, a detailed understanding of how and why C sequestration potentials vary, and a deeper understanding of the situation of methane emissions.

Appendix 1: Acknowledgments and References

Acknowledgements:
Contributions and materials came from members of the Kernza Research Team, members of the Kernza CAP management team, the Department of Soil, Water, and Climate, Co-PIs of a small workshop grant funded by the UMN Institute on the Environment (IonE), including participants of a fall 2020 Climate Adaptation Workshop, and members of the Forever Green Initiative.

References

1. Hunter M, Smith R, Schipanski M, Atwood L, Mortensen D (2017), Agriculture in 2050: Recalibrating Targets for Sustainable Intensification BioScience 67, 386–391.
2. Tilman D, Balzer C, Hill J, Befort BL (2011) Global food demand and the sustainable intensification of agriculture. Proceedings of the National Academy of Sciences of the United States of America 108, 20260–4.
3. Pryor SC, Scavia, D, Downer C, Gaden, M, Iverson, L, Nordstrom R, Patz J, Robertson GP (2014) Ch. 18: Midwest. . Pages 418-440 in Melillo JM, Richmond TC, and Yohe GW, editors. Climate Change Impacts in the United States: The Third National Climate Assessment. U.S. Global Change Research Program.
4. Hatfield JL, Wright-Morton, L, Hall, B (2018) Vulnerability of grain crops and croplands in the Midwest to climatic variability and adaptation strategies 146, 263–275.
5. U.S. Environmental Protection Agency (2020) Inventory of U.S. greenhouse gas emissions and sinks: 1990-2018.
6. Project Drawdown, 2020. Farming our way out of the climate crisis: a primer. https://drawdown.org/
7. Kane D, Bradford MA, Fuller E, Oldfield EE, Wood SA (2021) Soil organic matter protects US maize yields and lowers crop insurance payouts under drought. Environmental Research Letters. Accepted for Publication
8. Williams A, Hunter MA, Kammerer M, Kane DA, Jordan NR, Mortensen DA, Smith RG, Snapp S, Davis AS (2016) Soil Water Holding Capacity Mitigates Downside Risk and Volatility in US Rainfed Maize: Time to Invest in Soil Organic Matter? PLOS One 11:e0160974.
9. Minnesota Pollution Control Agency, 2021. Greenhouse Gas Emissions Inventory 2005-2018, biennial report to the Minnesota Legislature.
10. Minnesota Pollution Control Agency, 2019. Greenhouse gas reduction potential of agricultural best management practices, technical report.
11. Rakkar M, Jungers J, Sheaffer C, Grossman J, Li F, Gutknecht J (2021). Soil health improvements after short term intermediate wheatgrass cultivation. Agriculture, Ecosystems, and Environment, In final preparation to be submitted April 2021 for publication.
12. Ryan MR, Crews TE, Culman SW, DeHaan LR, Hayes RC, Jungers JM, Bakker MG (2016) Managing for Multifunctionality in Perennial Grain Crops. Bioscience: 1–15.
13. Blanco-Canqui H, Shaver T, Lindquist JL, Shapiro CA, Elmore RW, Francis CA, and Hergert GW (2015) Cover Crops and Ecosystem Services: Insights from Studies in Temperate Soils. Agronomy Journal 107: 2449–2474.
14. Paustian K, Larson E, Kent J, Marx E and Swan A (2019) Soil C Sequestration as a Biological Negative Emission Strategy. Frontiers in Climate 1, 8.
15. Dobbratz M, Gutknecht J, Wyse D, Sheaffer C, Jungers J (2021) Inconsistent effects of species diversity and N fertilization on soil microbes or carbon storage in perennial bioenergy cropping systems. Sustainability, in preparation for April 2021 submission.

