ACKNOWLEDGMENTS

We would like to extend our appreciation to everyone who contributed and provided guidance and support to the completion of our master's project.

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Additional Support:

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University of New Hampshire

University of Minnesota

We would like to extend our gratitude to the faculty and staff of the Bren School of Environmental Science & Management for their support.

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C: Carbon
CH_4: Methane
CO_2: Carbon dioxide
CO_2e: Carbon dioxide equivalent
EPA: Environmental Protection Agency
DNDC: Denitrification-Decomposition (Model)
GHG: Greenhouse Gas
GMO: Genetically Modified Organism
ha: hectare
IPCC: Intergovernmental Panel on Climate Change
kg: kilogram
N_2O: Nitrous oxide
NOAA: National Oceanic and Atmospheric Administration
RO: Regenerative Organic
ROA: Regenerative Organic Alliance
ROC: Regenerative Organic Certification
SOC: Soil Organic Carbon
SOM: Soil Organic Matter
Tonne: metric ton

ABSTRACT

Greenhouse gas emissions from the agricultural sector comprise roughly 30% of global anthropogenic emissions (including land-use change and fertilizer emissions). Current agricultural practices also contribute to dramatic declines in soil productivity and increases in soil erosion rates. Regenerative organic agriculture has been pioneered by many as a solution to these problems. Regenerative agriculture builds upon the USDA organic certification, requiring additional practices such as cover cropping, crop rotations, reduced or no-till, rotational grazing, and the use of compost or manure as fertilizer. These practices theoretically allow crops to pull more carbon from the atmosphere and store it in the soil, thereby mitigating climate change while improving soil health. Patagonia Inc. is interested in moving from organic to regenerative organic agriculture in the production of its fiber and food crops. Patagonia has commissioned this team to examine if regenerative organic practices for crops in their supply chain have increased carbon sequestration and soil health benefits over their current organic production. The team used the Denitrification-Decomposition Model (DNDC) to simulate soil organic carbon changes and net greenhouse gas emissions between organic and regenerative production of cotton, Kernza wheat, mangoes, and perennial grasses for bison grazing. The team found regenerative organic practices were successful in building soil organic carbon compared to organic practices for all four crops. However, changes in net greenhouse gas emission are more variable and depend on crop type, soil properties, and climatic conditions.

EXECUTIVE SUMMARY

Introduction

Due to the threat of climate change, more attention is being paid to what can be done to curb emissions and meet the Paris Agreement's goal to limit the global temperature rise to 1.5°C and well below 2°C. Governments and corporations are both becoming major players driving action plans to meet targets to achieve this goal. The EPA has identified the agricultural sector as one of the top 5 contributors to global greenhouse gas emissions. In order to meet the climate targets, current agricultural management practices need to be re-evaluated to include consideration for soil health and resilience as well as overall yield productivity.

Patagonia seeks to reduce its carbon footprint within its supply chain through the adoption of regenerative organic (RO) agricultural practices in the sourcing of raw material. Their goal is to promote carbon sequestration in the soil in hopes of turning their production line from a source of carbon to a sink of carbon while building climate resilient soils.

Objectives

This project analyzed the carbon sequestration potential and GHG emissions for different crops comparing RO scenarios to currently practiced organic scenarios.

The primary objectives were:

1. Assess the effectiveness of RO practices to store soil carbon over time.
2. Model greenhouse gas emissions over time and the effect of different practices on total GHG emissions.
3. Develop recommendations for Patagonia on which practices have the largest soil carbon sequestration potential and the lowest net GHG emissions.

In order to accomplish these objectives, the team answered the following questions:

1. Which RO practices had the largest soil carbon sequestration and the lowest GHG emissions?
2. How did other variables, such as climate and initial carbon soil stock, affect carbon sequestration and GHG emissions?
3. What feedback can be given on the ROC Framework, which is being considered for implementation by Patagonia?

Significance

The agricultural sector accounts for 30% of total anthropogenic emissions. This includes direct emissions from soil and livestock, as well as indirect emissions from fossil fuel use, agrochemical production, and land conversion to agriculture. However, opportunities exist to not only decrease GHG emissions in this sector but also to mitigate the effects of climate change on farming communities. This project seeks to explore solutions to these problems using RO practices. These practices have the potential to reduce agricultural emissions while also improving soil health and productivity.

Methods

The Denitrification-Decomposition model (DNDC) was used to model the soil carbon sequestration potential of RO agriculture over organic agriculture. This model was developed by the University of New Hampshire to simulate soil-level carbon and nitrogen dynamics in agro-ecosystems. DNDC predicts crop growth, soil organic carbon buildup, and trace gas emissions (CO_2, CH_4, N_2O) from the soil. It should be noted the trace gas emissions are only from soil emissions, not from the whole farm's operations (machinery, transport, etc). It was chosen over similar models (COMET and Century) due to its ability to simulate soil dynamics for locations both domestic and international, and to model soil carbon at necessary depths.

DNDC required data on-site climate, soil, and crop properties. Climate data entailed daily maximum and minimum temperatures, daily precipitation, and daily wind speed (optional). Soil data involved information on bulk density (tonne /m_3), initial soil organic carbon stock (g SOC/kg soil), pH, and soil texture (% clay content). Crop management properties included crop type, cover crops used, tillage, fertilizer, irrigation, flooding, and grazing practices.

Climate data for use with DNDC was obtained from NOAA for domestic sites, and online climate resources for international locations. Soil data for all sites and crops was obtained from the International Soil Reference & Information Center's SoilGrids, a meta-analysis on global soil carbon stock and properties. Crop management data was obtained from various sources. Cotton data on regenerative production in India was provided by Patagonia. Information on Kernza wheat came from interviews with its developers - The Land Institute and The University of Minnesota. Information on mangos was obtained from literature reviews, and data on bison grazing came from interviews with California ranchers.

DNDC outputs on soil organic carbon and GHG emissions were analyzed to determine if RO practices had different SOC and net GHG emissions relative to organic practices. A sensitivity analysis of the effect of each variable (climate, soil, crop management practices) was then conducted to determine which variables had the greatest impact on SOC and net GHG emissions.

Results

We modeled outputs for SOC and net GHG emissions across four crops (cotton, Kernza, mango trees, and perennial grasses) for RO and organic practices. We also analyzed methane and nitrous oxide emissions, the climate impact of different regions, and an analysis of crop yields. We have also performed a sensitivity analysis for cotton with perennial cover crops and added tillage scenarios. To further analyze our results, we compared cotton SOC results from the DNDC model to the COMET model for regenerative organic agriculture in Texas.

DNDC outputs show an increase in SOC from RO practices compared to organic practices over a 20-year horizon. For mangos, perennial grasses, and Kernza, RO practices improved soil carbon stock accumulation over time. Cotton, however, still lost carbon from the soil under RO management, but at a lower rate than under organic management. Under regenerative management, perennial crops (Kernza, mango, perennial grasses) behaved as a carbon sink where annual crops (cotton) still acted as a carbon source. This is due to the fact that perennial crops have a larger root biomass compared to annual crops. Comparison of net GHG emissions between RO and organic had variable results. We find that GHG emissions in RO practices were highly sensitive to nutrient additions and cropping location. N_2O fluxes from compost and manure additions were the greatest driver in higher net GHG emissions across modeled crops. Our modeled SOC and GHG results were also impacted by changes in location, likely due to differences in soil and climatic conditions.

Discussion

Our analysis showed appropriate agricultural practices could be used to increase soil organic carbon sequestration to address climate change. RO practices build soil organic carbon compared to organic agriculture. Soil organic carbon improves soil health, productivity, and drought resilience. However, it is important to analyze net GHG emissions in order to evaluate the overall climate impact, as changes in other GHGs - such as N_2O - can offset any potential benefit from soil carbon sequestration. Indeed, DNDC showed that net GHG emissions under RO practices were not always lower than under organic practices, with results differing for various crops, locations, and climatic conditions.

Our sensitivity analyses provide guidance on how to tailor the practices for specific site conditions to ensure decreases in net GHG emissions. Crop rotation and cover cropping generally increased soil carbon and reduced GHG emissions for all crops. Compost/manure addition increased soil organic carbon, but the impact on the net GHGs emissions was more variable. A literature review showed that the effect of organic fertilizer on the GHG emissions depends on fertilizer type, fertilizer application rate, crop type, soil properties, irrigation systems, temperature, and rainfall events. To limit the emissions from fertilizer use, it is important to control fertilizer application rate and irrigation events according to the soil and crop characteristics.

Climate benefits of RO practices can be maximized by tailoring management practices to site characteristics and climatic conditions. More research and data collection are needed to understand impacts on crop yields and overall net GHG emissions. Important factors to consider include changes in land-use, fertilizer application, and farm use of transportation and machinery.

Conclusion

Our analysis shows that RO practices build more soil organic carbon compared to organic practices. However, total net GHG emissions from RO practices may not be lower than organic practices under certain conditions.

We identified N_2O emissions from compost or manure additions as the major driver of GHG emissions. Proper management and application of these additives and irrigation management are necessary in order to minimize net GHG emissions. Our modeling demonstrates that perennial crops had a positive effect on carbon sequestration. The three perennial crops (mango, perennial grass, and Kernza wheat) acted as a sink of carbon. In the one annual crop (cotton), practices like cover and border cropping helped slow the loss of carbon. The use of perennial crops - either as main crops, border crops, or intercrops - helped store more carbon in the soil.

Overall, RO practices such as cover cropping, crop rotation, compost and manure use, as well as the use of perennial crops have the ability to sequester and store more SOC. However, these practices have varied effects on total GHG emissions.

Going forward, we recommend Patagonia collect more on-site data to check against our modeling and analysis to verify validity. Yields also need to be carefully tracked to confirm our result of comparable yields. Therefore, further on-site soil measurements should be collected to continue tracking SOC sequestration and GHG emissions.

PROJECT OBJECTIVES AND SIGNIFICANCE

Agriculture accounts for 30% of the total anthropogenic greenhouse gas emissions [1]. A large portion of these emissions come from the loss of soil organic carbon due to land-use change to cropland, as well as soil respiration and erosion. Additionally, a considerable portion of these emissions come from N_2O, stemming from the use of synthetic nitrogen fertilizer [2]. In fact, the use of nitrogen fertilizer is directly responsible for 79% of global N_2O emissions [3]. The intensification of industrial agricultural practices has made agricultural production a major contributor to climate change. These practices have also led to a decrease in soil health. This is seen in the fact that agricultural soils have lost 50-70% of their original carbon stock - a key metric for judging soil health [4]. This has also corresponded with an alarming erosion of topsoil that is one to two orders of magnitude larger than the rate at which topsoil is naturally replaced [5]. Large and inefficient use of synthetic inputs, along with the increasing trend of monocropping annual crops, has led to a massive amount of greenhouse gas emissions as well as the degradation of soil health and the rapid loss of topsoil.

Currently, agricultural soils behave as a large source of GHG emissions but have the potential to act as a sink for emissions. Soils contain three times as much carbon than is stored in the atmosphere. Therefore, even small increases in soil carbon sequestration can have a large impact on climate change mitigation [6]. Increases in soil organic carbon can have benefits beyond lowering the levels of atmospheric carbon. Soil organic carbon plays a major role in soil health, which influences the soil's productivity and provision of ecosystem services [7]. Soil organic carbon and soil organic matter (which consists of 45-60% carbon) are essential for: soil structure, improved water retention, nutrient retention (which can moderate non-point source water pollution), rhizospheric processes (which are able to suppress disease in the soil), influence the emissions of GHG gases from the soil, and lastly boost yields and productivity of the soil[7]. Improvements in the way agricultural soils are managed can yield benefits for both people and climate. Through the implementation of practices such as conservation tillage, the reduction of soil disturbance, cover cropping and crop rotation, and nutrient cycling with the use of compost and manure, soils have the potential to offset one third of yearly anthropogenic emissions if globally adopted - with the added benefit of improving soil health and climate resilience [4].

The goal of this project is to help Patagonia quantify potential carbon sequestration benefits from RO practices within its supply chain. There are 4 main objectives to this project that will guide Patagonia and the ROA on best practices for RO agriculture:

1. Review the practices thought to increase soil carbon stores and assess the environmental costs and benefits of these practices, including their net greenhouse gas emissions.

2. Run a soil organic carbon model that accounts for changes in soil carbon and net greenhouse gas emissions using existing data from a Patagonia pilot program, then model the soil carbon sequestration capabilities and greenhouse gas emissions of production for 20 years.

3. Identify and provide suggestions to Patagonia on which practices will yield the highest environmental benefit.

4. Provide Patagonia with options to improve the ROC and what additional data could be collected to improve the quantification of the benefits of the certification.

BACKGROUND

Climate change is a growing concern across the world, bringing countries together to work toward addressing it. The agricultural sector has been identified as one of the largest contributors to GHG emissions. Currently, 30% of anthropogenic GHG emissions come from agriculture [1] - mainly from methane and nitrous oxide. Conventional agricultural practices are also associated with a 50-70% loss in soil carbon stock and soil erosion rates 1-2 orders of magnitude greater [5] than natural erosion rates. Along with this, arable soils are the largest anthropogenic contributor of N_2O - currently, cropped plants only take up approximately 30-50% of nitrogen when synthetic fertilizer is applied. At the current rate of warming, it will not be enough to simply reduce GHG emissions to avoid the consequences of increasing temperatures. Solutions are needed to pull carbon dioxide from the atmosphere and store it long-term. Growing populations place a further strain on agricultural production, as more land is needed to meet additional food demands. This is one of the contributing factors to deforestation, ultimately leading to more carbon emissions and reductions in biodiversity.

Given the climate change threats and increasing GHG emissions from the agricultural sector, farmers could potentially benefit by reducing their GHG emissions and investing in developing more climate-resilient and drought-resistant soil practices. This would ultimately benefit them as temperatures rise, and climate change impacts worsen.

In the midst of a changing climate and degrading soil quality from current agricultural practices, regenerative agriculture is increasing in popularity. Regenerative have been identified as the tools needed to improve the health and resilience of agricultural communities decades ago. The goal of regenerative practices is to promote soil health and carbon storage and includes practices such as no-till, cover cropping, crop and grazing rotations, and no synthetic inputs. As the temperature change impacts are being felt more significantly in developing countries located closer to the equator, soil quality and water holding capacity are drawing attention back to the development and implementation of these practices [2]. Through improved cropland management, there is the potential to sequester 0.3-1.5 Pg of CO_2e per year [8].

Patagonia’s supply chain has been practicing 100% organic agriculture since 1996. As part of their climate change mitigation strategy, Patagonia is looking to add regenerative practices to their already organic supply chain. In their pursuit to implement these practices, Patagonia has been working with the Regenerative Organic Alliance, a coalition of ranchers, farmers, and brands who have designed the Regenerative Organic Certification (ROC) [9]. Organic certifications require that there is no use of GMOs, pesticide, herbicide, or fungicide, and that no synthetic soil additives be used. Under regenerative organic management, the organic requirements will remain, but additional practices such as cover cropping, no-till, and compost/manure use will also be required to build soil health. This certification is meant to be a form of eco-labeling emphasizing agricultural practices that enrich soils, value animals, and improve worker welfare. In our analysis, we focused on the practices meant to enrich and improve the health of the soil. The ROC promotes this primarily through the following:

- Increase of soil organic matter: Development of soil organic carbon (SOC) from photosynthetic activity. Higher SOC is indicative of crop and soil productivity and can also have climate benefits if the carbon is stored in the soil long-term.
- Conservation tillage: The ROC encourages no- or limited-till practices to obtain the certification, as they believe tillage increases carbon fluxed out of the soil (it is important to note the research on this matter is hotly contested).
- Cover cropping and biodiversity: Using cover cropping practice has shown to decrease erosion in soil and promote healthy soil microbial activity while sequestering more carbon in the soil. Biodiversity further promotes healthier microbial communities through nutrient cycling.
- No synthetic inputs: Compost additives are used for soil enrichment. Replacing synthetic inputs with high-quality soil amendment may increase water holding potential of the soil, improving drought-resilience.
- Rotational grazing: Systematically moving livestock from one area to another, allowing pastures to rest. This recovery time is meant to promote forage plant growth and increase soil carbon levels.
- No GMOs: Besides not using any synthetic additives, this framework also prohibits any crops derived from modified sources, which includes any technological advancement modifications.

There is research supporting that these practices increase carbon sequestration in soils, and provide co-benefits such as improved productivity, increased water retention, and fortified climate resilience [4].

Patagonia has always been a company with a sustainability and social equity focus and are interested in enhancing their already organic production to meet their climate mitigation goals. They are looking to implement this framework to their supply chain, more specifically the agricultural practices surrounding cotton, mangos, perennial grasses for bison grazing, and their new perennial wheat crop, Kernza wheat. Kernza is still a long way away from replacing annual wheat, as the grain’s yield and quality, among other attributes, are still in development [10]. Patagonia uses cotton as their primary fiber crop; mango, bison, and Kernza are part of their food and beverage line, Patagonia Provisions. This branch of Patagonia Inc. applies its mission to the food industry, where they are producing various food items for the outdoor enthusiast, including nut and fruit bars, dried bison jerky, smoked fish, and other meals oriented to backcountry expeditions [11].

How RO practices can build and store SOC

Soil contains three as much carbon than is stored in the atmosphere, and is one of the largest reservoirs of carbon, second only to the ocean [12]. Practices that can utilize this carbon reservoir while also improving the quality of the soil used for agriculture will become important tools as we face the realities of climate change. There is a range of consensus on which practices are best suited to sequester carbon in soils for significant time periods [13]. Therefore, it is important to examine the landscape of research on the practices promoted by the ROC to analyze their ability to sequester and store soil carbon before modeling. Listed below are the practices recognized by the ROC to sequester carbon with the analysis of each practice on its ability to sequester carbon and increase grain productivity.

Tillage:

Tillage is one of the most highly debated practices in RO agriculture because the results of research can be drastically skewed depending on the depth of the soil sample taken [14]. This is an issue, as there is compelling research noting that no-till can shift the profile of soil carbon to shallower depths. Therefore, studies that do not sample deeper than 30cm will incorrectly state that no-till shows an increase in carbon when they truly measure the shift of carbon in the soil profile [14]. Recently, the International Panel on Climate Change published a report on Land and Climate, which cites research stating that reduced tillage was an important strategy to reduce soil and nutrient erosion. Although it was not a compelling method for sequestering carbon due to most research limiting their soil samples to 30cm or less [14]. With this said, there is support for no-till having co-benefits outside of carbon sequestration. In some studies, it has been shown that no-till can reduce the amount of soil erosion by one third, which will have productivity and nutrient runoff impacts [15].

Cover Cropping:

Cover cropping is often seen as a compelling method for soil carbon sequestration. The IPCC has leaned on research in their most recent report stating that cover crops have the potential to sequester 0.12 Gt C per year with a saturation time of up to 150 years [16]. It is also key to understand which cover crops are most effective. Legume cover crops can be used to increase carbon sequestration as well as reduce the need for nitrogen fertilizer [17]. This is because legumes are able to fix atmospheric nitrogen and make it bioavailable in the soil [1]. Due to the use of legumes, cover crops pose the opportunity to reduce the use of nitrogen-based fertilizers. They also have the potential to improve water systems by limiting the amount of nitrogen runoff that is associated with the use of synthetic nitrogen fertilizer [18]. This increase in nitrogen will also become important for soil carbon sequestration as sequestration rates are closely linked to carbon: nitrogen ratios [19]. Based on the body of research, cover cropping is an effective tool for increasing soil carbon and nitrogen, while also reducing the need for nitrogen-based fertilizers.

Compost/Manure:

Research shows compost addition has a positive correlation to soil carbon sequestration but a potentially high global warming potential due to N_2O emissions [20,21]. This makes the use of compost complicated. If used properly, compost has the potential to increase SOC, soil nitrogen, and yields compared to the use of chemical fertilizer [22]. However, compost also has the potential to increase N_2O emissions. Compost is nitrogen-rich (which benefits soil health) but may increase the total emissions by fluxing N_2O during heavy rain events. N_2O is a much more potent greenhouse gas than CO_2, which could increase the total global warming potential of production [23].

