ACS ENGINEERING Au
AN OPEN ACCESS JOURNAL OF THE AMERICAN CHEMICAL SOCIETY

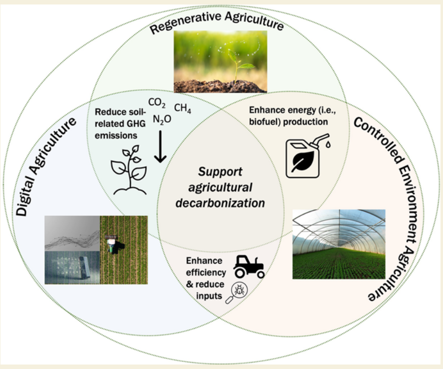
Decarbonization of Agriculture: The Greenhouse Gas Impacts and Economics of Existing and Emerging Climate-Smart Practices

Published as part of the ACS Engineering Au virtual special issue "Sustainable Energy and Decarbonization".

Kamila Kazimierczuk,* Sarah E. Barrows,* Mariefel V. Olarte, and Nikolla P. Qafoku

Cite This: *ACS Eng. Au* 2023, 3, 426−442

ABSTRACT: The worldwide emphasis on reducing greenhouse gas (GHG) emissions has increased focus on the potential to mitigate emissions through climate-smart agricultural practices, including regenerative, digital, and controlled environment farming systems. The effectiveness of these solutions largely depends on their ability to address environmental concerns, generate economic returns, and meet supply chain needs. In this Review, we summarize the state of knowledge on the GHG impacts and profitability of these three existing and emerging farming systems. Although we find potential for CO_2 mitigation in all three approaches (depending on site-specific and climatic factors), we point to the greater level of research covering the efficacy of regenerative and digital agriculture in tackling non-CO_2 emissions (i.e., N_2O and CH_4), which account for the majority of agriculture's GHG footprint. Despite this greater research coverage, we still find significant methodological and data limitations in accounting for the major GHG fluxes of these practices, especially the lifetime CH_4 footprint of more nascent climate-smart regenerative agriculture practices. Across the approaches explored, uncertainties remain about the overall efficacy and persistence of mitigation—particularly with respect to the offsetting of soil carbon sequestration gains by N_2O emissions and the lifecycle emissions of controlled environment agriculture systems compared to traditional systems. We find that the economic feasibility of these practices is also system-specific, although regenerative agriculture is generally the most accessible climate-smart approach. Robust incentives (including carbon credit considerations), investments, and policy changes would make these practices more financially accessible to farmers.



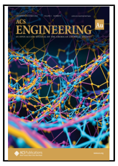
KEYWORDS: *greenhouse gas emissions, regenerative agriculture, digital agriculture, precision agriculture, controlled environment agriculture, climate-smart agriculture, soil carbon cycle, economics*

I. INTRODUCTION

The agricultural and food supply chain accounts for 26−31% of total global greenhouse gas (GHG) emissions.[1,2] The GHGs most responsible for agriculture's hefty climate footprint—and climate change in general—are CO_2, CH_4, and N_2O, with the latter two gases boasting global warming potentials 25 and 300 times that of CO_2.[3] Agriculture is a large source of these non-CO_2 emissions and can constitute more than 50 and 75% of total global emissions of CH_4 and N_2O, respectively, largely due to on-farm processes, such as enteric fermentation and manure management.[2,4,5] From 1990 to 2019, agricultural emissions from all three critical GHGs—CO_2, CH_4, and N_2O—increased 16%.[2] Forecasts project a continued increase (∼10% by 2030), especially of non-CO_2 emissions related to increased nitrogen fertilizer use and livestock numbers in economically developing nations.[6,7] The pathway toward emissions reductions ultimately presents an uphill battle, especially as environmental and socioeconomic stresses due to climate change worsen, but limiting global warming to 2 °C (per the Paris Agreement) fundamentally requires addressing the agriculture industry.[8]

Although agriculture represents a substantive emissions source, it also presents a viable emissions sink.[9] Terrestrial soils, composed of soil organic carbon (SOC) and soil inorganic carbon (SIC) pools,[10] can store almost three times as much carbon as the atmospheric pool.[11] Scientists have estimated that, by implementing practices that promote an increase in carbon storage and/or reduce turnover rates of existing carbon stocks in agricultural soils, four to five billion tons of carbon can be sequestered annually in managed ecosystems.[12] Scaling of SOC- and SIC-increasing activities

Received: July 14, 2023
Revised: September 29, 2023
Accepted: October 4, 2023
Published: November 3, 2023