16. Sanford GR, Posner JL, Jackson RD, Kucharik CJ, Hedtckea JL, Lin T (2012) Soil carbon lost from Mollisols of the North Central U.S.A. with 20 years of agricultural best management practices. Agriculture, Ecosystems, and Environment 162, 68-76.
17. Tautges NE, Chiartas JL, Gaudin ACM, O'Geen AT, Herrera I, Scow KM (2019) Deep soil inventories reveal that impacts of cover crops and compost on soil carbon sequestration differ in surface and subsurface soils. Global Change Biology 25, 3753-3766.
18. Duffy KA, Schwalm CR, Arcus VL, Koch GW, Liang LL, Schipper LA (2021) How close are we to the temperature tipping point of the terrestrial biosphere? Science Advances 7, 1052.
19. Slessarev EW, Nuccio EE, McFarlane KJ, Ramon CE, Saha M, Firestone MK, Pett-Ridge J. 2020. Quantifying the effects of switchgrass (*Panicum virgatum*) on deep organic C stocks using natural abundance ^{14}C in three marginal soils. GCB Bioenergy 12, 834-847.
20. Li J, Jian S, De Koff JP, Lane CS, Wang G, Mayes MA, Hui D (2018) Differential effects of warming and nitrogen fertilization on soil respiration and microbial dynamics in switchgrass croplands. GCB Bioenergy 10, 565–576.
21. Field JL, Richard TL, Smithwick EAH, Caie H, Laser MS, LeBauerg DS, Long SP, Paustian K, Qin Z, Sheehan JJ, Smith P, Wang MQ, Lynd LR, (2020) Robust paths to net greenhouse gas mitigation and negative emissions via advanced biofuels. Proceedings of the National Academy of Sciences 117, 21968–21977.
22. Mehra P, Baker J, Sojka RE, Bolan N, Desbiollesk J, Kirkham MB, Ross C, Gupta R (2018) A Review of Tillage Practices and Their Potential to Impact the Soil Carbon Dynamics. Advances in Agronomy 150, 185-230.
23. Fissore C, Espeleta J, Nater EA, Hobbie SE, Reich PB (2010) Limited potential for terrestrial carbon sequestration to offset fossil-fuel emissions in the upper midwestern US. Frontiers in Ecology and the Environment 8, 409–413.
24. Clark MA, Domingo NGG, Colgan K, Thakrar SK, Tilman D, Lynch J, Azevedo IP, Hill, JD (2020) Global food system emissions could preclude achieving the 1.5° and 2°C climate change targets. Science 370, 705-708.
25. Turner PA, Griffis TJ, Mulla DJ, Baker JM, Venterea RT. (2016) A geostatistical approach to identify and mitigate agricultural nitrous oxide emission hotspots. Science of the Total Environment 572, 442-449.
26. Jungers JM, DeHaan LH, Mulla DJ, Sheaffer CC, and Wyse DL (2019) Reduced nitrate leaching in a perennial grain crop compared to maize in the Upper Midwest, USA. Agriculture, Ecosystems and Environment 272, 63-73.
27. Yu X, Millet D, Wells K, Henze D, Cao H, Griffis T, Kort E, Plant G, Deventer MJ, Kolka R, Roman DT, Davis KJ, Desai AR, Baier BC, McKain K, Czarnetzki A, A Anthony Bloom A (2021) Aircraft-based inversions quantify the importance of wetlands and livestock for Upper Midwest methane emissions. Atmospheric Chemistry and Physics 21, 951-971.
28. Zhou, X, Zhou X, Passow FH, Rudek J, Fisher JC, Hamburg SP, Albertson JD (2019) Estimation of methane emissions from the U.S. ammonia fertilizer industry using a mobile sensing approach. Elementa Science of the Anthropocene. 7,19.

Appendix 2: Definitions and Conversion factors

Defining terms used here

Agriculture: the science or practice of farming, including cultivation of plants and the rearing of animals to provide food, fuel, fiber, and other products. The term agriculture encompasses all the management practices required for those various products.
Annual agriculture: Food, fuel, and fiber production from crops that complete their life cycle in a single growing season, thus requiring replanting each year.
Regenerative agriculture: management practices for food, fuel and fiber production from plants and animals that promote net carbon sequestration in plants and soils.
Perennial grain: Seeds harvested from perennial plants that can be consumed by humans to meet energy and nutritional needs.
Forages: Plants grown for the purpose of feeding directly to livestock.
Management practices: Activities associated with the preparation of soil, management of livestock, and planting, maintaining, and harvesting of crops for agricultural products.
Land retirement: Ceasing the production of crops and/or utilization of agricultural land for livestock.
Stacking benefits: stacking benefits are those benefits, here referring mostly to environmental benefits, where one benefit such as carbon sequestration also creates other benefits.
Statistical average and confidence intervals: The two figures presented here are based on a statistical analysis of results from all studies collected through a literature search performed to find studies of carbon sequestration levels for each of the identified regenerative systems presented. The results of that statistical analysis included two pieces of information: 1) the average amount of carbon sequestration across collected literature for a given practice and 2) the 95% confidence interval, defined as the range in values in which there is a 95% probability that carbon sequestration of a given regenerative practice will fall within this range. This probably is based on current evidence from the given set of collected literature.