Permanence of Carbon Storage:

With a knowledge of these practices, it is important to know the timescales at which carbon is stored in soils with respect to different soil depths. RO practices are more effective at storing SOC and improving soil health if they are applied for longer consecutive time periods. The top 30cm is considered the management zone of agriculture and is more likely to be exposed to disturbance and therefore soil loss, soil carbon that is stored in this zone is more likely to have a shorter residence time [24]. Gains in soil carbon can also be broken into active and passive pools of carbon. Active pools (plant residues and soil biota) will have a mean residence time of months, while resistant carbon pools (humified organic matter) will have a mean residence time of centuries to millennia [25]. The residence time of soil carbon is also increased with the depth of carbon storage and clay content of the soil which provides soil carbon physical protection from decomposition [25].

Yield Increases with Regenerative Practices

Now that we have analyzed the effect of the RO practices on storing SOC, we will further analyze the effect of these practices on overall productivity. Further, in order to address the increasing food demands due to a growing population and consequences of land-use change due to deforestation, it is important to understand the impact these RO practices will have on the crop yield.

Cover Cropping:

Cover cropping with legumes has been shown to increase grain productivity of winter wheat with the grain productivity being almost twice higher than the regional average. This did not just increase the total grain productivity, but also increased the protein content of the grain. Cover cropping also produced more straw, which is a source of N and leads to a lower amount of fertilizer needed [26]. For corn, the increase in yield from cover cropping with legumes was at 10%-20%. With sufficient application of nitrogen to the system the yield gains can potentially be higher as the SOC content of the soil increases. Research shows that for cotton, yield doubled after cover cropping with Bahia grass, which increased the pores in the soil, also increasing its water holding capacity [27].

Crop Rotation:

Crop Rotation in combination with no till practice has been shown to increase quality of the soil, including productivity and yield. Intense monoculture has been shown to have a negative effect on soil holistically, ultimately decreasing yield [27]. Introducing legumes into the crop rotation has also been found to increase productivity and yield through the increase in organic matter and nitrogen [38].

Compost/Manure:

Compost or organic manure has been found to increase soil health slowly over time, which in turn leads to higher yields. It is possible to achieve higher yields with compost/manure, but it is more difficult as this process is more reliant on temperature and adequate N release. Temperature changes between the seasons can have a detrimental impact on the crop [28]. In order to maximize productivity of the soil and crop yield, it is important to maintain the right proportion of C and N depending on the crop. [39] Compost application is one of the practices found to increase soil organic matter and is even more crucial in certain climate variable conditions. Research states that adding sufficient nutrients during the grain development stages can have a significant effect on yield. [40]

Tillage:

Limited or no-till cropping systems can potentially improve productivity and overall soil health. Generally, crop productivity is negatively affected by conventional tillage systems. In some cases, tillage may be preventing weed infestation, which would have a positive impact on productivity. However, Shahzad et. al (2016) states that the benefit of tillage on weed suppression is not always accurate, as tillage may simply postpone weed infestations. Poor weed management is often one of the major hurdles in full adoption of no-till practice in a regenerative agriculture system. Crop rotation is helpful with managing the weeds and often is a practice adopted with no till system [29]. Additionally, literature supports no-till systems as mechanisms to increase physical and chemical quality of soil, soil resilience through water holding capacity and microbial activity. Long-term, this means more productive soils with higher yields. Retaining the crop residue on the fields is a practice that goes hand in hand with the no till scenario [30]. Tillage is one of the more controversial practices and some research did support lower yields, unless supplemented with nitrogen additives. Even when additives were used it still took a few years to be able to produce a better yield [27].

The primary interest for Patagonia is in the carbon sequestration benefits associated with RO practices, with a side focus on co-benefits of soil health, productivity, and water storage capacity. This project will focus on modeling soil organic carbon (SOC) for four crops - cotton, Kernza wheat, mangos, and perennial grasslands for grazing - over a twenty year period, assessing surface-level carbon sequestration (associated with short-term benefits like soil productivity) and deeper carbon sequestration (correlated with long-term climate change mitigation), as well as measuring trace gas (CH_4 and N_2O) emissions, from both organic and regenerative scenarios. Recommendations will then be made to Patagonia on the carbon sequestration potential of regenerative agriculture over traditional organic agriculture for the given crops.

Of the four crops, cotton consists of the majority of Patagonia's spend, and therefore is the crop of primary focus for this project. Cotton is also the only annual crop of the four (Kernza, mangoes, and perennial grasses). According to the literature, annual crops have lower long-term carbon sequestration potential, as the process of planting and harvesting every year cycles soil carbon faster than perennial crops [3]. However, there are still avenues for RO cotton to have soil health benefits and have lower net GHG emissions over organic cotton, and these avenues will be assessed below.

METHODS

The Denitrification-Decomposition (DNDC) Model, developed by the University of New Hampshire, simulates soil carbon sequestration and greenhouse gas emissions of cotton, Kernza, mangos, and perennial grasses. DNDC simulates soil carbon and nitrogen biogeochemistry in both Region and Site modes (the Site mode was used for this project), and outputs soil carbon dynamics and emissions of trace gases like CO_2, CH_4, and N_2O, the three major greenhouse gases. DNDC models these emissions from the soil, not from the overall farm operations. This model was chosen due to its ability to model these outputs for locations both domestic and international, as it just requires site coordinates and soil properties. Another strength of DNDC is its ability to simulate soil carbon changes in different soil profiles (0-10 cm, 10-20 cm, 20-30 cm, 30-40 cm, 40-50 cm). Figure 1 below displays a simplified flow diagram of the DNDC process.

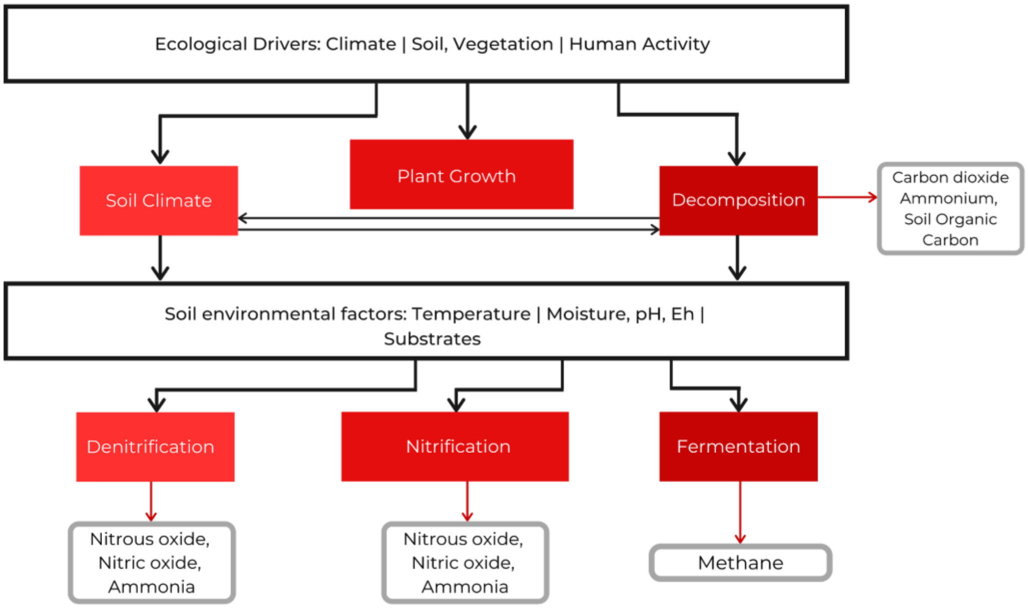
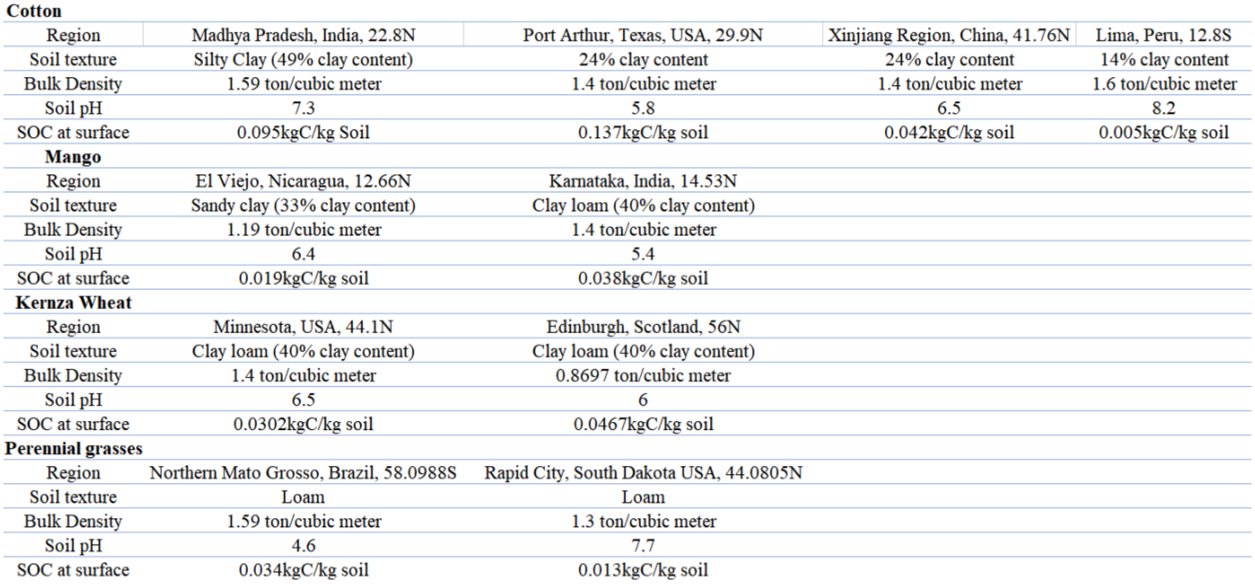


Figure 1. Denitrification-Decomposition Modeling Process: Process by which DNDC accounts for climate, soil, and crop management data to measure plant growth, and soil nutrient cycling.

DNDC was validated by a number of studies internationally. Li (1997) used the model to simulate long-term SOC trends in Europe and Australia and found mean percent differences between simulated and measured SOC was less than 0.07% for all but one of the 11 plots of land studied. Cai (2003) utilized DNDC to measure GHG emissions from croplands in Japan, China, and Thailand, resulting in satisfactory simulations of GHG emissions from cropping systems and land management - although there were discrepancies between modeled and observed seasonal patterns in CH_4 and N_2O emissions. Finally, Beheydt (2011) applied DNDC to simulate N_2O emissions from 22 sites in Belgium. This study found although DNDC both underestimated and overestimated N_2O emissions for specific sites, the general consensus was that overall, the model simulated N_2O emissions more accurately than different regression models.

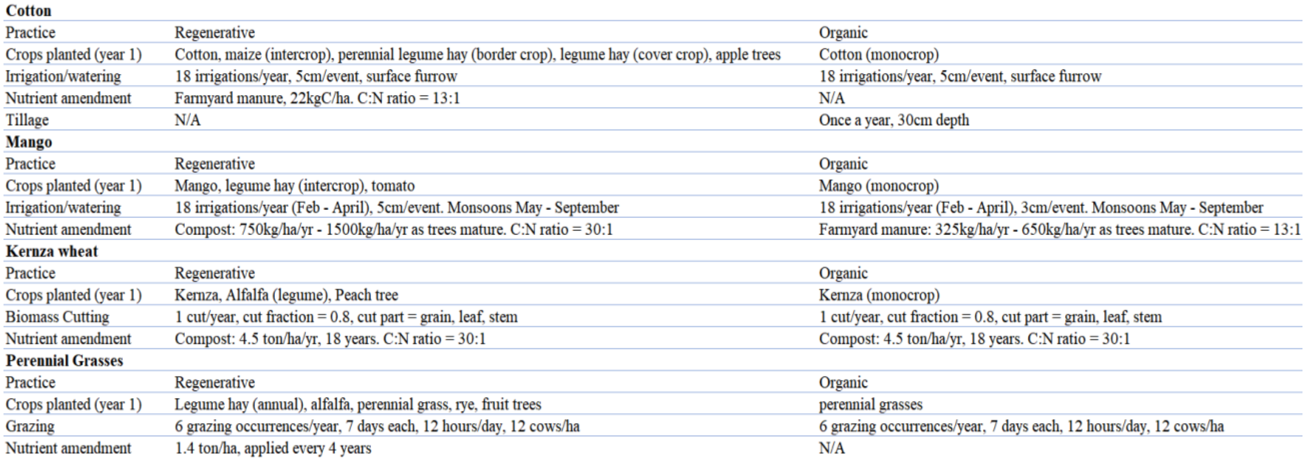
Data on site climate, soil, and crop management were required inputs in DNDC. Tables 1 and 2 below show geographical and crop management data used for the four crops.

Table 1. Site Information



Cotton				
Region	Madhya Pradesh, India, 22.8N	Port Arthur, Texas, USA, 29.9N	Xinjiang Region, China, 41.76N	Lima, Peru, 12.8S
Soil texture	Silty Clay (49% clay content)	24% clay content	24% clay content	14% clay content
Bulk Density	1.59 ton/cubic meter	1.4 ton/cubic meter	1.4 ton/cubic meter	1.6 ton/cubic meter
Soil pH	7.3	5.8	6.5	8.2
SOC at surface	0.095kgC/kg Soil	0.137kgC/kg soil	0.042kgC/kg soil	0.005kgC/kg soil
Mango				
Region	El Viejo, Nicaragua, 12.66N	Karnataka, India, 14.53N		
Soil texture	Sandy clay (33% clay content)	Clay loam (40% clay content)		
Bulk Density	1.19 ton/cubic meter	1.4 ton/cubic meter		
Soil pH	6.4	5.4		
SOC at surface	0.019kgC/kg soil	0.038kgC/kg soil		
Kernza Wheat				
Region	Minnesota, USA, 44.1N	Edinburgh, Scotland, 56N		
Soil texture	Clay loam (40% clay content)	Clay loam (40% clay content)		
Bulk Density	1.4 ton/cubic meter	0.8697 ton/cubic meter		
Soil pH	6.5	6		
SOC at surface	0.0302kgC/kg soil	0.0467kgC/kg soil		
Perennial grasses				
Region	Northern Mato Grosso, Brazil, 58.0988S	Rapid City, South Dakota USA, 44.0805N		
Soil texture	Loam	Loam		
Bulk Density	1.59 ton/cubic meter	1.3 ton/cubic meter		
Soil pH	4.6	7.7		
SOC at surface	0.034kgC/kg soil	0.013kgC/kg soil		

Table 2. Crop management data



Cotton		
Practice	Regenerative	Organic
Crops planted (year 1)	Cotton, maize (intercrop), perennial legume hay (border crop), legume hay (cover crop), apple trees	Cotton (monocrop)
Irrigation/watering	18 irrigations/year, 5cm/event, surface furrow	18 irrigations/year, 5cm/event, surface furrow
Nutrient amendment	Farmyard manure, 22kgC/ha. C:N ratio = 13:1	N/A
Tillage	N/A	Once a year, 30cm depth
Mango		
Practice	Regenerative	Organic
Crops planted (year 1)	Mango, legume hay (intercrop), tomato	Mango (monocrop)
Irrigation/watering	18 irrigations/year (Feb - April), 5cm/event. Monsoons May - September	18 irrigations/year (Feb - April), 3cm/event. Monsoons May - September
Nutrient amendment	Compost: 750kg/ha/yr - 1500kg/ha/yr as trees mature. C:N ratio = 30:1	Farmyard manure: 325kg/ha/yr - 650kg/ha/yr as trees mature. C:N ratio = 13:1
Kernza wheat		
Practice	Regenerative	Organic
Crops planted (year 1)	Kernza, Alfalfa (legume), Peach tree	Kernza (monocrop)
Biomass Cutting	1 cut/year, cut fraction = 0.8, cut part = grain, leaf, stem	1 cut/year, cut fraction = 0.8, cut part = grain, leaf, stem
Nutrient amendment	Compost: 4.5 ton/ha/yr, 18 years. C:N ratio = 30:1	Compost: 4.5 ton/ha/yr, 18 years. C:N ratio = 30:1
Perennial Grasses		
Practice	Regenerative	Organic
Crops planted (year 1)	Legume hay (annual), alfalfa, perennial grass, rye, fruit trees	perennial grasses
Grazing	6 grazing occurrences/year, 7 days each, 12 hours/day, 12 cows/ha	6 grazing occurrences/year, 7 days each, 12 hours/day, 12 cows/ha
Nutrient amendment	1.4 ton/ha, applied every 4 years	N/A

DNDC outputs for SOC and GHG emissions were assessed and compared between RO and organic scenarios. Carbon and nitrogen emissions are outputted by DNDC as kg C/ha and kg N/ha, respectively. SOC, CO_2, CH_4, and N_2O emissions had to be converted from kg C/ha and kg N/ha to kgCO_2/ha, kgCH_4/ha, and kgN_2O/ha, respectively. These then had to be converted to units of kgCO_2-equivalent/ha to be summed. The equations used for these conversions are listed below. DNDC outputs SOC in kg C/ha, CO_2 and CH4 in the units of kg C/ha and N_2O in kg N/ha. CO_2 equivalents for each are calculated by using the Eq. 1,2,3,4 below. Net GHG emissions were calculated as the sum of SOC (as a carbon-negative) sequestered, CO_2 emitted, CH_4 emitted, and N_2O emitted, all in the units of kg CO_2e by using the Eq.5 below.

SOC to CO_2-equivalent:

$$\frac{kg\ C}{ha} \times \frac{44\ kg\ CO2}{12\ kg\ C} \times \frac{1\ kg\ CO2-e}{1\ kg\ CO2} = kg\ CO_2\text{-}e\ sequestered \tag{Eq.1}$$

CO_2 to CO_2-equivalent:

$$\frac{kg\ C}{ha} \times \frac{44\ kg\ CO2}{12\ kg\ C} \times \frac{1\ kg\ CO2-e}{1\ kg\ CO2} = kg\ CO_2\text{-}e\ from\ soil\ CO_2\ emissions \tag{Eq.2}$$

CH_4 to CO_2-equivalent:

$$\frac{kg\ C}{ha} \times \frac{16\ kg\ CH4}{12\ kg\ C} \times \frac{28\ kg\ CO2-e}{1\ kg\ CO2} = kg\ CO_2\text{-}e\ from\ soil\ CH_4\ emissions \tag{Eq.3}$$

N_2O to CO_2-equivalent:

$$\frac{kg\ N}{ha} \times \frac{44\ kg\ N2O}{28\ kg\ N2} \times \frac{265\ kg\ CO2-e}{1\ kg\ CO2} = kg\ CO_2\text{-}e\ from\ soil\ N_2O\ emissions \tag{Eq.4}$$

Net GHG emissions:

$$(\textit{kgCO}_2\textit{-e from soil CO}_2\textit{ emissions}) + (\textit{kg CO}_2\textit{-e from soil CH}_4\textit{ emissions}) + (\textit{kg CO}_2\textit{-e from soil N}_2\textit{O emissions}) - (\textit{kg CO}_2\textit{-e sequestered}) \qquad (\textit{Eq.5})$$

It was then important to analyze what was impacting SOC and net GHG emissions values. To understand what was affecting these changes, the amount of nitrous oxide and methane emitted for each crop under both management practices was summed over 20 years. This was done to understand which gases were driving changes in net GHG emissions and which practices emitted more of these gases. Additionally, the relationship between SOC and net GHG results and location were analyzed by simulating crop production in different countries. Countries were chosen based either on where Patagonia currently sources the crop, or where there is significant production of the crop Patagonia can source from. These regions can be seen in Table 1 above. Next, different locations were modeled with the main location's climate, and then with the default climate data in DNDC, in an attempt to determine how much of the change in location was due to differences in climate as opposed to differences in soil properties. Finally, specific practices were broken down to examine their impact on SOC and net GHG emissions. The practices analyzed were soil nutrient addition, tillage, and cropping diversity.