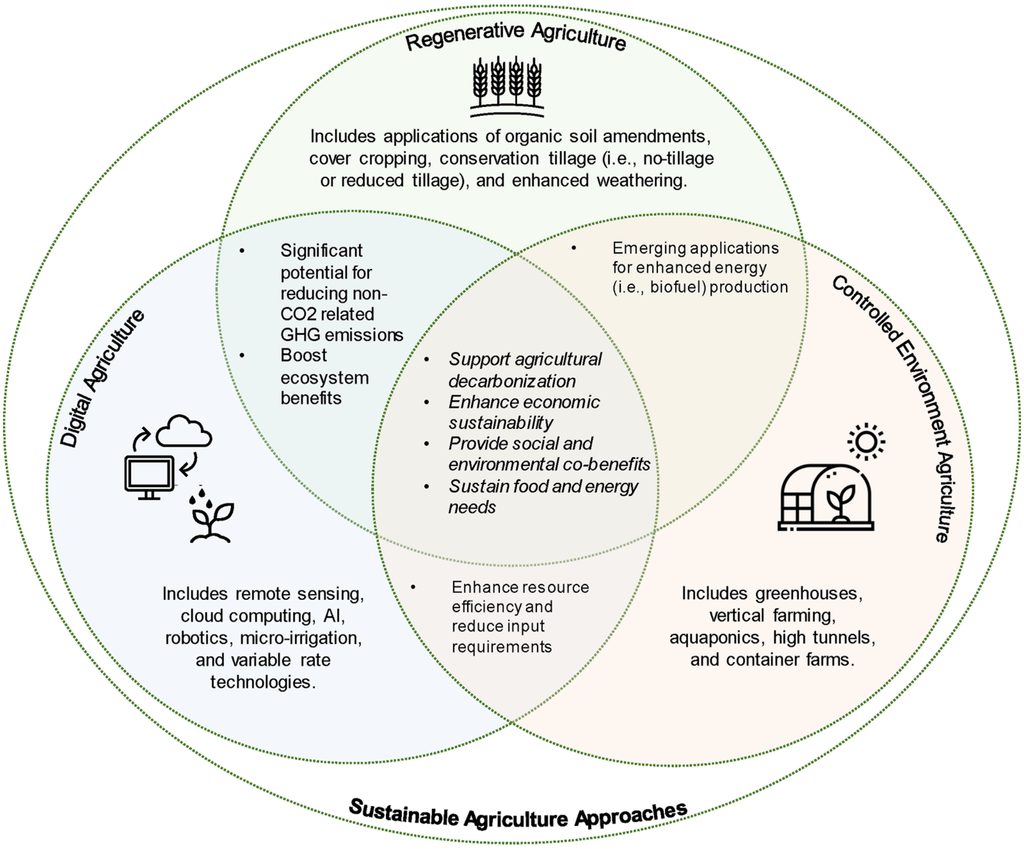


Figure 1. Shared principles of climate-smart agriculture among digital agriculture, regenerative agriculture, and controlled environment agriculture approaches.

across agricultural topsoils could result in the sequestration of up to 130 billion tons of carbon globally by the end of the century, at a cost between \$0 and \$100 per ton of CO_2.[13] However, the effectiveness of agricultural management practices in combating climate change is not just contingent on emissions mitigation potential, but also the environmental and economic cobenefits realized through implementation.[14] Climate impacts have already begun to challenge agricultural productivity and food and fuel security,[15] demanding solutions that reduce agriculture's contribution to climate change while also strengthening its resilience to climate risks.[16,17]

In this paper, we summarize the current literature regarding the mitigation potential of CO_2, CH_4, and N_2O emissions of three emerging and existing climate-smart farm management practices, as well as the economic viability of those practices, which influences farmer adoption. Climate-smart agriculture refers to farming practices that advance environmental, social, and economic sustainability through (1) reduced emissions and enhanced resilience to climate-related risks (e.g., drought); (2) increased productivity to sustain food and fuel needs; and (3) improved financial bottom line for farmers.[18,19] Regenerative, digital, and controlled environment agriculture have increasingly gained traction as promising climate-smart farming approaches, although claims made by proponents of these systems can be quite dramatic.[20−24]

Regenerative agriculture (RA)—a term that has increased in usage in the past decade[20]—can be defined as a "mashup of several systems of principles" that emphasize protecting and enhancing soil health.[23] In this paper, we use RA to refer to farming practices that can be applied synergistically to (1) build soil fertility, (2) increase water retention and percolation and/or reduce runoff, (3) bolster system biodiversity and resiliency (particularly through livestock grazing), and (4) invert carbon emissions via soil sequestration.[23,25,26] RA practices build upon techniques that enhance natural processes,[27] which lends to its widespread global adoption and positive impacts, such as increased long-term yields of staple crops.[28]

Digital agriculture (DA), another type of climate-smart agriculture, refers to farming systems that integrate technological innovations, such as data capture, management, and analysis, in order to positively affect yields, quality, and profits. DA can enable real-time or near real-time feedback between sensors and equipment to make automated adjustments, thus optimizing inputs and yields, which can also reduce GHG emissions. DA is associated with a wide variety of similar terms, including precision agriculture, climate-smart agriculture, intelligent agriculture, and Agriculture 4.0, all of which have increased in usage recently.[29]