Defining cropping practices used here (modified from MPCA, 2019)

Cover crop/catch crop: a plant sown after cash crop harvest to utilize unused water and nutrients and to prevent soil erosion. Cover crops are typically terminated prior to the planting of cash crops instead of being harvested for revenue generation. Cereal rye is the most commonly used cover crop in the US Midwest.
Reduced or no tillage: Reduced tillage practices avoid full soil inversion, but still results in some disturbance and some soil mixing. Variants of reduced tillage include: chisel till, ridge till, mulch till, sweep till, disk tillage, and subsoiling. No-tillage practices are those in which cropland soil is left undisturbed, before and during planting and after harvest. Seeding is done through direct drilling. Weeds are controlled with herbicides. Crop residues are left on the soil surface to decompose. The MPCA (2019) study this summary is based on evaluated no-till practices against either conventional tillage with moldboard plow or reduced tillage. That report found little difference between categories of reduced or no tillage in terms of carbon sequestration or potential emissions reduction, and so for simplification they are a combined category in this summary and reductions potentials were averaged among the two categories.

Perennial grass added to annual crop rotation: in a crop rotation with one or more annual crops, one to three years of alfalfa, other hay or grass leys added to the rotation to build soil organic carbon and to improve other soil physical characteristics.

Cropland to hayland conversion: conversion of upland or lowland cropland to alfalfa, other hay or perennial grasslands for forage production.

Defining land use changes used here (modified from MPCA, 2019)

Retire land to forests (cropland idling in trees): conversion of upland cropland to forested acres, without harvest removals or grazing, usually through a long-term or short-term easement.

Retire land to restored grasslands (cropland idling in restored grassland): conversion of upland cropland to unmanaged grassland, without harvest removals or grazing, usually through a long-term or short-term easement.

Constructed/restored wetlands: Constructed and restored wetlands intercept the flow of nutrients and sediments from croplands to water bodies. Constructed wetlands are engineered wetlands constructed on former croplands to intercept the flow of nutrients and sediments from croplands to lakes, rivers and streams. Restored wetlands are drained wetlands that have been hydrologically restored, typically by blocking drainage ditches or disconnecting drainage piping. Like constructed wetlands, restored wetlands act to intercept the flow of nutrients and sediments from croplands to water bodies.

Converting between amounts of land or greenhouse gases, and global numbers

1 ton carbon dioxide (CO_2) X 0.27 = 1 ton carbon

1 ton carbon / 0.27 = 1 ton CO_2

CO_2e = CO_2 (carbon dioxide) equivalents, a useful metric to take into account the different radiation (heat) holding capacities of different greenhouse gas emissions:

30 molecules of CO_2 have the same heat retention as 1 molecule methane

298 molecules of CO_2 have the same heat retention as 1 molecule nitrous oxide

Soil organic matter (SOM) is ~58% organic carbon

1 Pg (petagram) = 1015g = 1 Gigaton = 1 billion metric tons

1 metric ton = 1 Megagram = 1.1 US tons (also called short tons)

2.4 acres = 1 hectare

1 g/m2 is equivalent to 10kg/ha

Pools of carbon on earth, for reference (in Petagrams, 1 billion tons):

Atmospheric pool of C in CO_2: 800 Pg

Global amounts of soil organic C (Guo and Gifford 2002, Jobbagy and Jackson 2000, Jackson et al. 2017)
Top 1 m: 1500 Pg // Top 2 m: 2400 Pg // Top 3 m: 2770 Pg
Tillage is usually 0.3m, or 0.5-1 foot

How much total C has been lost from soils due to crop agriculture globally:
35-88 Pg (Sanderman et al. 2017, Smith et al. 2016, Lal 2016)

Potential C sequestration globally from improved land use practices (Thompson et al. 2008)
agricultural soils: 0.21 Pg C /yr
reforestation: 0.31 Pg C/yr
pasture: 0.31 Pg C/yr
All practices combined: 0.5-0.7 Pg C /yr