RESULTS

The results of the analysis performed are listed below. Practices and crops will be visualized for their impact on SOC and net GHG emissions impacts under RO and organic management over a period of 20 years. All four crops (Kernza, cotton, perennial grasses, mangos) will be analyzed in multiple locations.

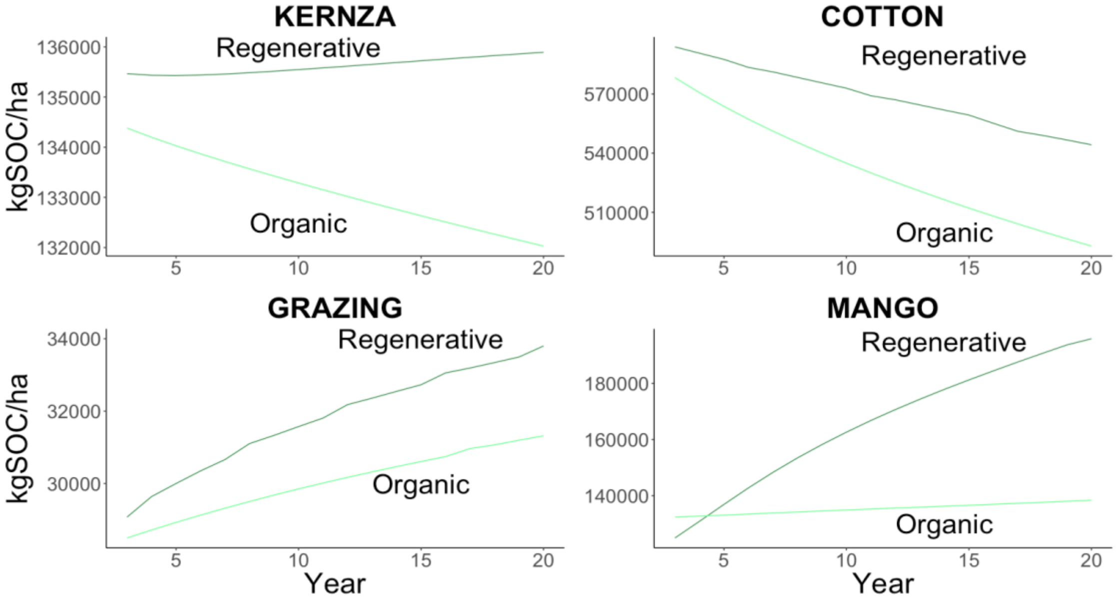


Figure 2. Time Series Plot of Soil Organic Carbon: Year to year variation in soil carbon stock in regenerative and organic practices over 20 years for the four crops analyzed

In Figure 2, each crop was analyzed for changes in total SOC over 20 years under both RO and organic management. In these plots Kernza is modeled in Minnesota, USA; cotton in Madhya Pradesh, India; grazing in South Dakota, USA; and mangoes in El Viejo, Nicaragua. Based on these results, RO management is seen to have a positive effect on SOC as can be seen in the time series plots in Figure 2. In all cases, RO management increased the stock of carbon in the soil when compared to organic agriculture. All of the perennial crops (Kernza, perennial grasses for grazing, and mangos) increase SOC over time, whereas cotton (the only annual row crop analyzed) decreases the carbon stock in both organic and RO scenarios. RO practices were not able to convert cotton into a sink of carbon, but they did limit the amount of carbon the soil lost after 20 years. After 20 years, Kernza under RO management had 3% more SOC than organic management, mango orchards contained 42% more SOC under RO management compared to organic, cotton lost 10% less SOC under RO management, and grazing on perennial grasses held 8% more SOC. These percentages show the difference in total SOC after 20 years under RO management and organic management. Time series plots of changes in SOC for each crop in all of their modeled locations can be found in the appendix.

Crop perennialism has a strong correlation to the plants’ ability to sequester atmospheric carbon long term [31]. This is mainly driven by perennial plants’ extensive root biomass, which spreads to the deeper levels of the soil as compared to annual crops. This enables the soil to build SOC by not only increasing root biomass, but also root exudates, and microbial communities [32]. From this initial analysis, it can be seen that regenerative agriculture is beneficial to SOC accumulation, but the type of crop will determine if this crop is actively sequestering carbon or emitting carbon under specific set of management practices.

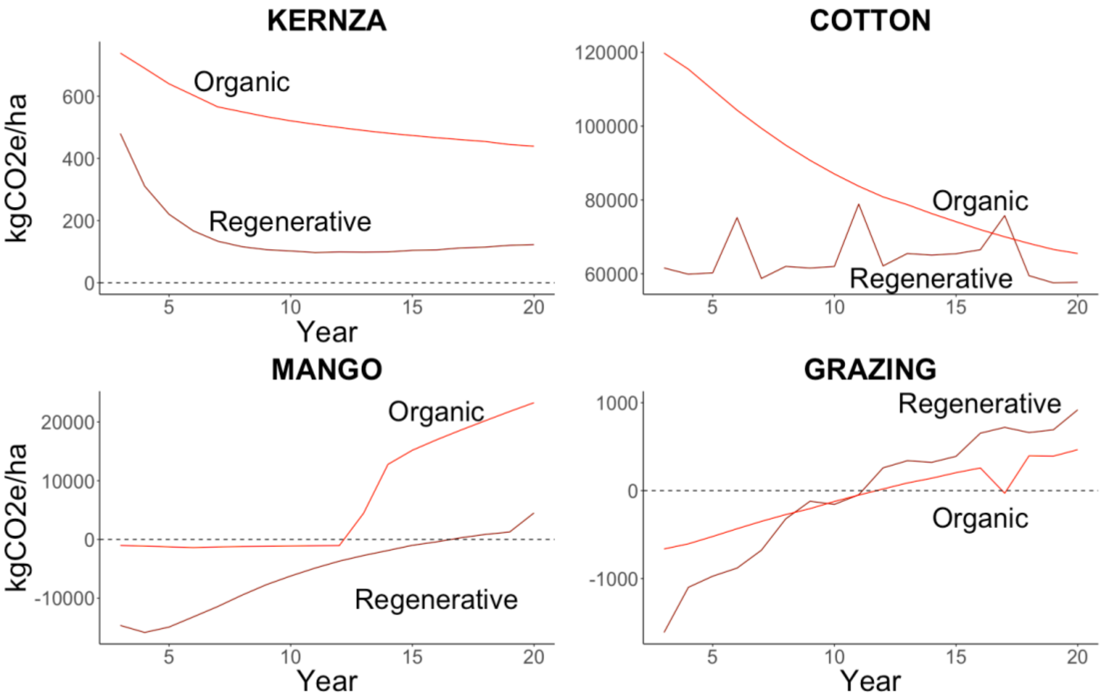


Figure 3. Time Series Plot of Net Greenhouse Gas Emissions: Year to year variation in the global warming potential of the four crops analyzed over 20 years

It is also important to analyze how RO practices affect the net GHG emissions of crop production. While increases in soil carbon have benefits to climate change mitigation, net GHG emissions provide a more complete picture of the practice's impact on climate from a soil level. It is important to note that this analysis only includes soil gas exchange and does not include GHG emissions such as the use of farm machinery or the production of fertilizer. With this in mind, RO practices have a much more variable effect on net GHG emissions when compared to organic agriculture (Figure 3). In some scenarios, RO models decrease overall net GHG emissions (as can be seen in Kernza and mangos). In other crops, net GHG emissions track similarly under RO and organic management, as can be seen in grazing and cotton.

In agricultural systems, it's important to consider all greenhouse gases associated with soil respiration (e.g. N_2O, CH_4). Some of the agronomic practices promoted as regenerative can actually increase the production of other greenhouse gases outside of CO_2. For example, the addition of compost can increase the production of nitrous oxide, which is 265 times more potent of a greenhouse gas than CO_2. Focusing on net GHG emission is important to better assess the impact of cropping systems.

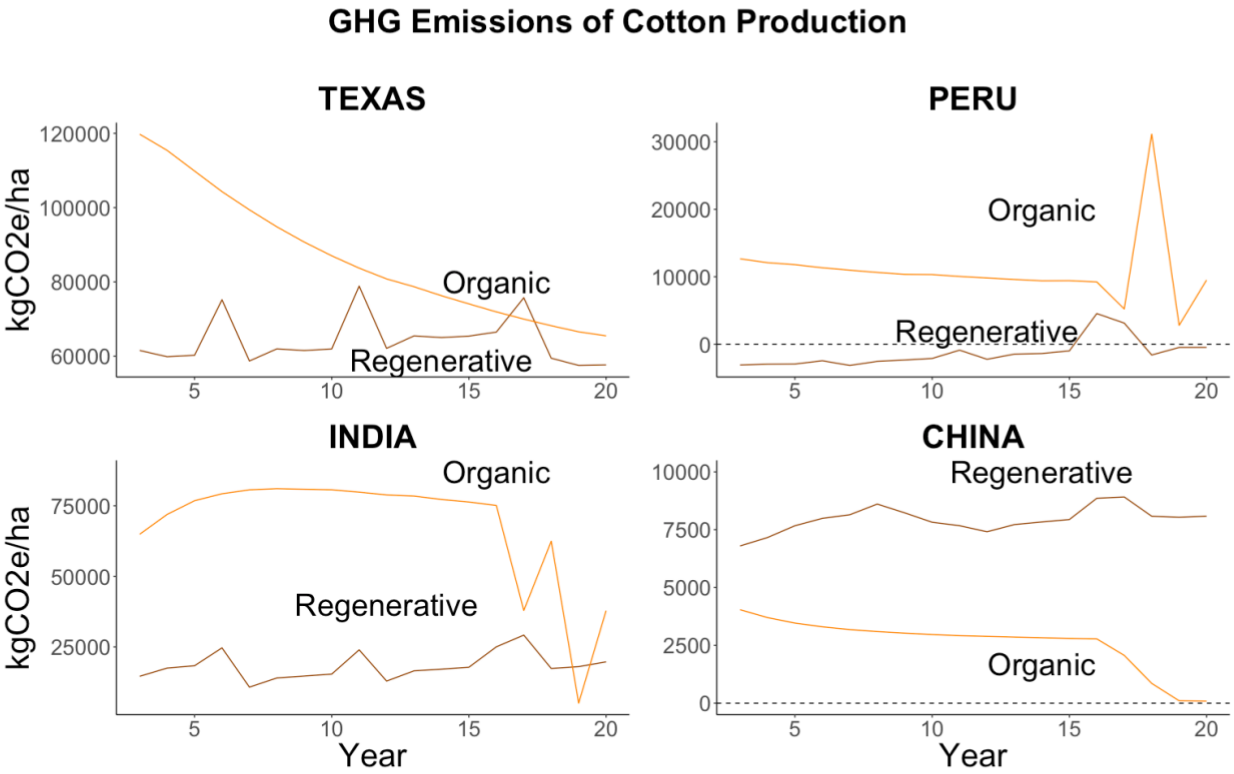


Figure 4. Time Series Plot of Net Greenhouse Gas Emissions in cotton production: Year to year variation in the net GHG emissions of four locations of cotton production analyzed over 20 years

Our preliminary analysis found that RO practices are successful at building soil carbon or limiting the loss of soil carbon in the case of cotton. When we accounted for all greenhouse gas emissions from the soil and analyzed the time series data, the benefit of RO agriculture became more unclear. It was also found that the location of cropping was extremely influential on net GHG emissions. Figure 4 shows the net GHG emissions of cotton modeled in Texas, Peru, India, and China. RO agriculture lowers overall GHG emissions in all locations except for China, which has higher emissions under RO management as compared to organic. The effect of location is similar through all modeled locations in other crops. This is likely due to differences in climate and soil properties across sites internationally. The time series graphs of each crop in all of their modeled locations are included in the appendix.

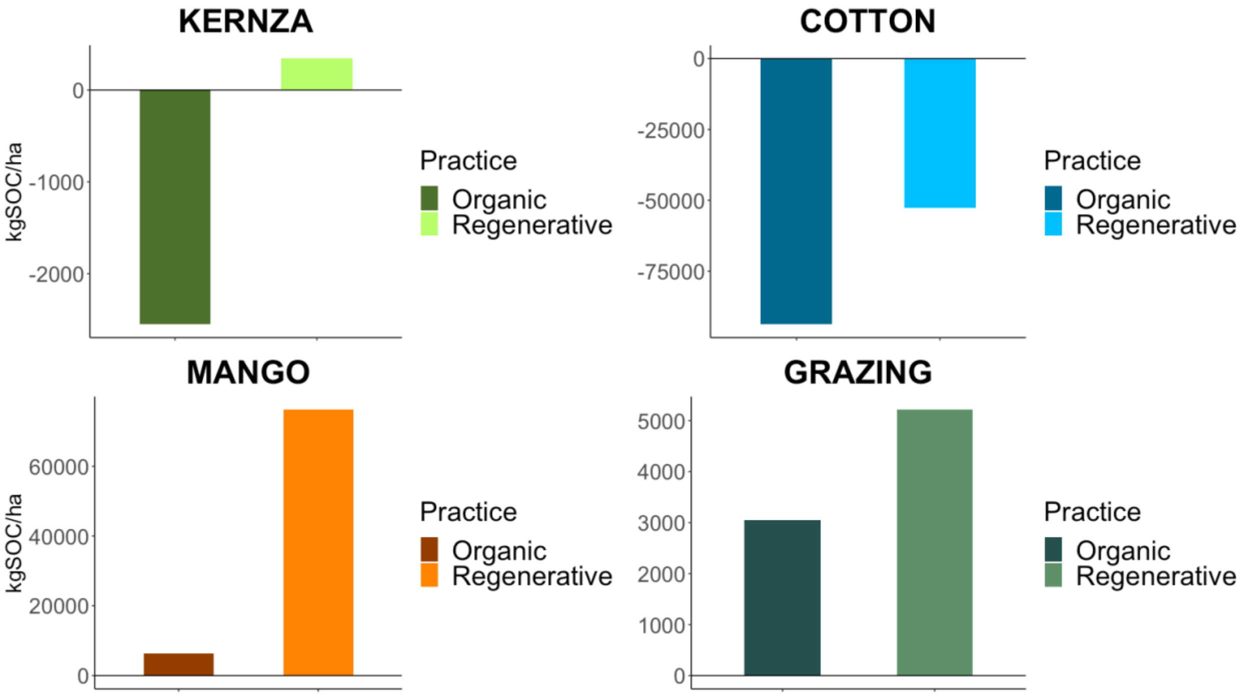


Figure 5. Sum of SOC over 20 years: Sum of the kg of soil organic carbon under regenerative and organic management over 20 years for the four crops analyzed

Figure 5 shows the total change in SOC under RO and organic management over 20 years. This is the sum of all the yearly changes in SOC within the modeled period. Negative values represent the total loss of SOC over 20 years and positive values represent the total gain in SOC over 20 years. Again, RO practices led to an increase in soil carbon, in some cases even reversing the fluxes of carbon from a loss of SOC to a gain in SOC (as shown in the case of Kernza). In total, after 20 years of production, cotton lost 44% less SOC under RO management, Kernza gained 113% more SOC under RO management, Mangos gained 115% more SOC under RO, and grazing on perennial grasses gained 71% more SOC under RO. The same effect of crop perennialism on SOC is again shown here. In the case of mangos, grazing, and Kernza, RO management can be shown to increase SOC sequestration. This is not the case in cotton production in which the land is losing SOC under both RO and organic management. Therefore, the effect of RO management on cotton production can be thought of as an emissions reduction (not a sequestration) as RO is limiting the loss of SOC when compared to organic management.

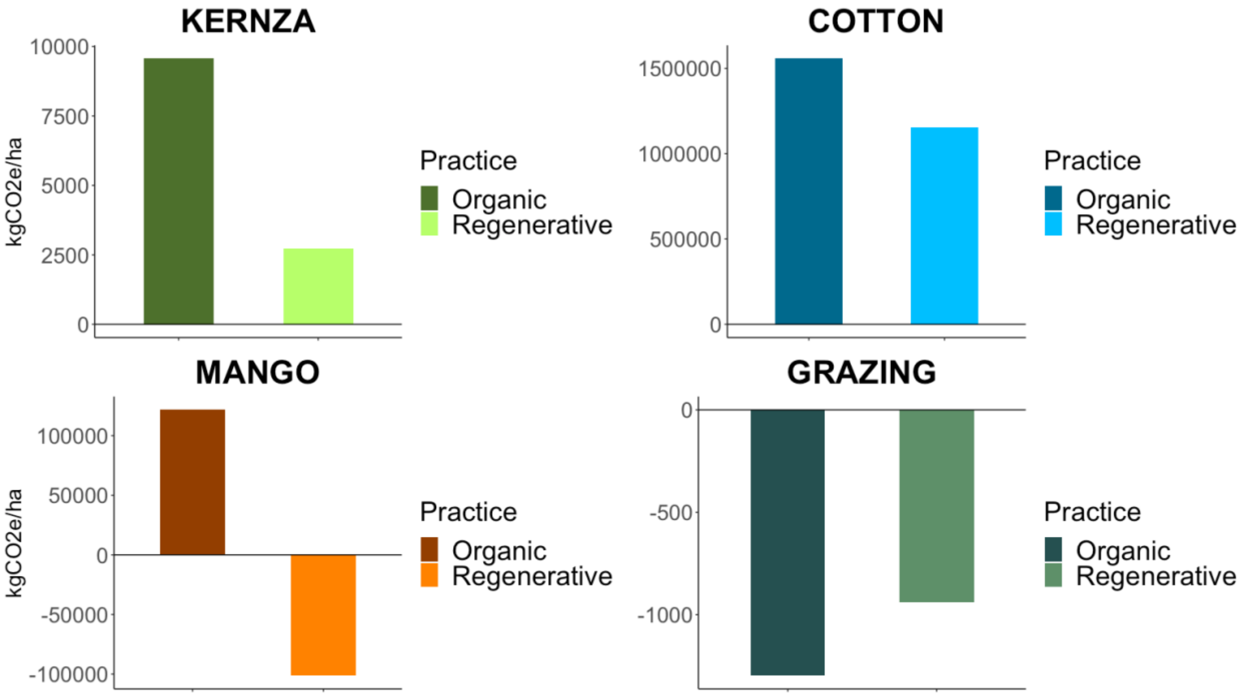


Figure 6. Sum of net GHG emissions: Sum of the global warming potential in kg CO_2e for the four crops analyzed over 20 years

Figure 6 shows the total GHG emissions after 20 years under both RO and organic production. In this plot, positive values represent a positive emission of GHGs, while negative values indicate that the system is sequestering more carbon than it is emitting all other GHGs (CH_4, N_2O, and CO_2) - meaning the crop has a negative emission of GHGs. In contrast to the time series plot shown in Figure 3, RO management was shown to lower GHG emissions in all crops except grazing. In cotton production, there was a 26% decrease in emissions; for Kernza production there was a 72% decrease; in mango production a 209% decrease; lastly in grazing RO practices lead to a 27% increase in total GHG emissions. While the GHG emissions under RO in grazing are still negative, they are more negative under organic practices. As we will discuss later, this is likely due to the increase in N_2O emissions from compost use. These results are also highly dependent on the location of cropping.