Controlled environment agriculture (CEA) describes a suite of technologies or indoor farming configurations that closely regulate the environment in which the food is grown. CEA technologies such as vertical farms, greenhouses, container farms, and integrated aquaponic systems have increased in popularity over the past decade, particularly in urban centers where soilless farms provide the opportunity to bring food production to the space-constrained built environment.[21,30] CEA systems can reduce land and water use in agricultural production, but they typically increase energy consumption, making their overall GHG impact and sustainability more complex to measure.[31]

With climate change impacts becoming increasingly palpable and the need to limit emissions, it is worth exploring the potential of RA, DA, and CEA to boost environmental and economic sustainability through improved environmental outcomes and the sustained well-being of farmers. Figure 1 shows the conceptual relationship between the approaches explored in this paper and principles of climate smart agriculture. These practices vary in terms of applicability (e.g., urban vs field conditions), economic scalability (e.g., sizing of operations), and nascency (e.g., emerging vs existing technologies), and thereby provide contrast in terms of benefits as well as opportunities for co-optimization to maximize deployment value. A combination of these practices can help improve the performance of managed lands to maintain or increase production, and thereby meet current and future food and energy needs, while also enhancing environmental outcomes.[32]

We contribute to the literature by (1) outlining the current state of knowledge on the CO_2, CH_4, and N_2O emissions mitigation potential of these practices, (2) informing the landscape for farmer adoptability through assessment of practices' economics, and (3) synthesizing the important research needs and gaps related to these practices that require further investigation for successful deployment. In Section II, we describe our methodology, and in Section III, we provide definitions for the management practices explored in this paper. In Section IV, we review the literature on regenerative, digital, and controlled environment agriculture, describing both the GHG impacts and the economic aspects of each practice. In Section V, we discuss our literature review findings, with conclusions offered in Section VI.

II. METHODOLOGY

Given the existence of a variety of farming practices that can bolster soil carbon sequestration (and thereby mitigate critical GHG emissions), research efforts were limited to three increasingly cited agricultural practices—regenerative agriculture, digital agriculture, and controlled environment agriculture, because they represent both existing and emerging climate-smart farm management strategies. They also provide a contrast in terms of applicability (for site-specific conditions) and economic scalability (for farming operations). The distinct environmental benefits, decarbonization potential, and economic impacts of RA, DA, and CEA provide a basis for comparing these practices at a high level, which, to the knowledge of the authors, has not yet been done.

We conducted our analysis through the lens of environmental and economic perspectives. This Review addresses three research questions, which are listed as follows:

1. What are the impacts of regenerative agriculture, digital agriculture, and controlled-environment agricultural farming systems on GHG emissions?
2. What is the economic viability of these agricultural approaches relative to yield impacts, input requirements, and farmers' overall bottom-line?
3. What research gaps must be explored in order to deploy suitable climate-smart approaches and increase future adoptability of climate-smart practices?

The environmental impacts considered in our review include 1) GHG fluxes of CO_2, N_2O, and CH_4 and 2) soil organic and inorganic carbon cycling and sequestration. We focus specifically on N_2O, CH_4, and CO_2 emissions because they are the major GHGs associated with agriculture. The economic impacts considered relate to farmer and societal benefits and costs in relation to crop yield, production costs (e.g., pesticide cost, fertilizer cost, labor cost, transport cost), and ecosystem services.

Using these guiding questions and topic areas, we performed a literature review through keyword searches of Web of Science and Scopus for peer-reviewed literature and conference proceedings and Google Scholar for highly cited gray literature and additional peer reviewed material that was not found on the Web of Science and Scopus platforms. As the most established and comprehensively studied approach of the three, a large body of work already exists on RA. To investigate generalizable emissions and economic trends from the many practices that fall under the umbrella of RA, we searched for meta-analyses when possible. Given the nascent technological nature of some DA and CEA practices, meta-analyses were not easily available, so we collected and used additional gray literature, such as organizational reports, newsletters, and educational and blog materials, to support a baseline assessment of each practice. We searched using keywords related to GHG emissions (e.g., greenhouse gas emissions, CO_2, N_2O, CH_4, etc.) in conjunction with RA (e.g., regenerative agriculture, biochar, conservation tillage, reduced until, no until, cover cropping, organic soil amendments, manure, compost, crop residues, biochar, enhanced weathering, basalt, etc.), DA (e.g., digital agriculture, precision agriculture, smart farming, agriculture 4.0, etc.), and CEA (controlled environment agriculture, greenhouses, vertical farming, container farming, aquaponics, indoor farming, etc.). To understand the remunerative aspects of these practices, we also looked for literature reports that described yields, input requirements, and incentive structures. We also considered the potential value added through enhanced ecosystem services.

The search was restricted to references that discussed environmental and/or economic aspects of RA, DA, and CEA as they relate to the aforementioned research questions. Ultimately, we gathered 151 literature sources, including articles, books, and the gray literature. The findings are summarized for each of these agricultural practices.

III. BACKGROUND

III.i. Definitions

The working definitions for the agricultural management practices reviewed in this work are described below.

III.i.a. Regenerative Agriculture (RA). RA practices are generally considered to build soil fertility, enhance water-retention and nutrient-holding capacities of soil, reduce erosion and surface runoff, and reduce carbon emissions via soil carbon sequestration, but the extent and magnitude of such benefits vary by practice and system. In building soil fertility, RA practices, such as no-till, livestock integration, and cover cropping, can feed the soil microbial community, which is responsible for nutrient cycling in soils,[33] although how much microbes contribute to the overall organic matter in soil is still hotly debated.[20,34,35] The following regenerative agricultural practices are considered in this review: applications of organic soil amendments and livestock integration, cover cropping (often grown in mixtures, or with multiple species), conservation tillage (no-tillage or reduced tillage), and enhanced weathering. These practices were chosen because they are among the most commonly explored within the existing literature and/or are gathering increasing research interest in their potential to sequester CO_2.[20,36,37] The GHG impacts of livestock integration are considered in conjunction with organic amendment application primarily because manure can serve as an organic amendment, although livestock can be integrated with other RA approaches. However, our focus on livestock is limited because soil carbon and nitrogen are removed and embedded in various livestock processes (consumption, respiration, enteric fermentation, etc.),[38] making the resulting nutrient cycles more complex than the scope of this review allowed. Other RA practices, such as contour plowing and planting trees between fields, are not covered in this review to allow for an in-depth exploration of the above practices.

The practices included in our definition of RA are defined as follows:

- Organic amendments: Organic materials such as crop residue, manure, compost, and biochar that are added to soils to improve water- and nutrient-holding capacity and soil structure.
- Cover crops: Crops that are planted outside of the primary growing season to cover the soil, which helps to improve soil health, decrease erosion, reduce nitrate leaching and runoff, and ameliorate pest and weed pressure.[39]
- Conservation tillage: Refers to reduced tillage or no tillage practices, which are farming techniques in which mechanical disruption of the soil is minimized. In reduced or no-till farming, crop residues are left in the field and subsequent planting is done without prior disturbance of the soil.[40]
- Enhanced weathering: Finely ground rock materials that are applied to soils to add essential nutrients, stimulate microbiological and biological plant activity, buffer soil pH, and promote aggregate formation improving soil physical properties.[41,42]

III.i.b. Digital Agriculture (DA). Examples of digital agricultural technologies include remote sensing, cloud computing, artificial intelligence techniques, decision support systems, robotics, and variable rate technologies that enable precise and location-specific application of fertilizer, herbicide, water, and other inputs to crop production.[29,43]

In DA, data are collected at different scales, temporal, spatial, and spectral, and can be gathered through proximal sensing installed in the field or through remote sensing from satellites, unmanned aerial vehicles, and more. Predictive analytics can be incorporated to help support farmer decisions regarding unknowns such as future weather conditions, market behaviors, and water availability. Though more rare, sometimes other technologies are also included in the definition of DA, such as genetic engineering, meat culturing, and circular economies,[29] but we do not consider these technologies here due to practical constraints.

III.i.c. Controlled Environment Agriculture (CEA). Much like DA aims to better manage the growing environment in the field, CEA aims to influence the growing environment indoors. Examples of CEA technologies include greenhouses, vertical farming, aquaponics, high tunnels, and container farms.[43] The type of environmental control associated with this type of agriculture creates a number of highly debated trade-offs, such as more productive local farming with less wastewater and water use but at the cost of greater energy use (and associated emissions from that power production). Regardless of the technology used, the semicontrolled production environment has made more localized farming possible around the world, including urban areas where traditional agriculture is unfeasible because of climate-related issues—such as hard freezes and low light or dry desert climes, as well as challenges with production land and water scarcity.

IV. RESULTS: LITERATURE REVIEW FINDINGS

IV.i. Environmental Impacts

The GHG impacts of RA, DA, and CEA are presented in the subsections below. The state of knowledge surrounding these practices' impacts on the biggest agriculture-related GHGs, CO_2, N_2O, and CH_4, is evaluated by order of research confidence on these fluxes, with CO_2 impacts presented at the forefront due to breadth of literature. Methane mitigation potential by practice is evaluated last, as research in this space is comparatively the least-explored.

IV.i.a. Regenerative Agriculture (RA). Many claims have been made about the efficacy of climate-smart agriculture practices, and RA is no exception. For example, Minasny et al. suggested that about 20%–35% of global anthropogenic GHG emissions could be offset through agricultural soil management practices in 20 global regions.[44] However, Schlesinger and Amundson made the argument that RA practices—even the most promising ones (e.g., biochar application and enhanced weathering)—are unlikely to make deep decarbonization cuts, offsetting 5% of global emissions at most.[45] Regardless of magnitude, RA appears to have an effect on the CO_2 emissions via soil carbon sequestration. A 2021 report funded by the Natural Resources Defense Council reported carbon sequestration of regenerative practices from various studies to range from 1.1–35% of total global annual emissions, assuming an emissions rate of 10 PgC/yr.[46] In the following paragraphs, we consider the GHG fluxes from the practices mentioned above in our definition of RA: organic soil amendments and livestock integration, cover cropping, conservation tillage, and enhanced weathering.