Individual GHG Fluxes

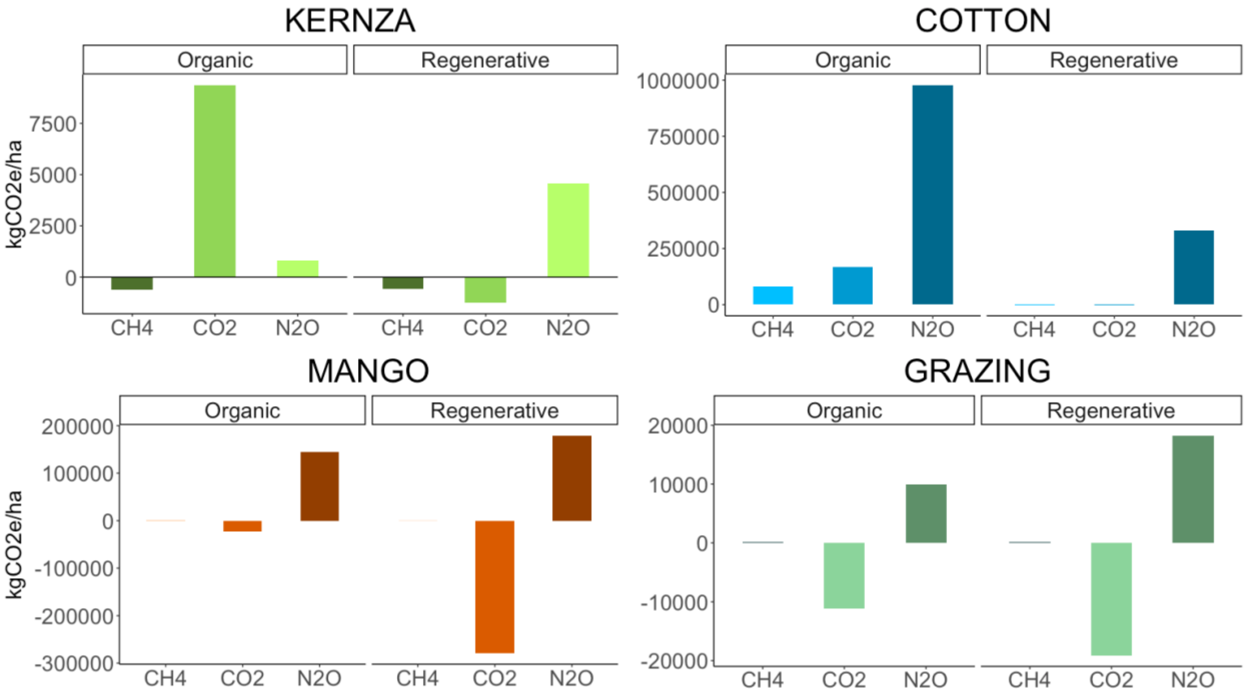


Figure 7. CH_4 & N_2O emissions: Sum of the CH_4, N_2O, & CO_2 emissions in kg CO_2e over 20 years under regenerative and organic management for the four crops analyzed

It was also important to analyze what gases were driving these changes in total GHG emissions. In Figure 7 the emission or sequestration of each gas were summed over the 20-year period. It can be seen that in all scenarios the outcome of total GHG emissions is mainly dependent on CO_2 sequestered and N_2O emitted. This highlights that if RO agriculture is to reduce total GHG emissions, the CO_2 sequestered must offset the N_2O emitted. This is important for RO practices such as compost and manure use which are associated with higher N_2O emissions.

Increases in GHG emissions for each crop (Kernza was modeled in Minnesota USA, cotton in Madhya Pradesh India, Bison in South Dakota USA, and mango in El Viejo, Nicaragua) seem to be driven by increases in N_2O emissions. Figure 7 shows that RO practices increased the amount of N_2O fluxed from the soil in all crops except for cotton. RO practices such as manure and compost applications increase the amount of N_2O fluxed in agricultural soils and drive increases in GHG emissions [21].

Impact of Location

The next portion of the analysis was done to find the impact of location on increases in SOC and net GHGs across the four crops. Kernza was modeled in Minnesota, Kansas, and Scotland. Cotton was modeled in India, Texas, China, and Peru. Mangos were simulated in India and Nicaragua. Finally, Bison grazing was modeled in South Dakota and Brazil. The goal of this analysis was to examine if location impacted RO practices' ability to increase the amount of SOC and decrease net GHG emissions. These locations were chosen as they are regions where Patagonia is currently sourcing these crops or could source crops in the future.

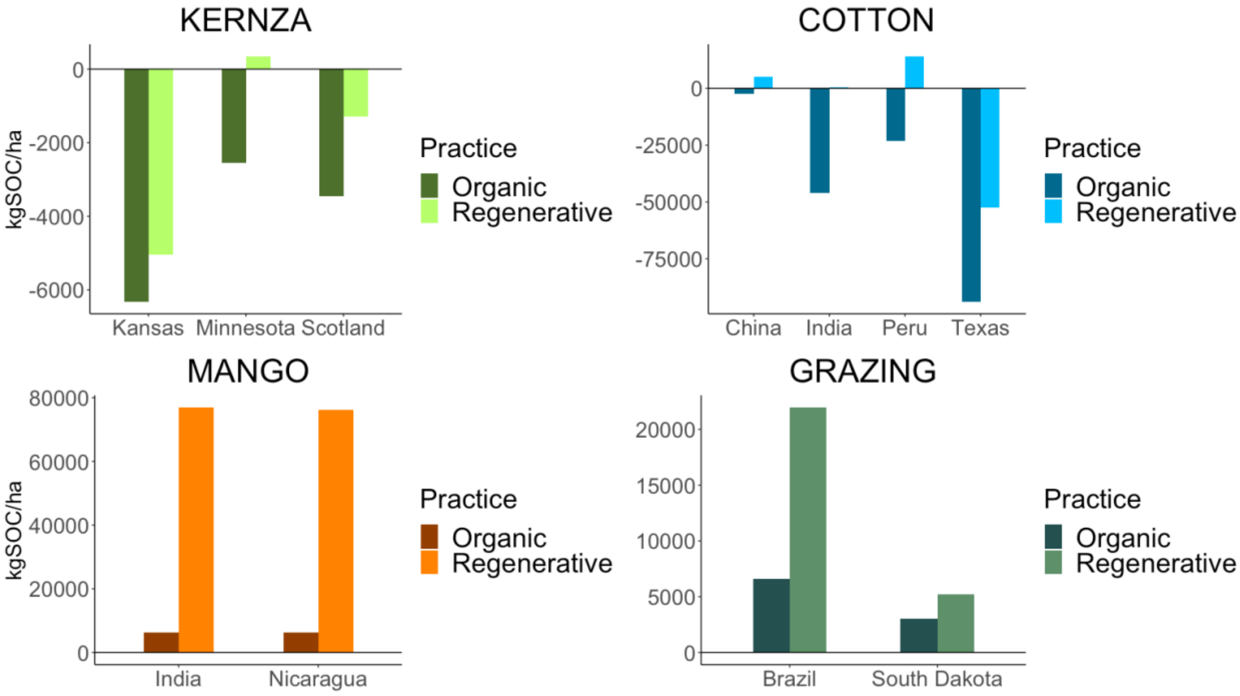


Figure 8. Impact of location on SOC: Sum of soil organic carbon in kgSOC/ha in all modeled locations over 20 years of regenerative and organic management

Figure 8 shows the total change in SOC over 20 years under both RO and organic management for each crop in different modeled locations. Looking at these results it can be seen that the conclusions drawn in Figure 5 are highly sensitive to cropping location. Although in all sites, RO management built more SOC (or limited the loss of SOC) when compared to organic management, the amount of SOC accumulated is variable across locations. This is because soils with higher clay content and bulk density (which are variable across location) affect soils' ability to sequester and store SOC [25].

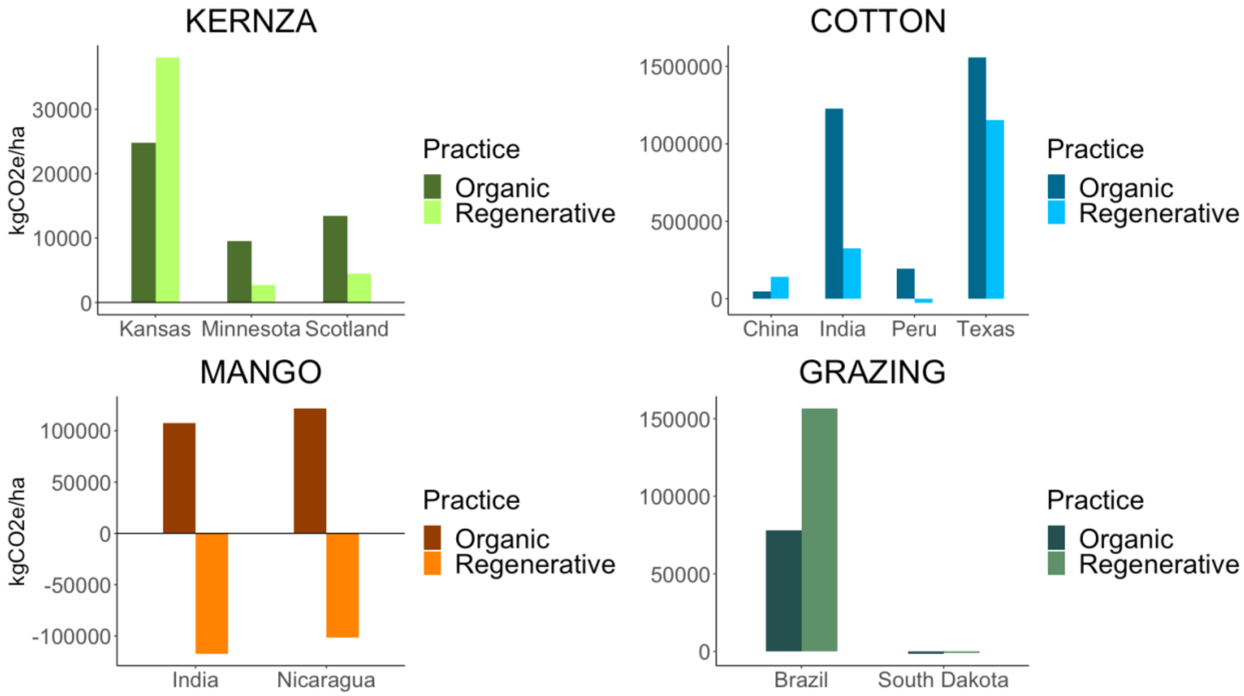


Figure 9. net GHG emissions Impact of location: Sum of Global Warming Potential (kg CO_2e) for each modeled location under regenerative and organic management for the four crops analyzed

Figure 9 shows how total GHG emissions vary across location and practice for each crop modeled. Unlike Figure 8, certain locations show a higher net GHG emissions under RO than organic management. For example, in cotton production RO management leads to a lower GHG emission in all locations except China. The same can be said for Kernza planted in Kansas. In Figure 9, it is again shown that RO grazing has larger net GHG emissions than organic grazing.

It can be concluded from these results that location can impact the rate at which SOC is accumulated in soil, and the overall net GHG emissions of production. Soil properties such as percent clay, bulk density, and initial carbon stock affect each location's ability to sequester and store SOC [25]. Climate events such as heavy rainfall can also affect the net GHG emissions of each location by fluxing more N_2O from the soil through the denitrification of compost and manure [25].

Sensitivity Analyses

After modeling for organic and RO practices of four different crops in multiple locations, sensitivity analyses were conducted to understand how changes in different parameters impact the outputs of soil organic carbon and net greenhouse gas emissions. These analyses also allow us to understand which practices had the highest impact on the outputs under which conditions to be able to inform ROC. Sensitivity analyses were conducted for 2 main variable types: climate conditions and crop management. Under crop management, three practices were analyzed: crop rotation, compost/manure addition, and tillage.

Climate:

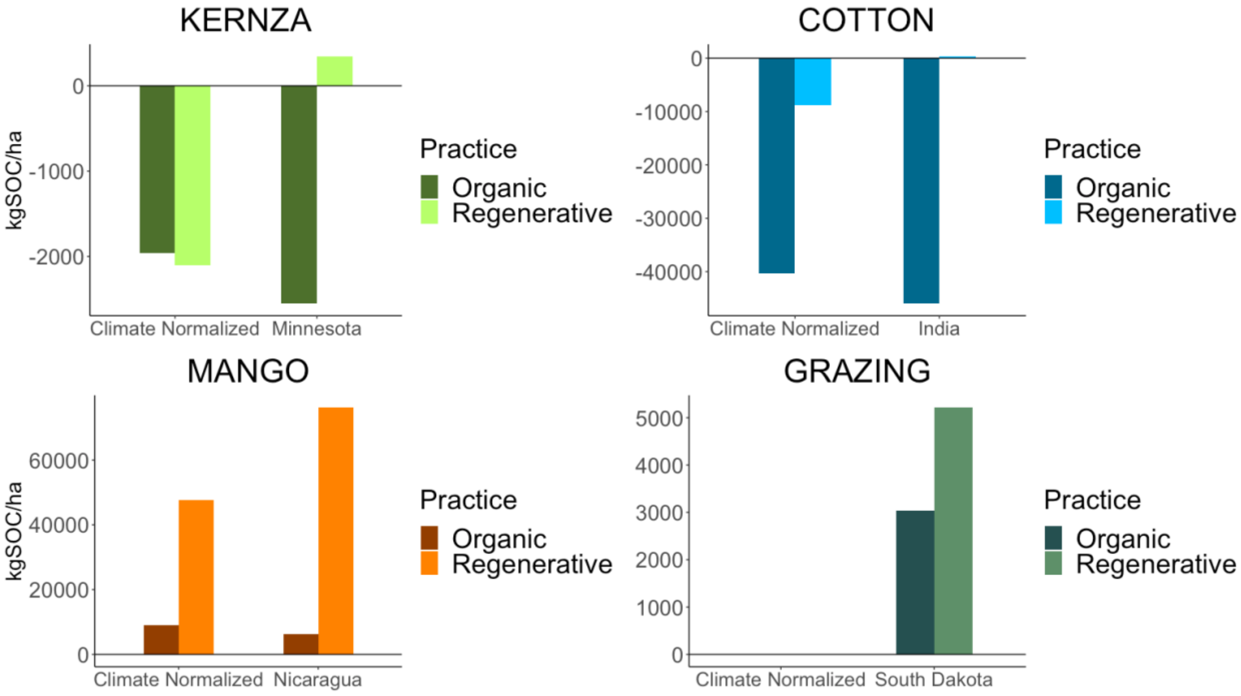


Figure 10. SOC impact of Climate: Sum of SOC in kgC/ha in one location with climate from that location and then run again in the same location with normalized climate data from the DNDC default climate data

To analyze the impacts of climate conditions, we ran both RO and organic scenarios for each crop with the same default climate data file (represented as "climate normalized" in Figure 10) included in the DNDC model for the main locations of production. The default data file was picked from simulated climate data files in the DNDC model. The same practices were applied to the same location with two different climatic inputs. First, SOC levels of climate normalized models compared to the previously modeled organic and RO scenario. The results are presented in Figure 10 above. Bar charts express the total change in SOC over 20 years.

All results had a marked effect on SOC accumulation and net GHG emissions in both RO and organic systems. This revealed SOC accumulation and net GHG emissions are highly sensitive to climatic conditions in the location of cropping. In the case of Kernza (as seen in Figure 10), the climate the crop experiences can actually change the soil from a source of carbon to a sink of carbon. This same variability is seen in GHG emissions when crops are exposed to two different climate scenarios in the same location (observed in Figure 11).

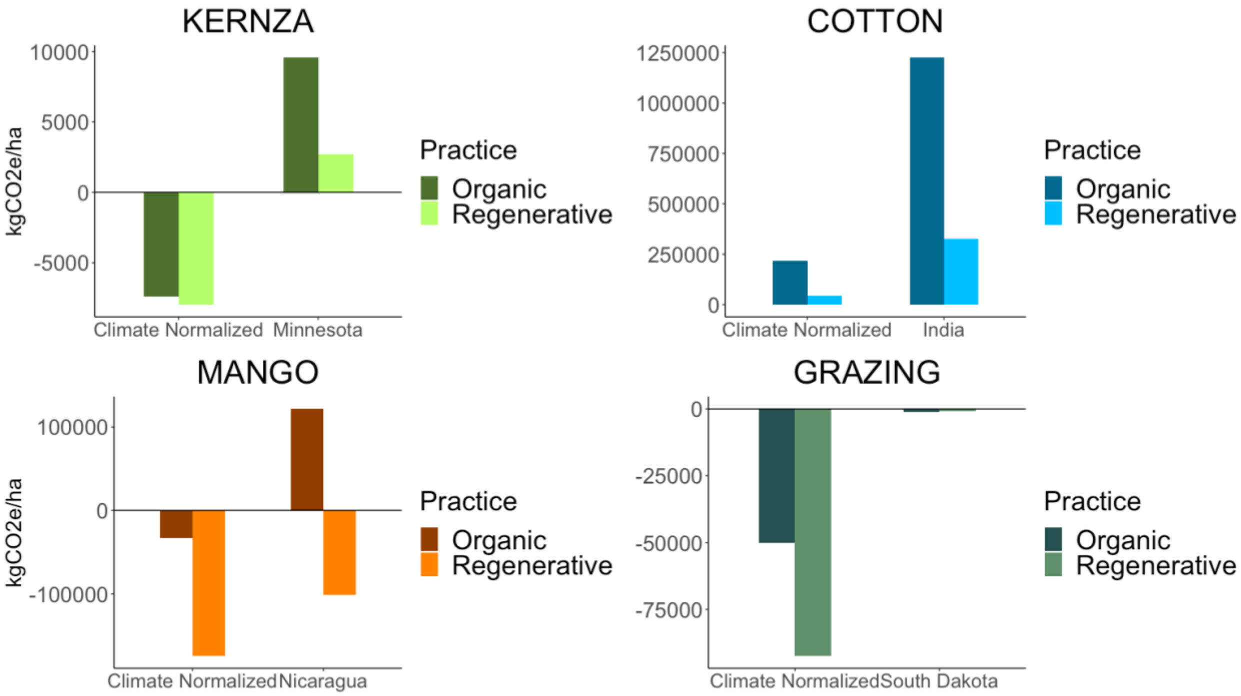


Figure 11. Net GHG emissions impact of climate: Sum of net GHG emissions (kg CO2e) in one location with climate from that location and then run again in the same location with normalized climate data from the DNDC default climate data

Compost & Manure:

After climate conditions, crop management practices were analyzed. First, the effect of nutrient management in RO practices on SOC and net GHG emissions was assessed. For bison grazing, Kernza wheat, and mango, RO practices include compost addition. In cotton production, farmland manure was added to the soil based on the data from the ROC pilot programs. The analysis was conducted for the main locations Patagonia sources the product: Kernza was modeled in Minnesota, USA; cotton in Madhya Pradesh, India; Bison grazing in South Dakota, USA; mango in El Viejo, Nicaragua. For each crop, the nutrient amendment was removed from the RO scenario, and the model was rerun. The results of the total change in SOC and net GHG emissions are presented in Figures 12 and 13 below.

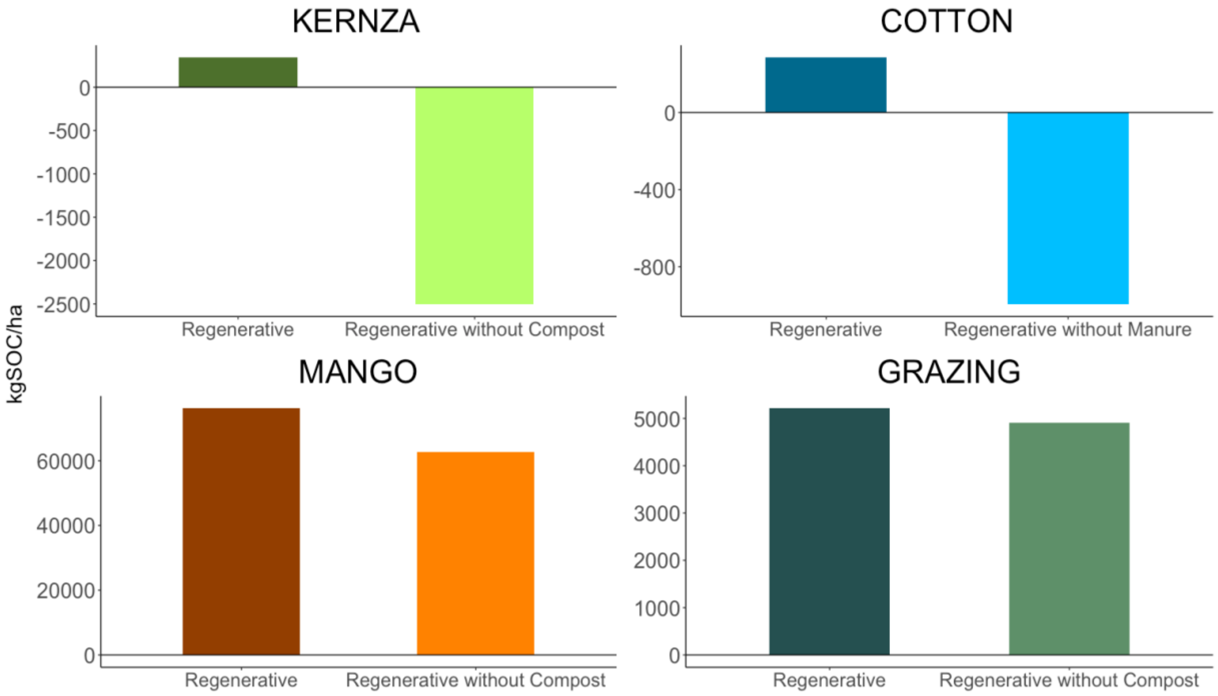


Figure 12. Impact of compost on SOC: Sum of SOC in kgC/ha in regenerative management with compost removed

The effect of nutrient management on SOC varied across crops (Figure 12). For Kernza, there was a 114% decrease in the amount of soil carbon with the removal of compost. For cotton, the removal of manure led to a 129% decrease in the amount of SOC accumulated. Compost removal for mangos led to a 21.6% decrease in soil carbon. Finally, for grazing, the removal of compost led to a 6.2% decrease in the amount of soil carbon accumulated.