The carbon sequestration potential of organic amendments is documented by extensive literature, including long-term field experiments and literature reviews and meta-analyses of those experiments. For example, Diacono and Montemurro, and Gravuer et al. consistently report increases in SOC with long-term, multiyear application of organic amendments; the former documents SOC gains anywhere from 24 to 92% above baseline conditions with amendments of municipal solid waste, farmyard manure, and compost, with the latter finding that most of these gains taking two or more years to become evident. With livestock manure specifically, GHG fluxes are a bit more complex to track.[47,48] The abundance of carbon, nitrogen, and water in liquid and solid animal waste feeds microbial activity that generates CO_2, N_2O, and CH_4 emissions, but the use of livestock manure instead of synthetic fertilizers can result in a lower overall emissions footprint and increased soil carbon storage, as determined by a study on anaerobic dairy lagoons in California.[49] Moreover, high-nitrogen amendments such as manure are expected to provide greater SOC gains over lifetime application compared to low-nitrogen amendments, partially due to their quicker decomposition and the greater nutrient availability for plant growth.[48]

The trampling effect of livestock on manure incorporation was also been studied. To a certain point, trampling assists with carbon sequestration, but if too heavy, it can actually accelerate release of soil carbon for legumes.[38] However, research on the GHG fluxes and trade-offs of integrated crop-livestock systems is still poorly understood.[50]

The GHG-mitigation potential of biochar, another organic amendment, is particularly impressive. According to data collected from published meta-analyses, biochar amendments can increase SOC stocks by as much as 40%.[51] Short-term studies show that biochar can be approximately four times more efficient than soil organic matter to produce persistent carbon in soil at longer residence times (>100 years).[51] The application rate of biochar, among its carbon-to-nitrogen ratio and soil pH, are the biggest factors in its GHG mitigation potential.[52] While the literature generally indicates that organic amendments have an ability to remove atmospheric carbon via enhanced soil sequestration, further research is needed to understand how long carbon gains persist[48] and how the availability of nitrogen (in amendments) influences this storage process.[53] Another key concern is whether amendment decomposition and increased root respiration could negate the plant and soil carbon gains made with such applications.[48]

Depending on crop type and rotation, cover cropping has also been demonstrated to promote SOC sequestration through the additional carbon input provided by the cover crops, though the nitrogen cycle is important to account for as well.[54] In a "green manure" cover cropping scenario (in which nitrogen-fixing cover crops are incorporated or plowed back into the soil before the main crop is planted), a meta-analysis by Poeplau and Don suggests that carbon sequestration could last for more than 100 years, although 50% of the total effect on SOC stocks is likely to occur within the first 20 years.[55] Under this scenario, a sequestration rate of 0.32 Mg C/ha/year would take 155 years to reach soil carbon saturation (in the first 22 cm of soil).[55] Another global meta-analysis reported a higher average sequestration rate under cover cropping—0.56 Mg C/ha/year.[56] The authors of that analysis found the significant SOC increases associated with cover cropping to be related to nitrogen fertilizer application rates, interactions with soil pH, and soil bulk density.[56] A meta-analysis on cover crop-cash crop rotations (in various soil and climatic conditions across the world) also finds cover crops increase soil carbon by 15% compared to systems with no cover crops but may increase CO_2 emissions because of increased cover crop biomass and incorporated cover crop residues in the soil.[57] Soil texture and management practices can greatly influence emission fluxes of cover cropping for both CO_2 and N_2O,[57] the latter of which can increase, albeit marginally, with cover crops.[56] An uncertainty of the sequestration potential of this practice arises from the counteracting effect of resulting N_2O emissions, making it difficult to understand cover cropping's overall impact on the net GHG balance.[56]

Conservation tillage can also improve SOC but typically mostly in soil surface layers.[58,59] SOC impacts vary depending on site-specific characteristics (e.g., soil saturation, climate conditions, etc.), and substantial inconsistencies in individual field experiments, particularly in terms of measurement depth, have long obscured actual GHG mitigation.[60] A recent meta-analysis shows that under certain soil types and climate conditions, SOC is increased with no until practices, but uncertainties in the distribution of carbon throughout the soil profile (particularly deep soil) may compromise the full picture.[59] While no-till practices likely reduce carbon losses in the field, sampling studies that have gone beyond the 30 cm benchmark show no consistent gains in SOC.[61] A meta-analysis by Cai et al. on no-tillage compared to conventional tillage practices found that SOC sequestration under the former are limited to surface soil, and SOC storage is reduced in the entire soil profile compared to the latter (although this reduction stabilizes over time).[58] Ogle et al. found the impact of SOC from no-till practices to be restricted to topsoil (<20 cm), with full tillage showing higher SOC stocks beyond the surface (>20 cm), especially for soils in tropical and warm temperate climates.[59] The authors of both meta-analyses suggest that the GHG mitigation of no-till practices is limited.[58,59] Maucieri et al. reported an increase in CO_2, N_2O, and CH_4 emissions from no-till practices due to soil changes facilitated by the decomposition of residues.[62] The level of soil disturbance (or redistribution of organic carbon) and decomposition rates within the soil profile can influence sequestration potential.[59] Some empirical studies have shown that conservation tillage reduces net system CO_2 emissions,[59,63] but it is important to stress that these studies relied on data from limited soil depths. Whether no-till practices generate any climate benefits in the form of emission reductions remains an important research topic in the scientific community.[64]

Enhanced weathering, or the application of finely ground rock to farming systems, has particularly high SIC sequestration potential because it mimics chemical weathering of silicate rocks, which sequesters atmospheric CO_2 as carbonate minerals in soils.[10,41,42] As an example, a recent study looking at the North American Corn Belt region found that applying basalt annually at a rate of 50 tons/ha/yr to 70 million hectares of land could sequester up to 13% of global annual agricultural emissions (or 1 billion tons of CO_2).[41] Strefler et al. also found substantial CO_2 removal potential with both basalt and dunite, writing that either could potentially reduce 4 Gt CO_2 per acre per year.[42] However, to sequester even just a quarter of that would require more than 3 Gt basalt to be applied annually, which is a significant amount of basalt.[42] The energy demand from mining, grinding, and pulverizing these minerals could ultimately offset 10−30% of the CO_2 sequestered.[65]

There is a connection between the weathering rate of these silicate materials and their grain size, with larger sizes having the potential of having slow weathering rates.[66] Weathering rate also is subject to site-specific conditions.[42] For example, an Oxford University study found that climatic conditions are a key factor behind the efficacy of enhanced weathering, noting that tropical conditions (i.e., warmer and more humid climates) accelerate CO_2 drawdown due to quicker breakdown of rocks and minerals.[67] The study also found that 99% of the crushed basalt applied to the study soil cores did not dissolve, leading to formation of a projected 10-in. layer accumulation over 50 years, which suggests that enhanced weathering may not sequester as much carbon as previously thought.[67] Much like no-till practices, there also are researchers who believe that the GHG mitigation potential of enhanced weathering is limited and unscalable to adequately compensate for needed climate change mitigation measures.[68] Clearly, additional research efforts are required to investigate how different soil types and climate conditions influence the ability of enhanced weathering technologies to sequester inorganic carbon.[67] Because the chemical weathering reaction requires water, the dynamics between soil hydrology and water flow paths also needs to be unraveled to better estimate rates of CO_2 consumption from the weathering process.[42]

While organic amendment application, cover cropping, conservation tillage, and enhanced weathering have the potential to enhance SOC and SIC, these practices have been shown, in the case of SOC, to provide greater SOC retention at the onset of application and then stabilize over time.[69,70] In other words, as soil carbon inputs increase with these practices, SOC levels move toward an equilibrium state, making carbon gains increasingly smaller within a system over time.[12] These SOC retention mechanisms still are not understood well and require further research.[71] In terms of the SIC−SOC relationship, studies have found a positive correlation between the two but this is not always the case and more research is needed to investigate this relationship under various anthropogenic and environmental conditions, as well as explore the mechanisms of SIC accumulation in alkaline soils.[72,73]

In terms of the impact of RA on other GHGs, results are variable by practice and context and can even potentially negate the overall GHG mitigation potential of the practice. Organic amendments, cover cropping, and conservation tillage can increase N_2O emissions in certain situations. Organic amendments of compost and manure can enhance denitrification rates, particularly through anaerobiosis and soil nitrogen availability, increasing N_2O emissions.[74] Similarly, Chen et al. found that crop residue amendments generally do not lower soil N_2O emissions, although the residue effects on emissions are highly dependent on soil moisture content and texture.[75] This also is consistent with the results presented in the study by Pilecco et al. who demonstrate that animal manure promotes N_2O emissions, but they also found that higher carbon accumulations in manured soils more than offset these emissions.[76] Brenzinger et al. suggest that N_2O fluxes of various nonpyrolyzed organic amendments are influenced highly by soil moisture, especially under water-saturated conditions.[77] While nonpyrogenic organic amendments can amplify the N_2O emissions profile of various soil types, biochar amendments have been shown to decrease denitrification due to their absorptive capacity for nitrogen in the mineral.[78] In fact, biochar addition can decrease soil N_2O emissions by an average of 38%, according to a recent meta-analysis.[78] Biochar applications appear to reduce N_2O emissions via reduced nitrogen availability, enzyme activity, and nitrification/denitrification rates.[79]