In all cases, soil organic carbon in the RO scenario was greater than the scenario without the nutrient amendment. Lal (2003) states that soil organic carbon concentration can be increased by 15 to 120% by soil fertility management practices. The amount of increase in SOC concentration depends on the crop type, crop rotation, duration, and other site characteristics [27].

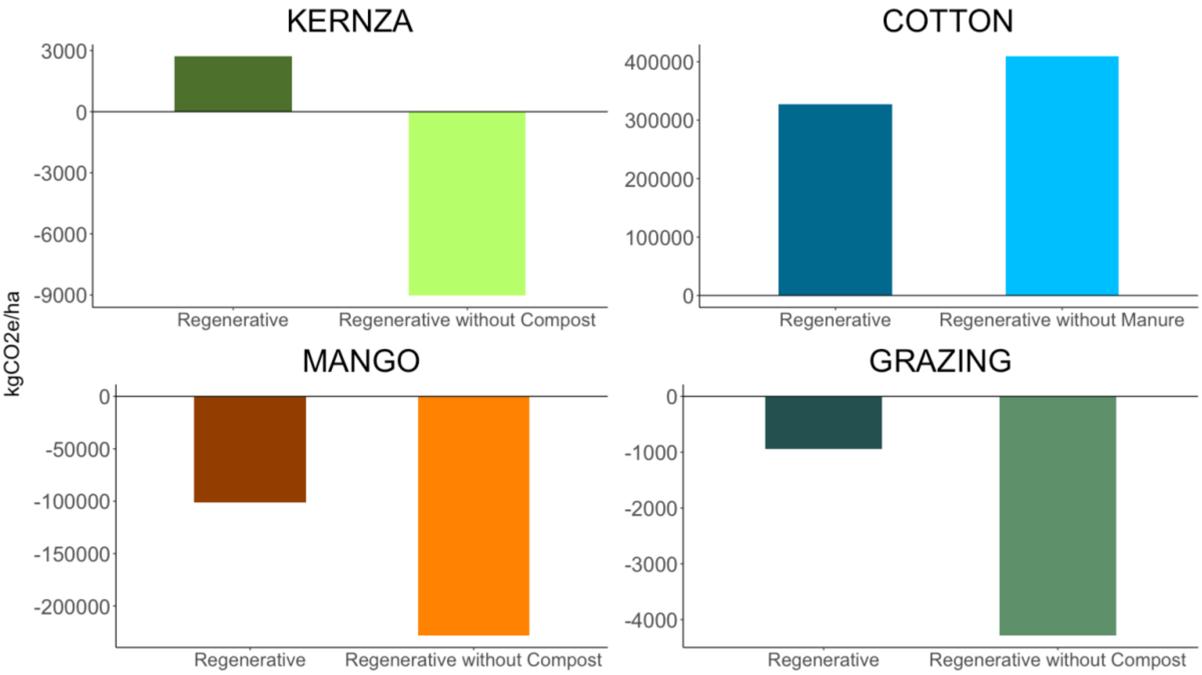


Figure 13. Net GHG emissions impact of compost: Sum of net GHG emissions (kgCO_2e) in regenerative management with compost removed

Net GHG emissions did not show a consistent pattern across different crops. For Kernza, there was a 130% decrease in net GHG emissions after compost was removed. In cotton, the removal of farmyard manure increased net GHG emissions by 20%. When growing mangoes, there was a 55% decrease in net GHG emissions when compost was removed. Finally, the removal of compost for bison grazing caused a 77% decrease in net GHG emissions. Now comparing results in Figures 12 and 13, compost use in a crop such as perennial grasses for grazing may be unwise. This is because compost use in grazing is boosting SOC by 6.2% but the removal of compost leads to a 77% decrease in overall GHG emissions. This opens the door for inefficiencies within the ROC in which the cost of a practice (in the form of increased GHG emissions) may outweigh the benefit (represented by increases in SOC) but is still promoted in the ROC framework because they increase SOC.

The above patterns can be explained by Lal's argument that the increase in SOC depends on the combination of practices used and on-site conditions. The increase in productivity due to soil fertility management depends on the soil type, fertilizer type, and the crop type. For cotton production, farmland manure was used as fertilizer whereas other crops used compost. The emissions from fertilizers depend on the fertilizer type. In cotton's case, the emissions from the fertilizer did not surpass the benefits from increased benefits of soil carbon sequestration. As soils become more productive, it leads to an increase in biomass and increased soil organic carbon stock, which then potentially leads to reduced greenhouse gas emissions. Hence, the net greenhouse gas emissions of regenerative organic cotton production were lower than the scenario without nutrient amendment. The fluctuations in net GHG emissions can be explained by the N_2O fluxes from the application of compost [33]. For every crop except cotton, the application of compost boosted the amount of carbon that is accumulated in the soil but also increased the net GHG emissions of that crop. For cotton, SOC increased and net GHG emissions dropped after compost was applied. This indicates applying compost will have a positive climate impact if the amount of increased carbon stored outweighed the amount of N_2O emitted from the compost.

Tillage:

Tillage is practiced only in cotton production. Therefore, a sensitivity analysis was conducted across four different locations of cotton production: China, India, Peru, and Texas. ROC requires no-till or reduced tillage, therefore RO cotton production was modeled as no-till. To model the effect of tillage on SOC and GHGs, tillage with a depth of 30cm was added to the RO scenario. The results for total change in SOC and net GHG emissions are represented in Figure 14 and 15 below, respectively.

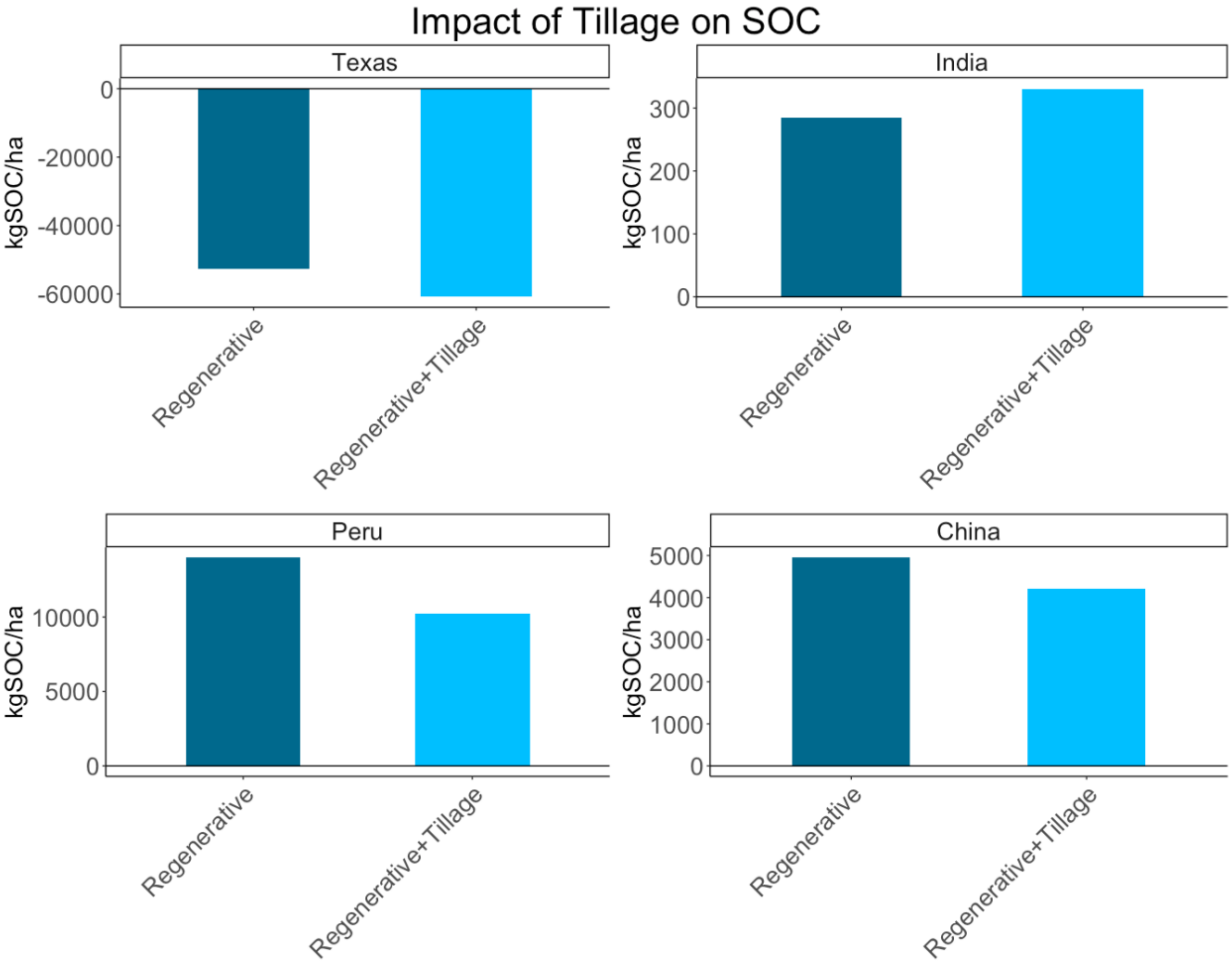


Figure 14. SOC impact of tillage: Sum of SOC in kgC/ha under regenerative management with tillage applied

The effect of tillage on SOC showed mixed results. Adding tillage in China led to a 17% decrease in SOC over 20 years; in India tillage contributed a 13.5% increase in SOC; in Peru tillage led to a 37% decrease in SOC; in Texas tillage led to a 13.5% decrease in SOC. These results show a mixed effect of tillage on soil carbon that varies across locations.

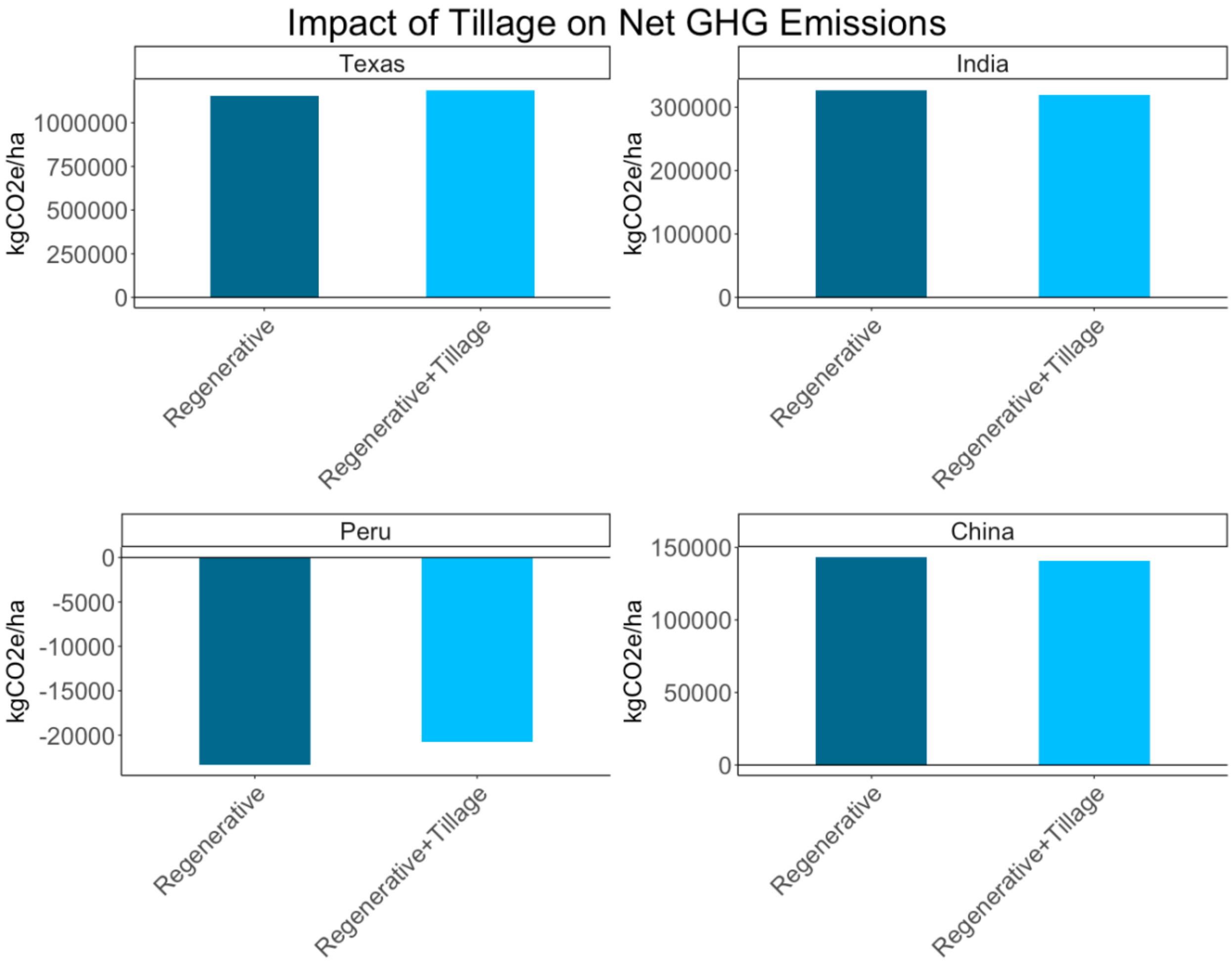


Figure 15. Net GHG emissions impact of tillage: Sum of net GHG emissions (kgCO$_2$e) under regenerative management with tillage applied

Figure 15 shows net GHG emissions with and without tillage in different locations. In China, tillage led to a 1.6% decrease in net GHG emissions; in India, a 2.3% decrease in net GHG emissions; in Peru, a 12.7% increase in net GHG emissions, and in Texas a 2.8% increase in net GHG emissions. As with SOC, the impact of tillage on net GHG emissions is varied and unclear from the modeled results in the four locations tested.

The literature on the impacts of tillage is also highly varied. Baker (2007) states that no-till has little effect on soil organic matter, other than altering the distribution profile. In the no-tillage scenario, the SOC is accumulated in the topsoil, whereas in the tillage scenario it is moved to the deeper layers [14]. Therefore, the sampling depth of the experiments affect the SOC measurement. Johnson (1985) argues that under no-till, soil temperature is lower, thus reducing growth of biomass [34]. The soil also has a higher bulk density and is harder to penetrate in no-till, which prevents roots from expanding deeper into the soil. The results of the analysis could be improved by integrating these factors in the DNDC model. However, it is challenging because the loss or increase of the carbon due to tillage occurs due to the interactions between different processes. Different systems of different soil temperature, different soil carbon distribution and bulk density might respond differently to the application of tillage. Another challenge for testing the impact of tillage in the field as the depth of sampling can be highly influential to the results drawn from tillage experiments.

Tillage also had an effect on net GHG emissions. However, there was not a consistent pattern across different locations. Net GHG emissions in the tillage scenario was greater than the no tillage scenario in Texas, while it was lower in India. The net GHG emissions is the combination of SOC change (carbon negative), CO_2 flux, N_2O flux, and CH_4 flux. Dendooven (2012) states that N_2O emissions are the result of the combination of many interacting processes, hence it is hard to detect the difference between no tillage and tillage scenarios. In the no-till scenario, higher soil organic matter will result in more emissions, while better soil structure and lower temperature will decrease the emissions [30]. Overall, N_2O emissions will depend on how soil structure and soil organic matter changed, and it is unclear how much of it is due to tillage. Therefore, it is difficult to make a conclusion of the net GHG emissions of tillage practices.

Our analysis concludes that it is unclear whether there is a difference in soil organic carbon across soil depths. The DNDC model predicts the soil profile down to 50 cm depth. Although the total soil organic carbon over the years did not significantly decrease with the addition of tillage, it is important to note that no-till still has other benefits for the soil, such as reduced erosion rates, reduced production costs, and reduced consumption of fossil fuels [14]. To further improve the results for net GHG emissions, gas exchange studies can be conducted to observe how no-till affects overall greenhouse gas emissions.

Crop Rotation:

To analyze the impact of crop rotation and to be able to detect which crop combinations result in the most changes in SOC and net GHG emissions, we reran the regenerative scenarios, this time removing one cover crop at a time. The types of crops removed are tabulated below in Table 3 for the four crops in the main locations.

Table 3. Crop Rotation Scheme for Each Crop Production

	Regenerative	**Four Crops**	**Three Crops**	**Two Crops**	**Monocrop**
Cotton in India	Cotton, Corn, Legume hay, Legume hay (Perennial), Apple Trees	Cotton, Corn, Legume hay, Legume hay (Perennial)	Cotton, Corn, Legume hay (Cover crop)	Cotton, Corn	Cotton
Grass in South Dakota	Perennial Grass, Trees, Rye, Legume Hay, Alfalfa	Perennial Grass, Trees, Rye, Legume Hay	Perennial Grass, Trees, Rye	Perennial Grass, Trees	Perennial Grass

Mango in Nicaragua	Mango Trees, Legume hay, Tomato	-	-	Mango Trees, Legume hay	Mango Trees
Kernza Wheat in Minnesota	Kernza Wheat, Alfalfa, Pear Trees	-	Kernza Wheat, Alfalfa, Pear Trees	Kernza Wheat, Alfalfa	Kernza Wheat

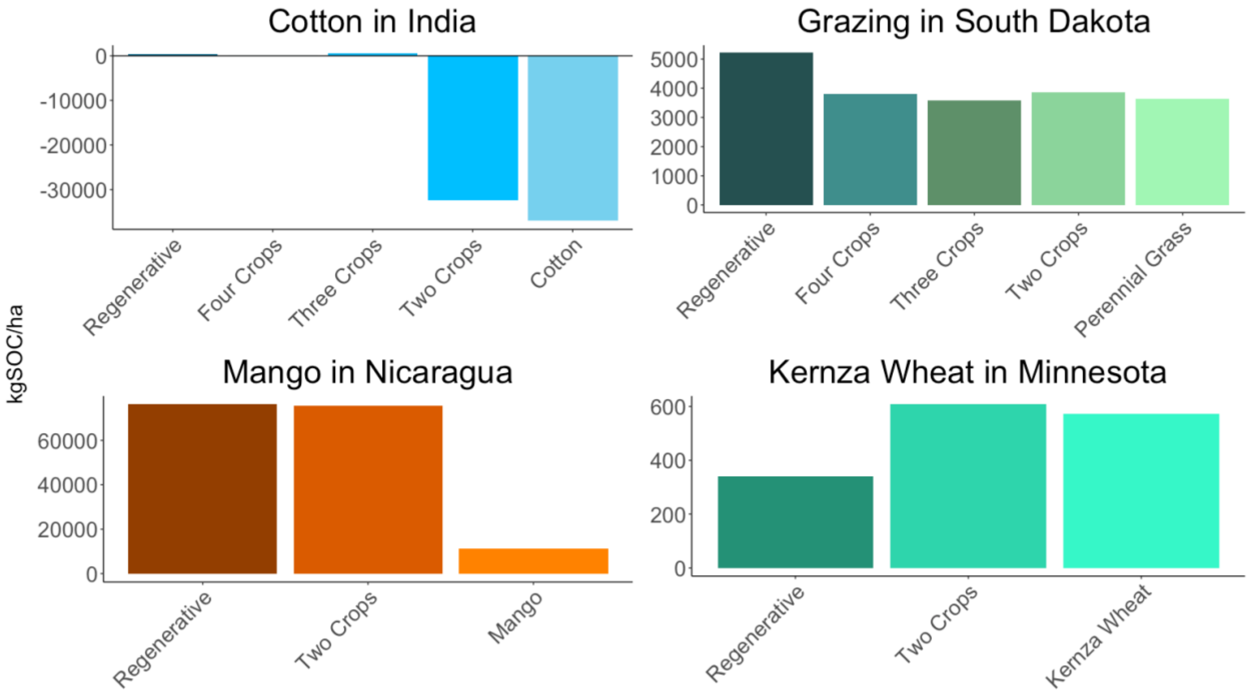


Figure 16. Impact of crop diversity on SOC: Change in soil organic carbon in kgC/ha when the diversity of crops planted is decreased

For cotton, grasses, and mango, increasing the functional diversity of the crops increases soil organic carbon. For Kernza wheat, addition of trees resulted in a decrease in soil organic carbon. Figures 16 and 17 show that the magnitude of impact can differ by location and crop type. Lal (2001) states that the effects of crop rotation on soil organic carbon depends on tillage, antecedent SOC pool, and soil properties [36]. In the scenarios modeled, all the crops were simulated in different locations with different soil carbon pools and properties, which might lead to the differences in the percent increases.