Conservation tillage and cover cropping may increase the level of N_2O emissions. Measuring N_2O emissions under field conditions is challenging, expensive, and, as such, usually short-term. Findings from a 2018 meta-analysis on soil N_2O emissions concluded that conservation tillage practices can promote denitrification and subsequent soil N_2O emissions as much as ∼18% more (on average) than conventional tillage, although soil chemical and physical properties such as pH and clay content significantly affect these emissions.[80] Mei et al. found that emissions were greater under no-till practices compared to reduced tillage, with soil aeration and substrate availability—factors that influence nitrification and denitrification processes—mainly contributing to this variability.[80] With respect to cover cropping, a "green manure" scenario can increase atmospheric releases, partly due to the higher nitrogen input associated with cover cropping and biological nitrogen fixation replacing or exceeding mineral fertilization.[54] However, cover cropping may reduce indirect N_2O emissions by decreasing field runoff.[39,81] A meta-analysis on cover crops conducted by Abdalla et al. also found that this practice significantly decreased indirect emissions via decreased nitrogen leaching, but with no major effect on direct N_2O emissions.[56] In fact, the authors concluded that the increased SOC and reduced indirect N_2O release of cover crops contribute to its lower net GHG balance compared to the control (i.e., a fertilized primary crop with a fallow period between the next harvest season).[56] In contrast, Lugato et al. found that under a milder end-century temperature-rise scenario, fields using cover crops could become a net source of GHGs by 2060 because initial enhancements of SOC are progressively offset by higher N_2O emissions over time.[54] Some studies have documented correlations between N_2O emissions and the type of cover crop used as well as the climatic conditions of the site. Higher N_2O emissions are seen when legume cover crops are used and in high precipitation areas.[57] Unlike cover cropping, enhanced weathering may potentially limit N_2O emissions through its soil pH management properties.[82] A carbon modeling study found that enhanced weathering can reduce soil acidity—a key factor of soil nutrient efficiency—and optimize N usage, resulting in N_2O emissions reductions as large as 1.5 Mt CO_2e/yr on UK croplands by 2070.[83] Another modeling study by Blanc-Betes et al. also reported N_2O reductions with enhanced weathering, showing that soils amended with basalt reduced the N_2O emission factor of maize and miscanthus cropping systems.[84] However, the mechanisms guiding these reductions varied by crop type: phosphorus added to soil through basalt amendments decreased N_2O emissions from the nutrient-limited maize system but not from the miscanthus.[84]

The impacts of RA on CH_4 emissions, another significant GHG byproduct of agricultural operations, are not as well understood or researched as CO_2 and N_2O fluxes—especially beyond the context of livestock-related emissions. Across all RA practices examined in this paper, CH_4 emissions are either variable or unknown. By examining the abundance of methanogens (a common anaerobic microbe and proxy for CH_4 emissions) in straw residue-amended soils, Zhou et al. found that residue application increased soil CH_4 production, and ultimately, atmospheric releases of CH_4.[85] In terms of pyrolyzed additives, biochar effects on CH_4 emissions can be dependent on water saturation and soil pH, with flooded fields and acidic soils tending to have reduced CH_4 emissions when biochar is added.[86] This is consistent with results reported by Joseph et al., whose summary of meta-analyses shows that biochar application can reduce non-CO_2 GHG emissions in soils by 12−50%.[87] Much like biochar, soil temperature and moisture are significant factors on net CH_4 emissions for conservation tillage systems.[62] Previous studies have demonstrated CH_4 emission reductions in no-till farming of rice due to increased oxidation activity,[62,88,89] but Hao et al. noted increased emissions due to the continuously flooded conditions.[90] Depending on the application, cover cropping can act as a CH_4 source, as documented in rice paddies,[91,92] and also a CH_4 sink, as documented in Mediterranean soils.[93] Higher CH_4 emissions have been observed in cover crops with high carbon-to-nitrogen ratios, which stimulate CH_4 emissions under anaerobic conditions; however, the same has been observed for residues with low carbon-to-nitrogen ratios, as the elevated amounts of NH_4^+ and NO_2^- in these residues pose a strong inhibitory effect on CH_4 uptake.[94] Farming systems, crop residues, fertilization, and fertilizer types are the main driving forces of CH_4 emissions; for example, the presence of nitrogen fertilizer in the soil can reduce the CH_4 oxidation capacity of the soil. Regarding enhanced weathering, one study found that applying basalt to conventionally managed crops and artificial silicate to rice does have the potential to abate soil N_2O and CH_4 emissions, respectively, although more research is needed to qualify and quantify the effects of enhanced weathering on non-CO_2 GHG emissions.[95]

IV.i.b. Digital Agriculture (DA). DA can provide several important environmental benefits. It can reduce overapplication of inputs by better matching the application of fertilizer, pesticide, herbicide, and water with spatial and temporal needs in the field, such as patterns in soil fertility, crop nutrient need, and pest pressure.[96,97]