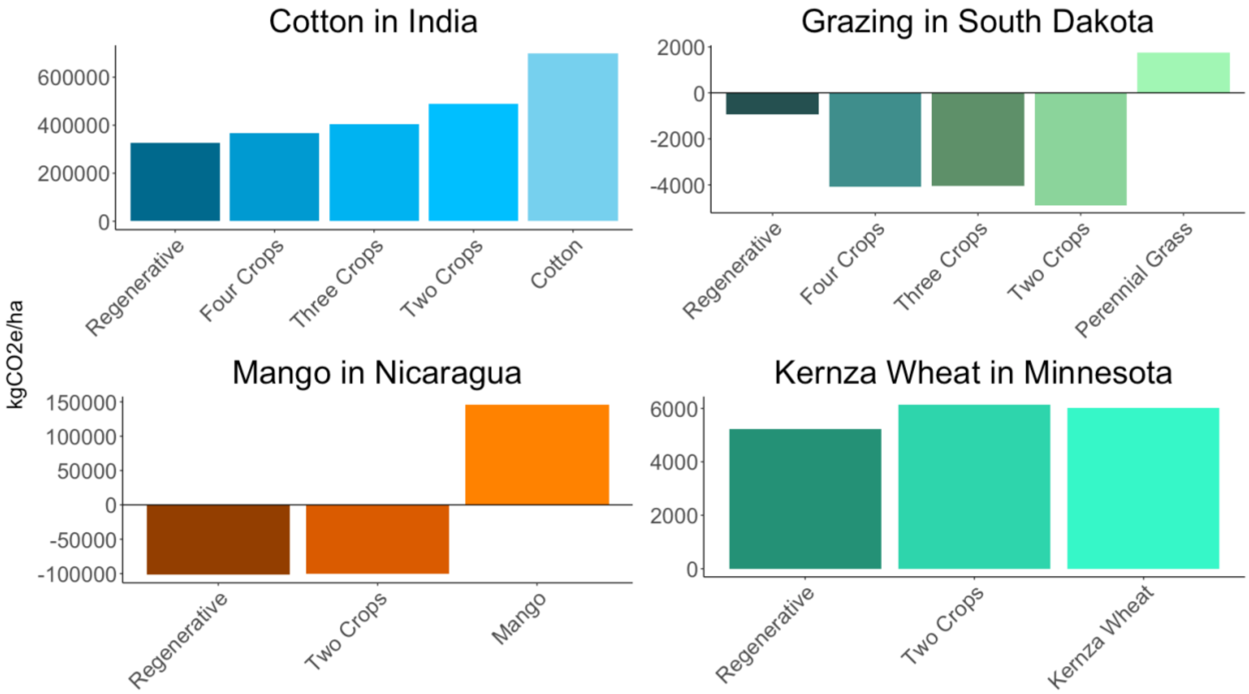


Figure 17. Impact of crop diversity on net GHG emissions: Change in global warming potential in kgCO2e when the diversity of crops planted is decreased

For regenerative cotton and mangoes, a decrease in crop diversity corresponded to an increase in net GHG emissions. In regenerative grasslands, the lowest emissions were associated with just planting perennial grasses and trees as windbreaks. RO Kernza had lower emissions than monocrop Kernza, however, emissions were highest when Kernza was planted with one other crop. Across the board, regenerative models had lower net GHG emissions than the monocrop models.

For both cotton and mango scenarios, the addition of legumes resulted in substantial SOC gains. Further addition of legumes and trees had lesser impact. This is consistent with Marek (2003)'s argument that deep root systems with higher root-shoot biomass ratio (such as legumes) are more suitable for soil carbon sequestration, due to improved soil structure and micro aggregation [27]. It is also important to note that the first legume added to the cotton scenario was used as a cover crop. According to King, relative to crop rotations of only grains, perennial cropped and cover cropped rotations increased SOC concentrations by 6.2% and 12.5%, respectively [31]. Bison grazing and Kernza cases also supported King's argument. The addition of alfalfa - a perennial legume - led to a great increase in soil carbon. Much of the benefit of legume crops is their ability to fix nitrogen into forms other plants can use. Soil carbon sequestration has a close relationship with C:N ratios in the soil [37]. If more nitrogen can be added to the soil by planting nitrogen-fixing cover crops, then soil carbon sequestration will increase. A co-benefit of planting nitrogen fixers is the ability to use less nitrogen fertilizer [18].

Comparison of DNDC and COMET models:

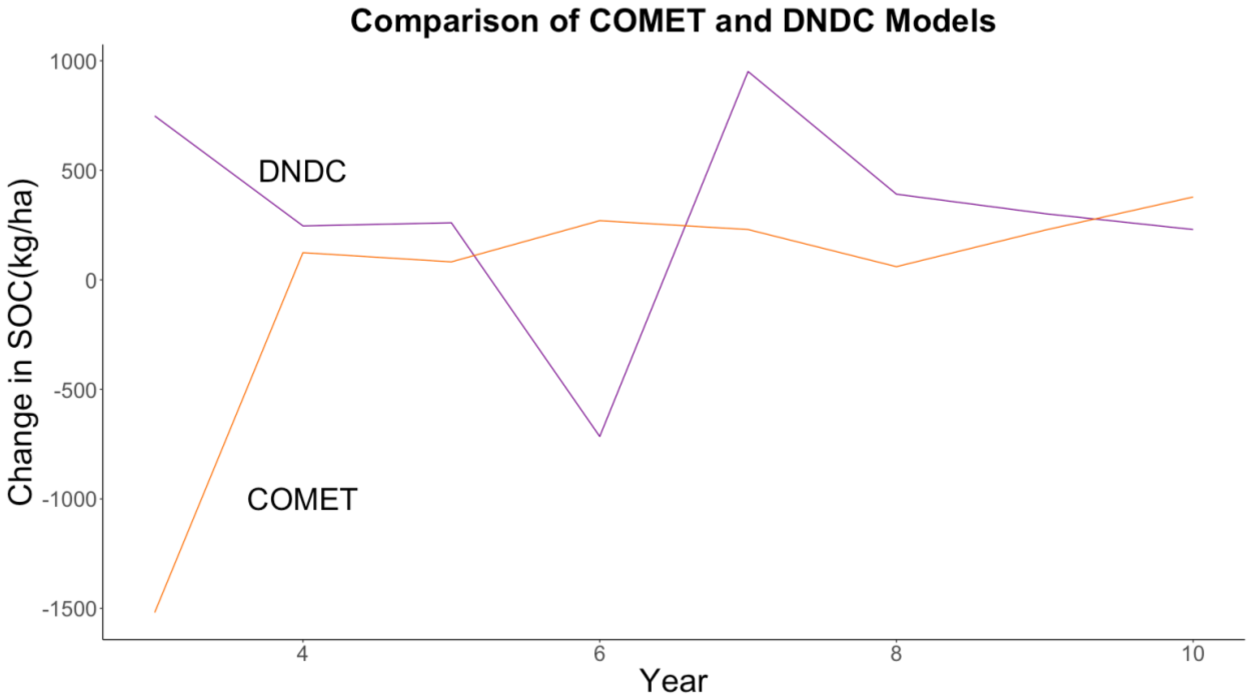


Figure 18. Comparison of model results of yearly change in SOC in kgSOC per ha over 10 in both the DNDC and COMET model.

To ensure that the model results were not biased based on model selection, results from the DNDC model were compared to results from the COMET model used by the USDA. The RO cotton scenario in Texas was compared in both models, and the outcome of yearly change in SOC was compared over 10 years. One of the reasons the COMET tool was not chosen for analysis was because it is only able to model scenarios 10 years into the future, which is why this comparison of models is over a 10-year period. As seen in Figure 18, the models do not track exactly but trends are similar. This leads us to believe the results of the previous analysis should not be substantially biased by model selection.

Comparison of Regenerative, Organic, and Conventional:

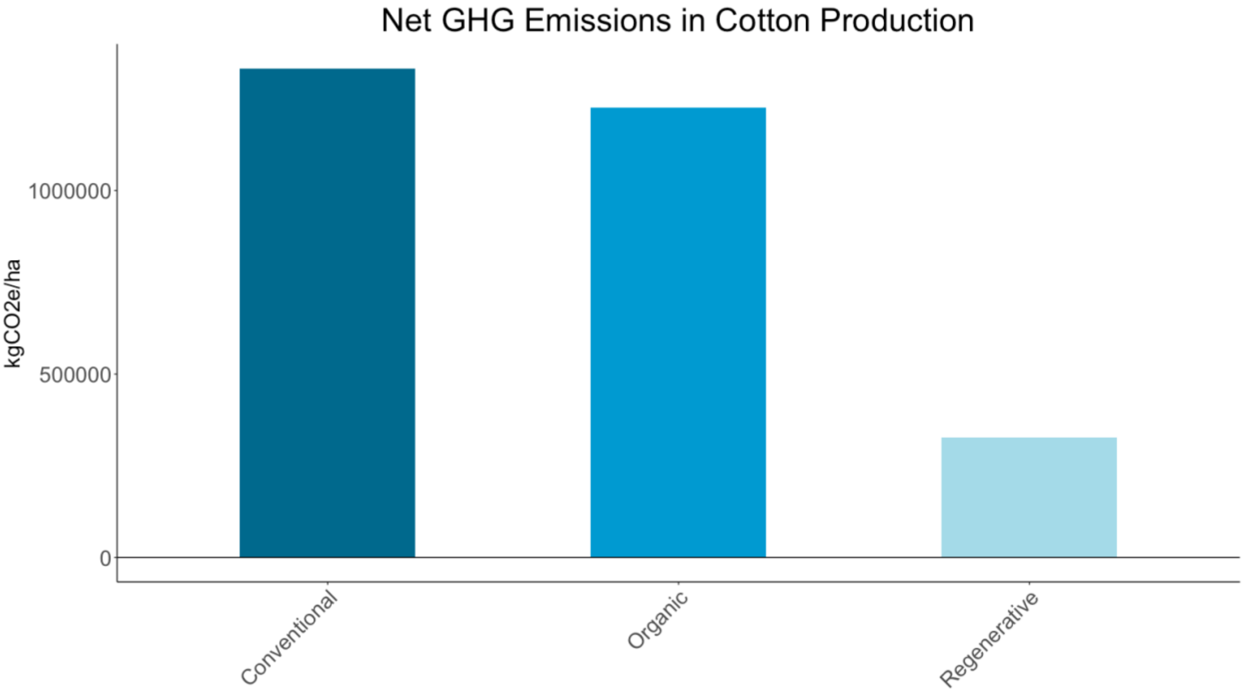


Figure 19. Comparison of Net GHG emission of cotton production under Regenerative, Organic, and Conventional management.

To analyze how RO and organic compared to conventional production, the model for cotton production in India was run for regenerative, organic, and conventional management scenarios. In the conventional scenario, synthetic fertilizer was applied while all other practices were held constant. The total change in SOC was no different between organic and conventional production, and the loss of carbon was reduced by the same amount as when transitioning from organic to RO practices. There was a difference between all three management scenarios when examining net GHG emissions as shown in Figure 19. There is a decrease in emissions when moving from conventional to organic management, and an even larger reduction in emissions when transitioning to fully regenerative management.

Yields

A sensitivity analysis on yields between organic and RO was conducted. The literature (referenced in the Background section above) indicates yields should theoretically increase from RO practices like cover cropping and compost use. The DNDC output on yields for cotton, mangos, and Kernza indicated no major difference between the yields of organic and regenerative scenarios.

However, we modeled scenarios where there are hypothetical drops in yields from RO cotton compared to organic cotton (from 1% yield drop to 50% yield drop) and accounted for the GHG emissions from the land-use change required to convert more land to cropland as a result of decreased yields. We used factors from Hergoualc’h et. al’s 2013 study examined land-use change GHG emissions in Southeast Asia and calculated that converting one hectare of degraded forest to cropland would result in 48,848 kg CO_2e emissions from carbon dioxide, methane, and nitrous oxide [41]. We assumed a 10% drop in yield from regenerative would require a 0.1 hectare increase in land use. The emissions from converting 0.1 hectares of degraded forest to cropland were added to the Year 1 impact for RO cotton. This increase in land area cropped will proportionally increase yearly soil emissions, so annual soil emissions were multiplied by 1.1. The total emissions were graphed below. This calculation was repeated for a 20%, 30%, 40%, and 50% drop in yields. These results were then compared with the emissions from organic cotton production in India. The results of this sensitivity analysis are shown below in Figure 20.

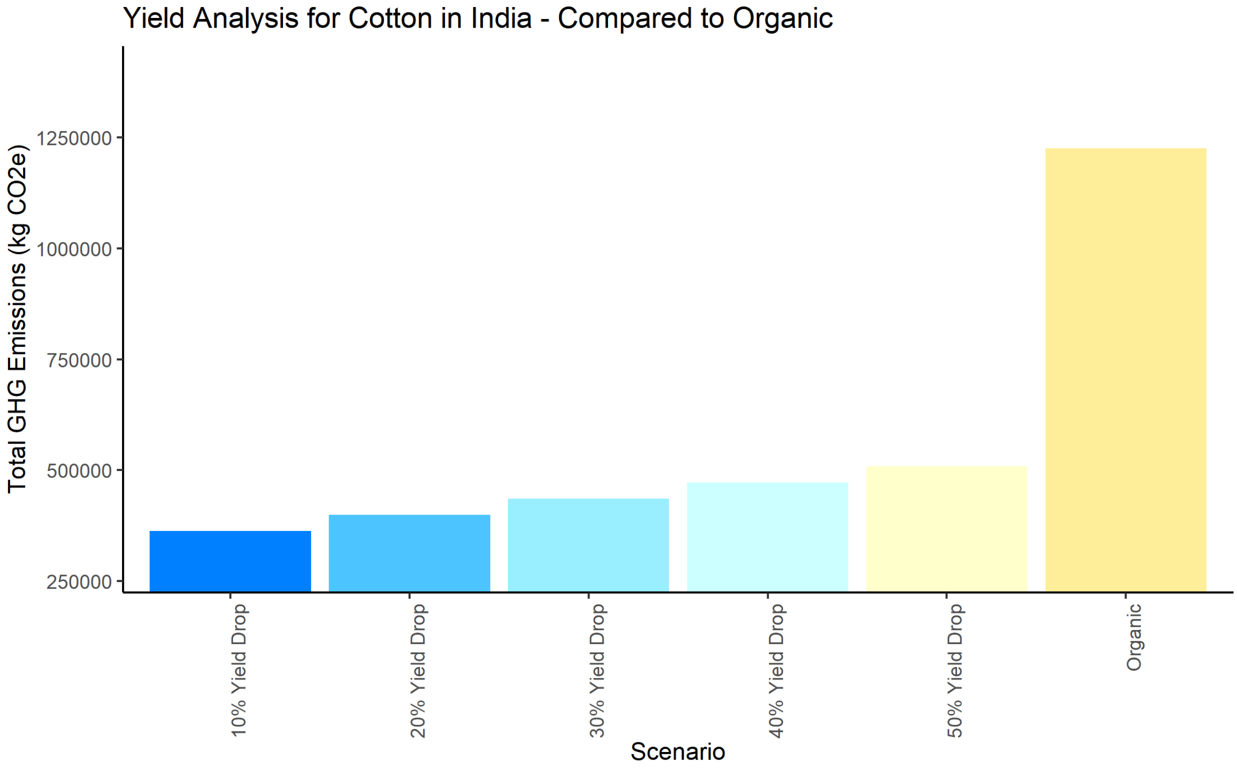


Figure 20. Comparison of emissions from regenerative organic cotton yield drops and emissions from organic cotton production in India.

LIMITATIONS

This assessment has several potential limitations in both the data and the model used. Agricultural management data was available only for cotton production in India. We assumed the same practices are used in all four locations of cotton production. For the rest of the modeling, we obtained data from the literature. Unfortunately, the literature was unable to provide data for initial soil organic carbon stock, bulk density, soil structure. Instead, we relied on satellite data for the region. Previous literature indicates that the model outputs are highly sensitive to the changes in bulk density. Consequently, it would be beneficial to collect farm-level soil property data for the future research to increase the accuracy of the model.

Another limitation is the lack of on-site soil organic carbon data to validate the modeled results. It is important to compare modeled and measured soil organic carbon in various soil depths to test and improve the DNDC model for the future research.

The model requires daily climate data including minimum and maximum temperatures, precipitation, and wind speed. Sufficient data was found only for U.S. locations. For international locations such as India and Nicaragua, monthly averages were used instead of daily temperatures and precipitation, while wind speed was not included in the inputs.

Besides these data limitations, the DNDC software does not allow access to examine and modify the source code. This made it difficult to understand the impacts of interacting processes on the outputs. Also, it limits the ability to make modifications to specific situations. For example, DNDC only accounts for 50 cm root depth; however, the crops modeled in this study (particularly perennial grass, Kernza wheat, and mango trees) have roots that grow far deeper than 50 cm depth. Therefore, the models may underestimate the total soil organic carbon for the three crops listed. However, it is also important to note that the other soil carbon models only allow for 20-30 cm, and DNDC is the best available model for deep-rooted systems.

Apart from the listed limitations, hemp, the fifth crop that Patagonia is interested in practicing RO agriculture for, is left out from this analysis. DNDC does not include hemp as one of the built-in crops, and sufficient crop property data to create the data inputs in DNDC was unavailable.

DISCUSSION

As climate change and food security become more severe global concerns, appropriate agricultural management practices will be instrumental to tackle these problems. Our project provides guidance on appropriate management practices for crops in Patagonia’s supply chain. Based on the modeling and analysis, we recommend Patagonia look for opportunities to transition from annual cropping systems to perennial systems to increase root biomass and root exudates. Kernza wheat, for example, shows that it might be beneficial to examine avenues to perennialize fiber crops in the supply chain. For example, switching to perennial linens or perennializing cotton might be very impactful. Cotton makes up the largest part of Patagonia’s agricultural supply chain. Even though practicing RO decreases the loss of soil organic carbon relative to organic practices, cotton production will still behave as a source of carbon dioxide to the atmosphere. Therefore, looking for alternative materials or perennializing cotton will have a great impact on Patagonia’s aim to address climate change through agriculture.

The analysis showed that RO has many benefits if adjusted and applied according to the specific site conditions. In general, crop rotation and cover cropping led to an increase in soil organic carbon and decrease net greenhouse gas emissions. Addition of compost/manure also increased soil organic carbon due to increase in soil productivity and biomass. However, the greenhouse gas emissions were more variable across different fertilizer types, application rates, and site conditions. The main driver of the GHG emissions was N_2O emissions. According to previous studies, N_2O emissions are affected by fertilizer type, application rate, crop type, soil properties, irrigation systems, temperature, and rainfall events [42]. In our modeling, the differences between the sites within the same crop can be explained by different soil properties and climate events. The differences in the effects of fertilizer across crops has a more complex structure and stems from the combination of fertilizer type, application rate, crop type, soil properties, irrigation systems, temperature and rainfall events.

Heavy rainfall events and wet rainy seasons cause an increase in N_2O emissions due to denitrification [43]. Similar patterns are also seen in irrigated systems. Drip-irrigated soils generally have lower N_2O fluxes compared to surface furrow where the soil receives high-water applications [44,45]. In general, if the soil receives water in lower quantities and its applied equally, the N_2O emissions will also be lower.

There is no scientific consensus around the relationship between fertilizer rates and N_2O emissions. The IPCC proposes a linear relationship, whereas experimental studies show that the relationship might be non-linear, N- shaped or exponential [42]. Our modeling results for mango and Kernza showed halving compost application dramatically reduced N_2O emissions, while only marginally decreasing SOC.

Overall, proper fertilizer and water management can decrease N_2O emissions. It is important to consider the crop and soil type for precise fertilizer application rate. For water management, it is important to consider main rainfall events, and irrigate less to avoid high volumes of water in the soil at any time.

There needs to be more research around the effect of these practices on yield. Our yield analysis indicates that even a 50% drop in Indian cotton yields from RO practices still would not cause emissions from regenerative to eclipse emissions from organic practices. The DNDC model results show comparable yields for the crops modeled. However, it is important to note that the DNDC model has not been verified for yield results. The model is tested and peer-reviewed for soil carbon dynamics and trace gas emissions internationally with various crops. For future research, it will be useful for Patagonia and other participating organizations to collect data on yields as well as the cost of practices to optimize the ROC.

Also, modeled results need to be compared to the field measurements to verify and improve the model. As mentioned earlier, the DNDC model only models up to 50 cm. Therefore, making deeper soil carbon measurements down to 100 cm, broken into composite soil depth, will increase the accuracy of the results, especially when analyzing the impact of tillage.

Patagonia aims to set an example for the entire apparel industry, and this research is an attempt to structure the Regenerative Organic Certification to help guide them in this mission. Future work should aim to acquire data for on-site soil measurements, yield measurements, cost of practices, and cost of the other requirements of the certification around the animal welfare and social fairness pillars to be able to come to a conclusion about the benefits of the certification. This research is an initial attempt to provide guidance to

Patagonia and the rest of the apparel industry on how to use their supply chain to enable farmers to boost soil health while actively combating climate change.

CONCLUSION

The results of our analysis indicate that the RO practices accomplish the goal of building soil organic carbon when compared to organic practices. However, RO practices impact on overall GHG emissions is unclear. Our results show that RO agriculture does not always decrease overall net GHG emissions compared to organic agriculture. This is due to increased emissions of N_2O from practices such as compost and manure application. Practices to limit the amount of N_2O that is emitted from the soil such as drip irrigation and precise fertilizer application will be integral to ensuring the soil carbon sequestration benefit of the ROC is not overpowered by N_2O emissions.

Our results revealed that perennial crops (such as mango trees, perennial grasses, and Kernza wheat) are more likely to act as a sink of carbon, while annual crops such as cotton are more likely to act as a source of carbon. Therefore, cropping systems that have a focus on planting perennial crops will have a higher soil carbon sequestration over systems that continually plant annual crops. We also found legume cover crops were the most effective at sequestering soil carbon compared to other cover crop options.

Further analysis on the RO should be run around the other two pillars that are focused on animal and social welfare to ensure that the certification is a profitable endeavor for producers. We recommend that as the ROC collects more on side data from participants and that this data be compared to our model results to check for validity. We also recommend that yields be carefully tracked to confirm our result of comparable yields.

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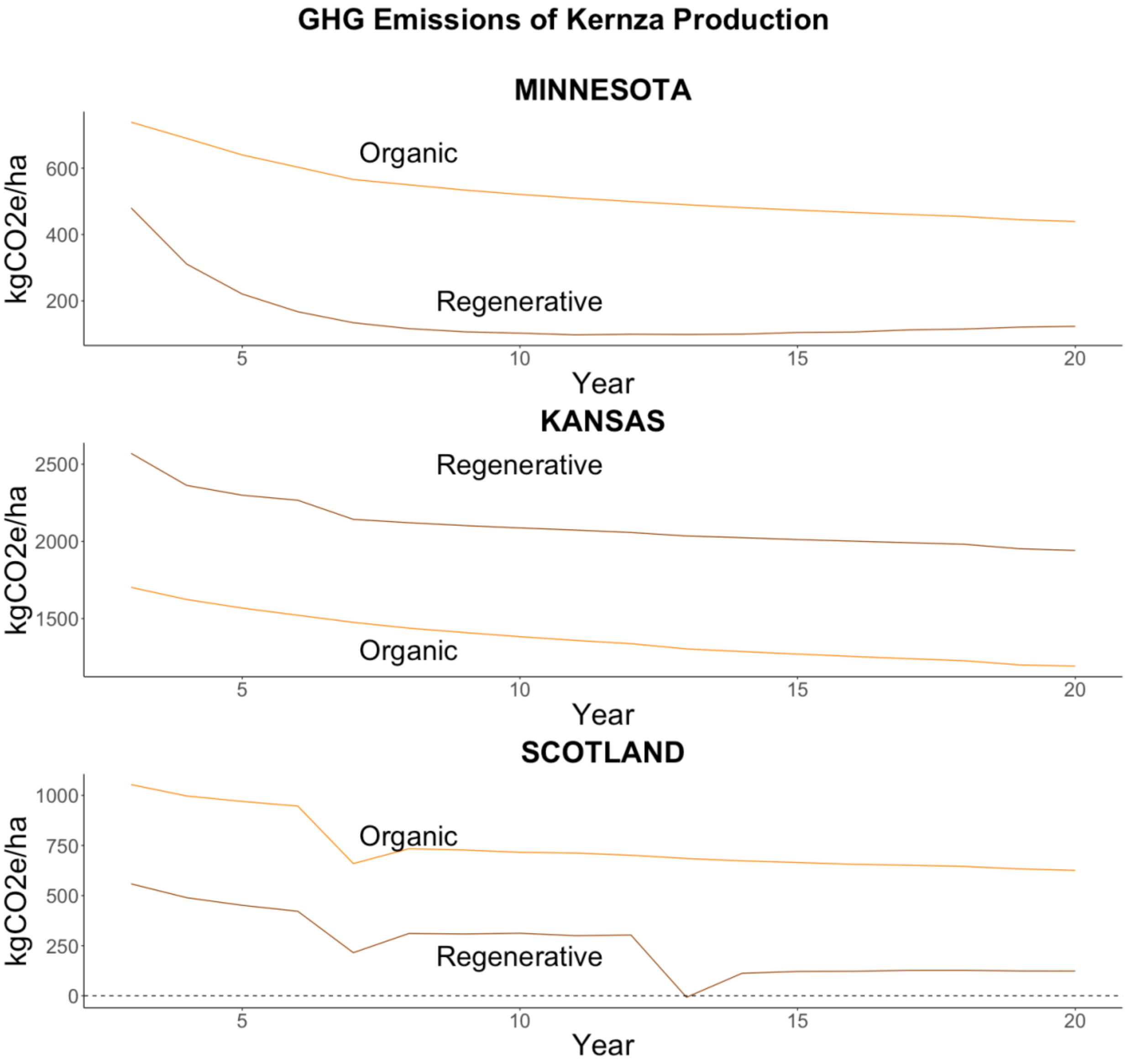
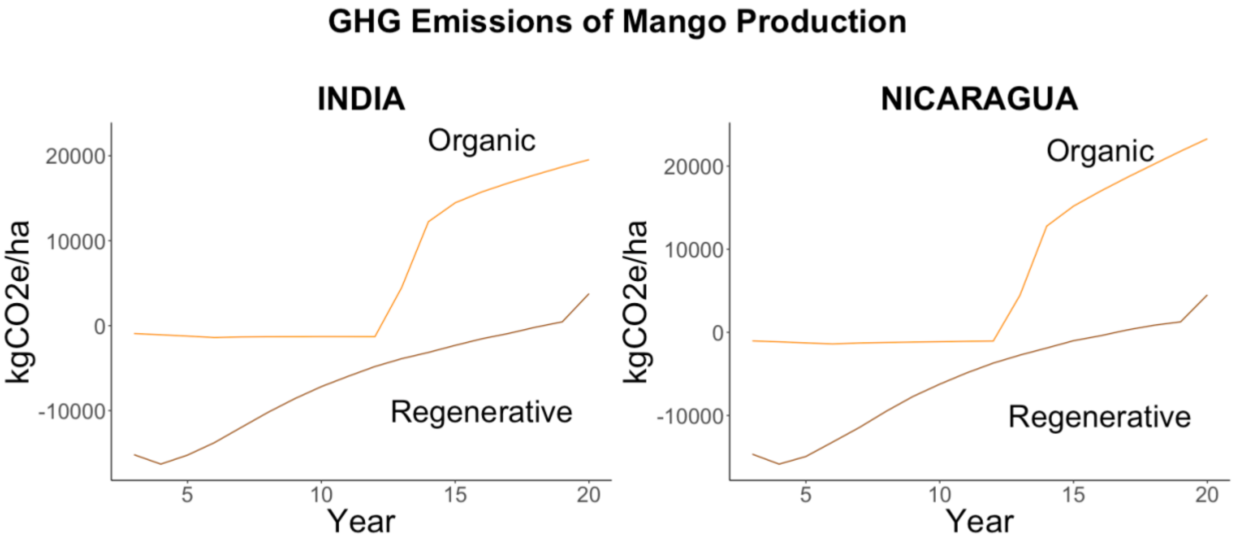
APPENDIX

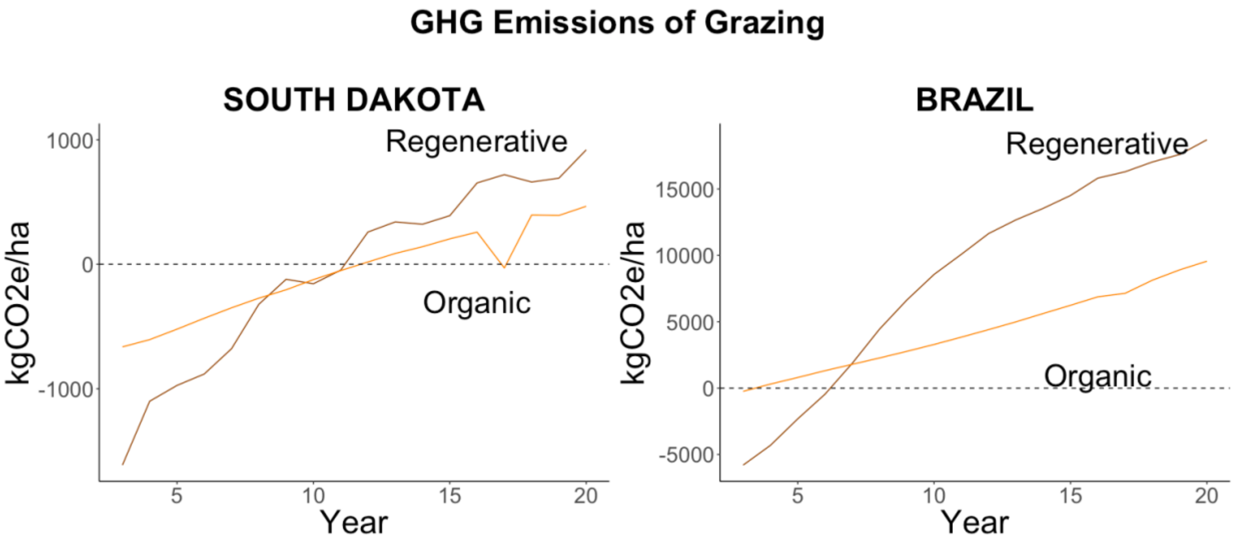
List of appendix Figures:



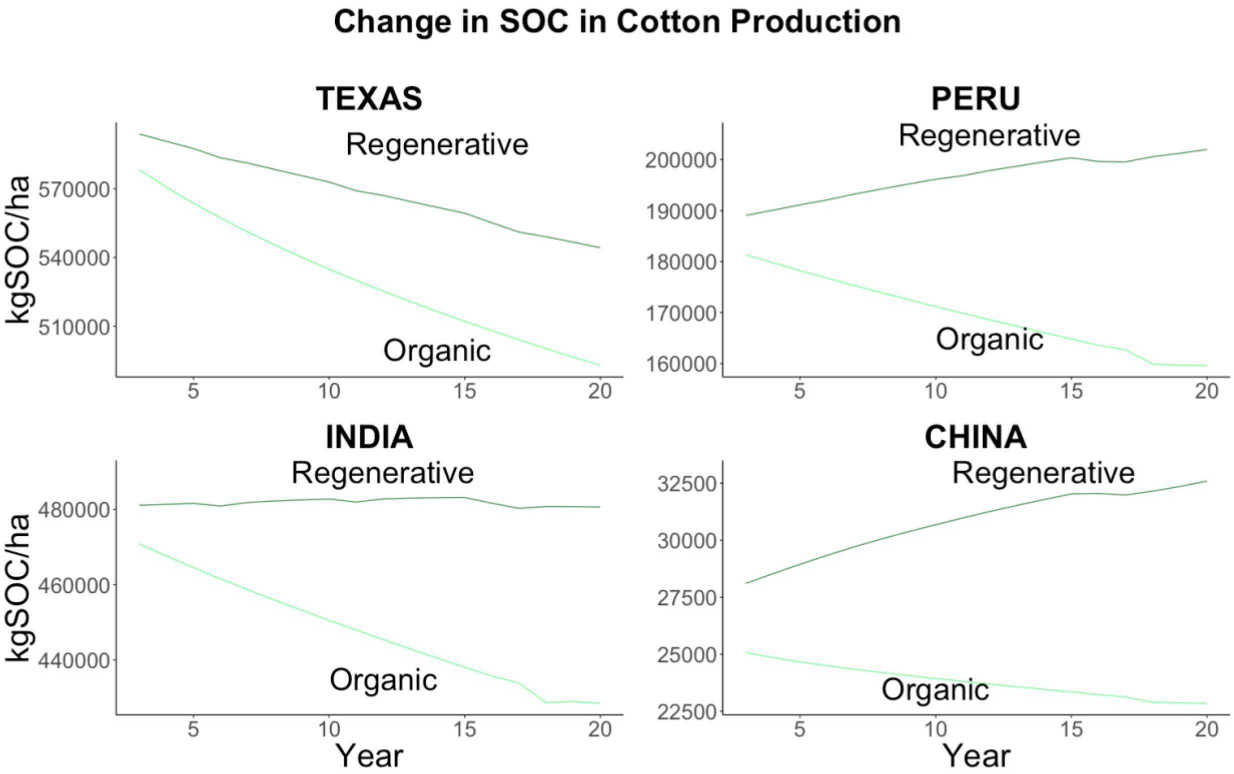
1. *Time Series Plot of the Net GHG Emissions in Kernza Production: Net GHG emissions (kgCO2e/ha) of regenerative and organic Kernza in Minnesota, Kansas, and Scotland.*



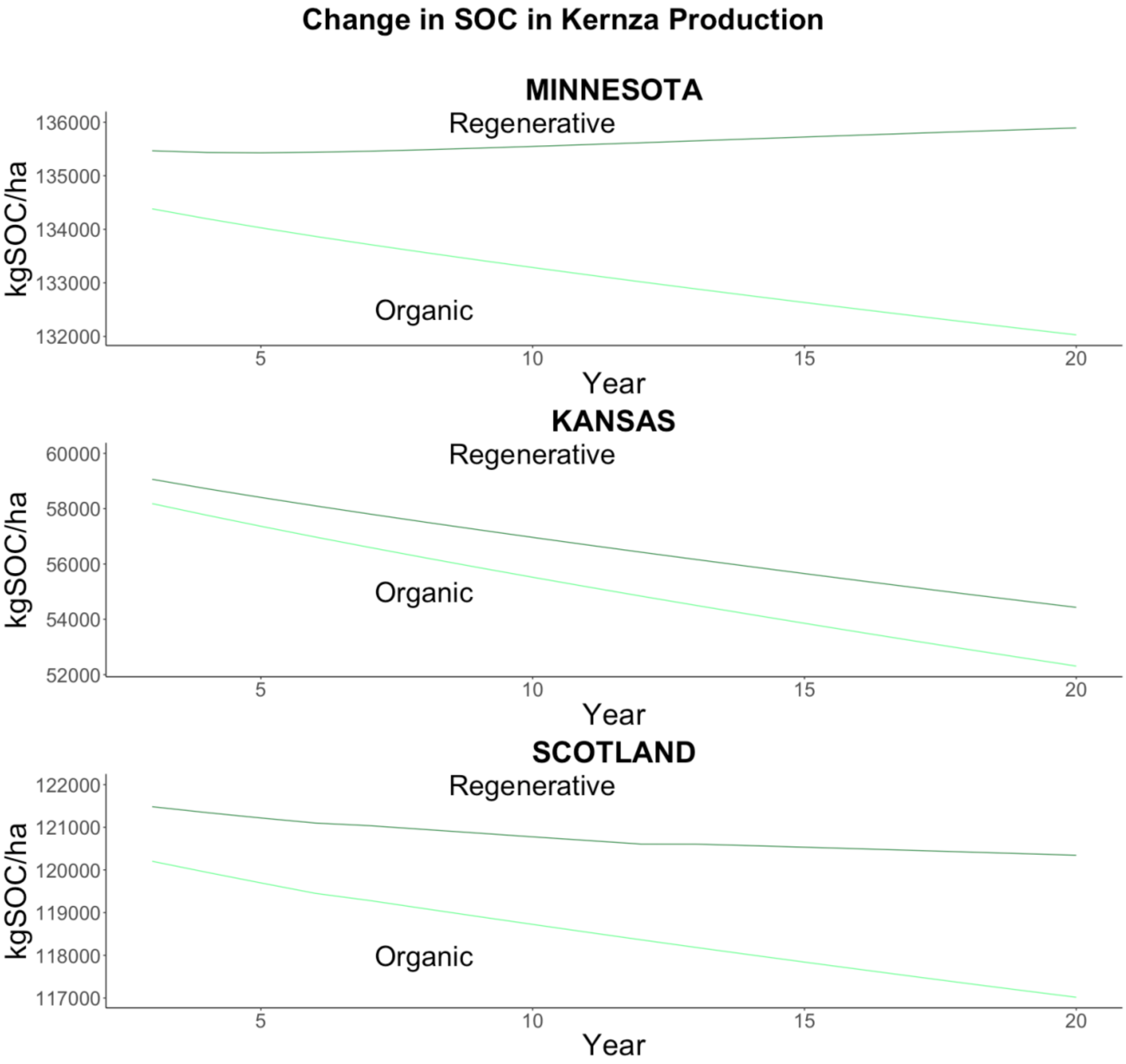
2. *Time Series Plot of the Net GHG Emissions in Mango Production: Net GHG emissions (kgCO2$_e$/ha) of regenerative and organic Mangoes in India and Nicaragua.*



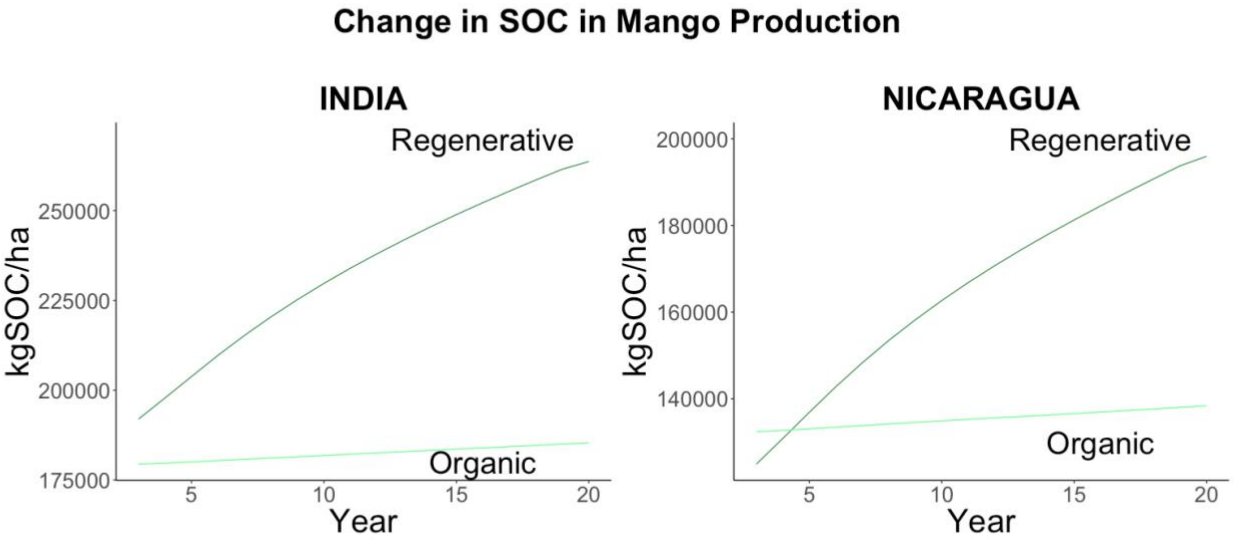
3. *Time Series Plot of the Net GHG Emissions in Grazing: Net GHG emissions (kgCO2$_e$/ha) of regenerative and organic grazing on perennial grasses in South Dakota and Brazil.*



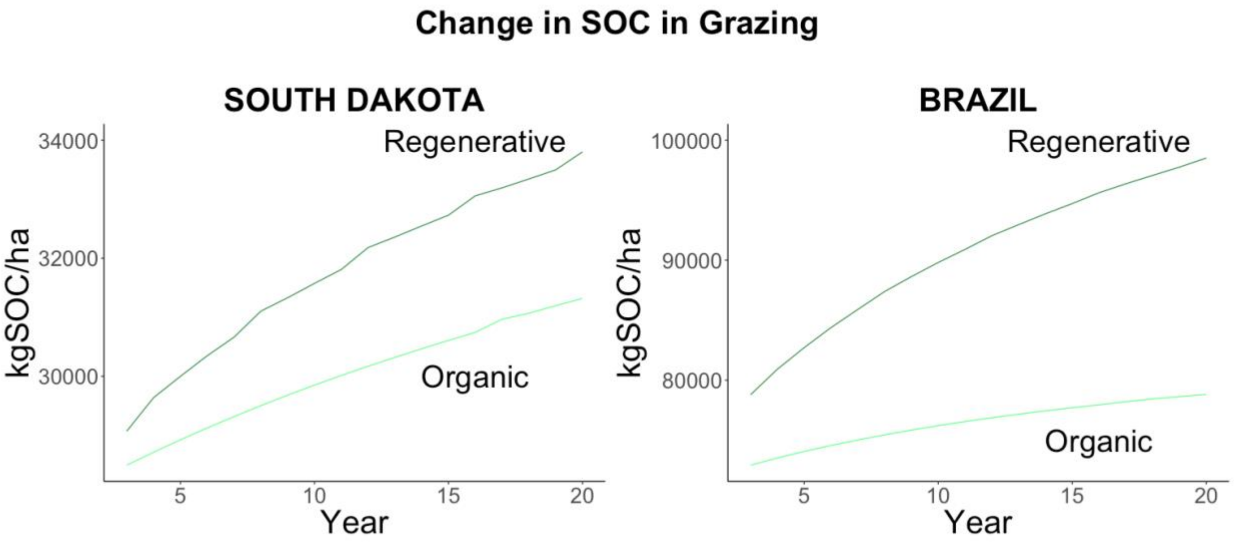
4. *Time Series Plot of the changes in SOC in Cotton Production: Year to year variation in soil carbon stock of cotton production under regenerative and organic practices in Texas, Peru, India, and China.*



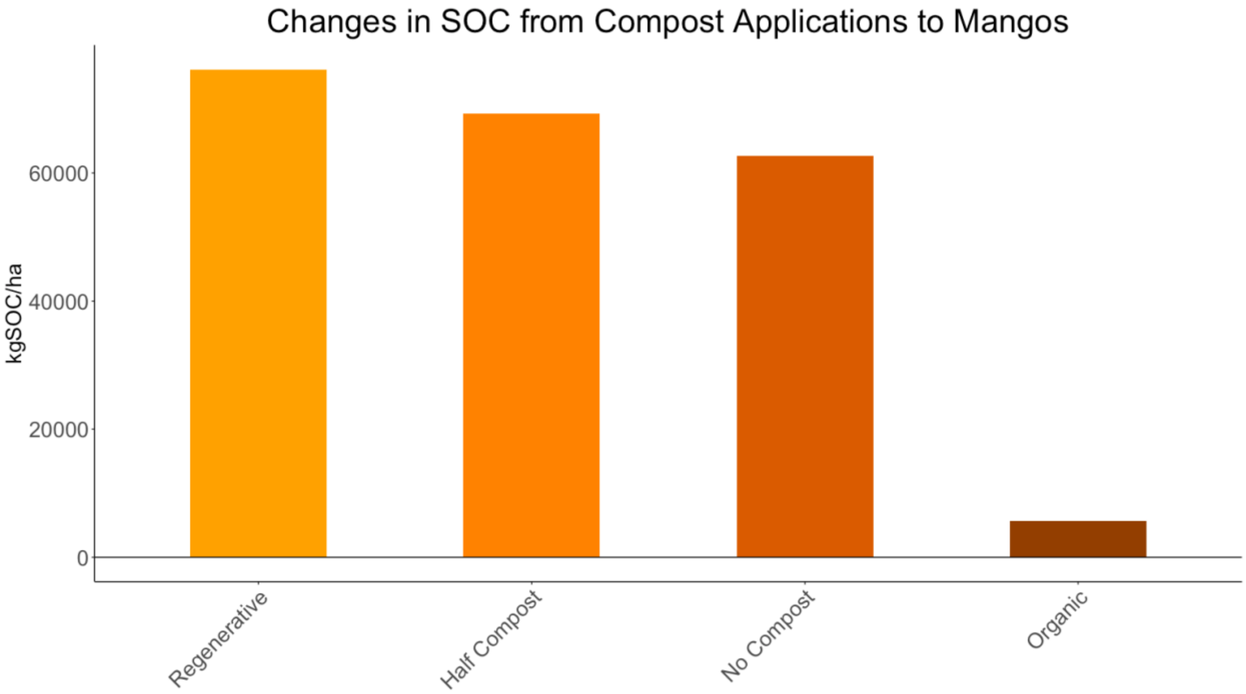
5. Time Series Plot of the Changes in SOC in Kernza Production: Year to year variation in soil carbon stock of Kernza production under regenerative and organic practices in Minnesota, Kansas, and Scotland



6. *Time Series Plot of the Changes in SOC in Mango Production: Year to year variation in soil carbon stock of mango production under regenerative and organic practices in India and Nicaragua.*

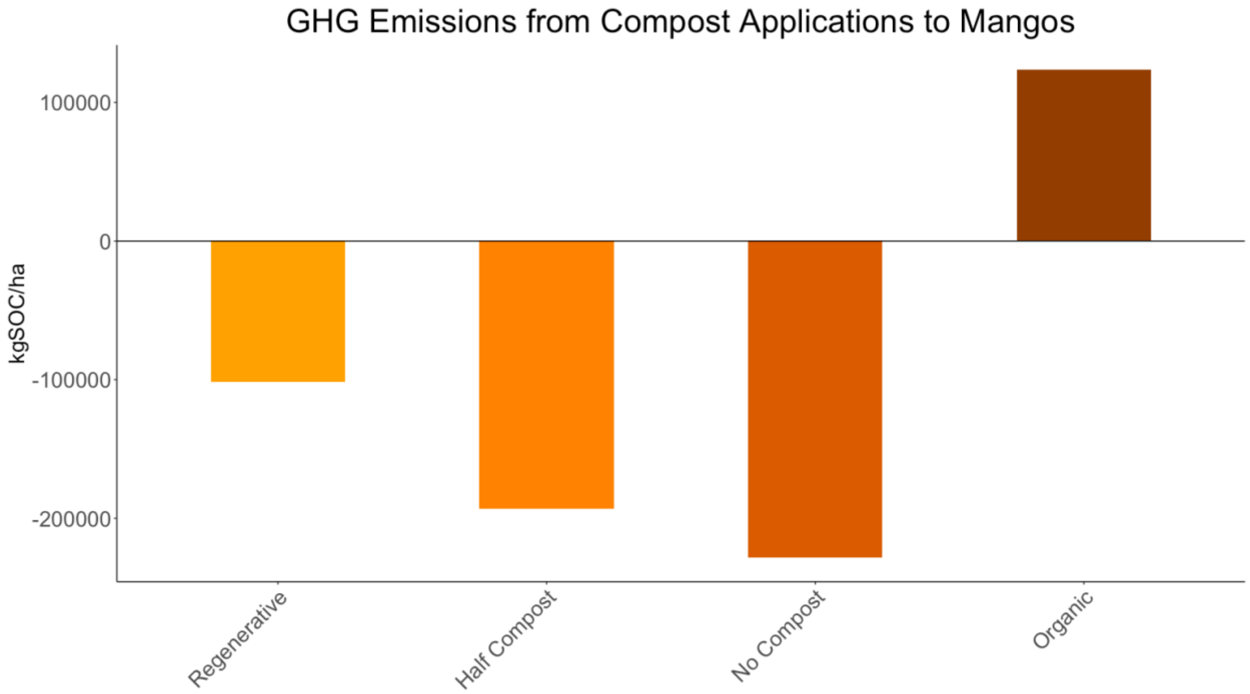


7. *Time Series Plot of the Changes in SOC in Grazing: Year to year variation in soil carbon stock of grazing on perennial grasses under regenerative and organic practices in South Dakota and Brazil.*



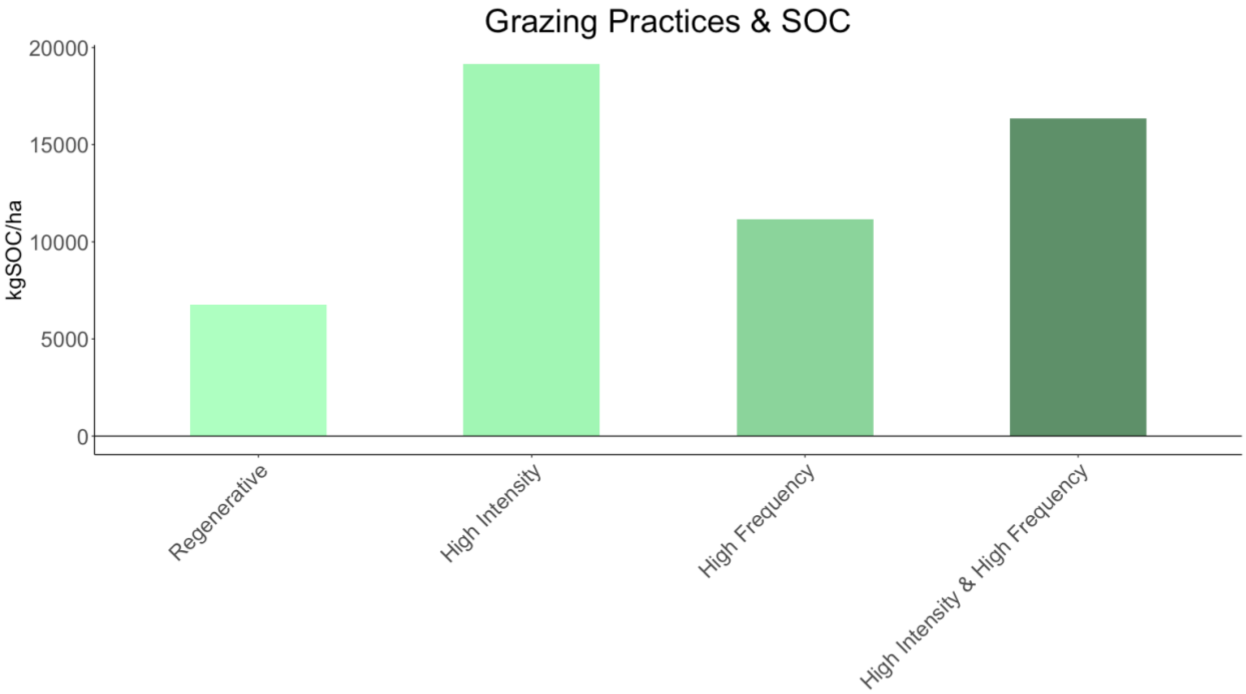
8. *Impact of Compost Application on SOC in Mango Production: Impact of different amounts of compost applied to mango production in Nicaragua on changes in total SOC over 20 years.*

Analysis of how different amounts of compost affected the accumulation of SOC in the regenerative production of mangos. Mangos were modeled under RO management with full compost application (750kg/ha - 1500kg/ha as the trees mature). This scenario is denoted in Figure 8 as “Regenerative”. A half compost application was also modeled (375kg/ha - 750kg/ha as the trees mature) and is denoted in Figure 8 as “Half Compost”. Then a no compost under RO management was run along with the previously modeled organic management. The takeaway from this is as the use of compost decreases, the amount of SOC accumulated also decreases. Compost use accounts for 13,519.56 kg of carbon over the 20 year period, or 17% of the total SOC in the regenerative scenario.



9. *Impact of Compost Application on GHG Emissions in Mango Production: Impact of different amounts of compost applied to mango production in Nicaragua on changes in net GHG emissions over 20 years.*

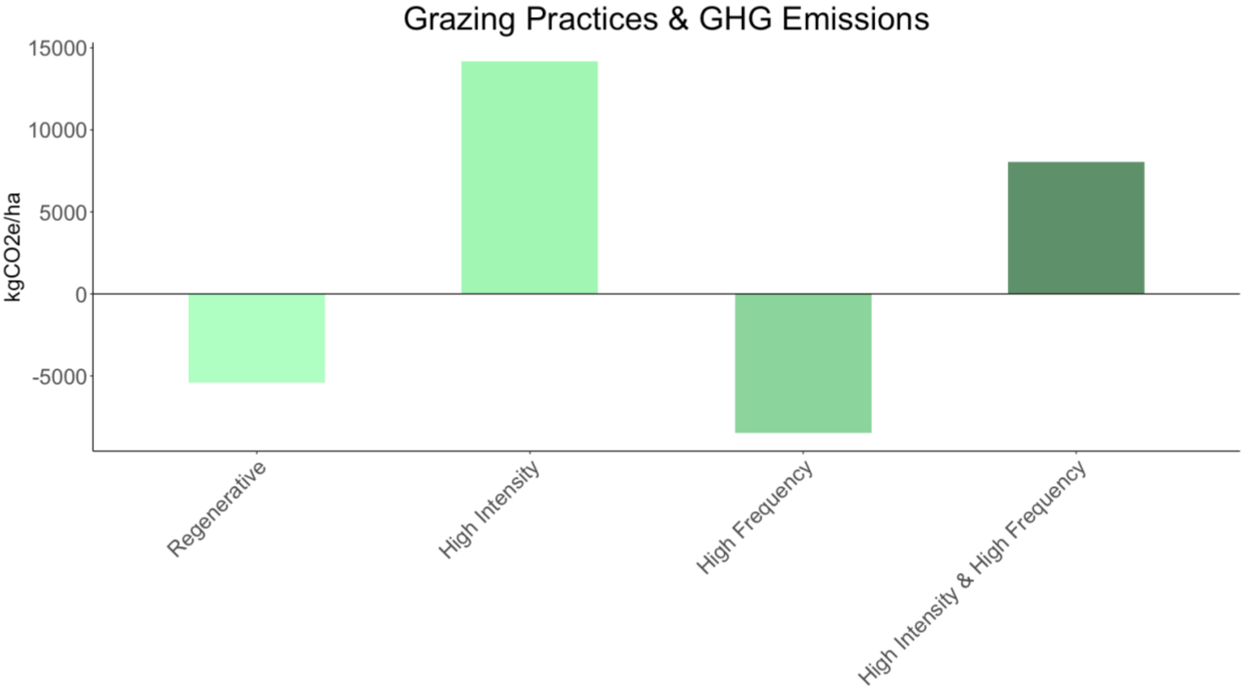
Similar to the analysis done in Figure 8, Figure 9 shows the same analysis of different amounts of compost application on the amount of net GHG emissions in mango production. Again in the “Regenerative” scenario, compost is applied at a rate of 750kg/ha-1500kg/ha as the trees mature and in the “Half Compost” scenario compost is applied at a rate of 375kg/ha-750kg/ha as the trees mature. It can be seen in Figure 9 that as less compost is applied the more negative GHG emissions become. This is likely due to a decrease in the amount of N_2O that is usually associated with compost application. Eliminating the use of compost in mango production would account for a reduction of 126,646.1kgCO_2e in production, or a 55% increase in the amount of carbon (kgCO_2e) sequestered by the soil. With this analysis in mind it is important to realize that some practices (such as compost use) can increase the amount of carbon sequestered to the soil but also increase the overall GHG emissions of production by emitting potent greenhouse gases such as N_2O.



10. Impact of Grazing Intensity and Frequency on SOC in Perennial Grasses: Impact of increased intensity and frequency of grazing on the amount of SOC accumulated over 20 years under regenerative management.

To access the impact of grazing frequency and intensity on SOC accumulation in regenerative management, a grazing sensitivity analysis was conducted. In the RO scenario, 12 heads of cattle were grazing per hectare on 6 occurrences per year. Each occurrence lasted 7 days and the cattle grazed for 12 hours per day. With this baseline established, a “High Intensity” scenario was modeled, in which there were still 6 grazing occurrences per year, but 24 heads of cattle grazed per acre, lasting for 14 days. Additionally, a “High Frequency” scenario was modeled in which 12 heads of cattle grazed per hectare, but there were 12 grazing occurrences per year. In each grazing occurrence, the cattle grazed for 7 days, 12 hours a day. Finally, a “High Intensity & High Frequency” scenario was modeled. In this scenario there were 12 grazing occurrences per year in which 24 heads of cattle grazed per hectare for 12 hours a day for 14 days.

As shown in Figure 10, the frequency and intensity of grazing does have an impact on the amount of SOC accumulated over 20 years. The high intensity scenario accumulated the most SOC - 12,391.93 kg C, more than the RO scenario.



11. Impact of Grazing Intensity and Frequency on GHG Emissions in Perennial Grasses: Impact of increased intensity and frequency of grazing on net GHG emissions over 20 years under regenerative management.

The same sensitivity analysis shown in Figure 10 is shown in Figure 11 measuring the impact of net GHG emissions from changes in grazing intensity and grazing frequency. Unlike in Figure 10, the high intensity scenario has the largest emission of greenhouse gases with 14,199.56 kgCO_2e. In regards to overall GHG emission, the high frequency scenario has the lowest GHG footprint, with an overall emission of -8,462.71 kgCO_2e. The base RO scenario had a GHG emission of -5401.32 kgCO_2e. This is another example of a practice that has the ability to increase the amount of carbon sequestered but also raise the overall GHG emissions.