DA can also improve nutrient management, reducing volatilization of excess nitrogen into N_2O and the overall quantity of inputs required.[96] This leads directly to reduced N_2O emissions from soil, which is the main source of emissions from agriculture. Because large amounts of energy are needed to produce fertilizers and because they often must be transported long distances to points of application, reducing fertilizer use can reduce the lifecycle emissions associated with crops.[98] A study on precision fertilizer management for paddy fields found that application timing and controlling total N input increased overall rice yields (and in tandem, net profit) and N use efficiency compared to conventional farmer practices, resulting in lower total N_2O emissions fluxes (3.5 kg ha^{-1} for select DA practices vs ∼5 kg ha^{-1} for conventional practices).[99] This is echoed by Sanches et al., who find that intensifying Brazilian bioenergy (i.e., sugar cane) production with DA technologies to meet future emissions reductions and supply targets could reduce the global warming impact of sugar cane production (on a per-Mg basis) by roughly 13% compared to a business-as-usual situation, primarily due to lower use of agricultural inputs (e.g., fertilizers and agrochemicals).[100] Similarly, in a case examining the use of optical crop sensors for variable rate nitrogen application in Austrian wheat production, DA was linked to a global warming potential reduction of 8.6% compared to conventional fertilizer application.[101] These types of sensors have also reduced 9,548 tons of GHGs (CO_2e) since pilot demonstrations were first deployed in in wheat-producing regions of Mexico in 2012.[102] In a study assessing the relationship between digital technologies and the carbon intensity of dairy farms in China, results found that precision feeding, followed by manure management technologies, had the greatest statistical correlation to improved CO_2 emissions outcomes via optimization of feed input and effluent management on farms—which ultimately helped to improve carbon emission efficiency by nearly 12% in adopting farms compared to nonusers.[103] DA techniques were also examined in a study on cotton grown in India, where N fertilizer management was tailored to leaf N status as measured by leaf color charts (with chlorophyll content or "greenness" as a proxy for N-estimation); this cost-effective, low-tech strategy for N applications lowered N_2O emissions by almost 67% compared to the soil test-based N application (and without any yield loss).[104] Precise application of inputs also can reduce the risk of leaching pesticides, herbicides, and nitrogen to land surfaces and groundwater.[105]

Research is still needed in using big data to drive positive management practices for certain environmental benefits, such as reducing agricultural energy demands, increasing pollination, improving local water and air quality, and managing pests. To facilitate the gathering of large data sets, more research also is needed in the development of sensitive microsensors and nanosensors with strong connectivity and resistance to adverse weathering conditions that can be used in distributed sensor networks to continuously collect data in different ecosystems. While remote sensors are the most used DA technology,[106] sensor adoption by famers has been limited primarily due to technological and data management barriers.[107] For example, the ability of sensors to measure complex soil variables such as plant stress factors or nutrient concentration and cycling processes, especially over the long-term (for minimal maintenance) and in extreme conditions (over seasons of sun and storms), is not yet robust.[107] While physical sensors can measure traditional phenomena such as soil moisture, pH, and temperature and imaging sensors can help inform yield and system health projections, next-generation sensors using advanced technology (such as quantum or electrochemical) are needed to accurately prescribe the state of GHG fluxes and mitigative actions. Additionally, the ability of farmers to meaningfully use the big data in agricultural systems needs to be better understood so that decision-making by farmers is supported, rather than becoming overwhelming and leading to inaction.[106]

IV.i.c. Controlled Environment Agriculture (CEA). Regarding GHG impacts of CEA, current studies vary in their results and can be difficult to harmonize because of their different units of measure, systems considered, locations, and crop type investigated.[108] For example, one life-cycle analysis found that surrounding climate factors and CEA practices can cause indoor farming to increase GHG emissions in comparison to on-field cultivation.[109] Benis et al. found that, while rooftop greenhouse farming significantly reduced emissions in all the tested climates, shipping container farms only had significant positive GHG impacts in large cities located in colder climates (hence, traditionally relying on longer distances to import foods).[109] The GHG impacts of CEA remain difficult to quantify on a full supply chain spectrum, as energy requirements for heating, cooling, and lighting can increase its emissions footprint (especially if relying on fossil-fuel generated energy), but urban applications of CEA can reduce the distance from "farm to fork" and thereby limit transportation emissions.[110]

Several attempts have also been made to quantify the carbon footprint of various CEA technologies, with most studies finding the footprint of this produce to be marginally better, if not the same, as field-grown produce. For example, studies have found that vertical farms can grow produce at a comparable carbon footprint to produce grown in open field operations (0.156−0.74 kg CO_2-eq per kg of lettuce from vertical farming compared to 0.29 kg CO_2-eq per kg of lettuce grown in a field).[111,112] Nicholson et al. compared the environmental impacts of lettuce grown via CEA methods (i.e., greenhouses) and conventional field-production approaches, finding that CEA lettuce supply chains may have higher global warming potential than field-based supply chains, although CEA operations used less water per kilogram of lettuce than field production.[113] This is consistent with Barbosa et al. 2015, who found that lettuce grown in a greenhouse with the use of hydroponics delivered not only 11 ± 1.7 times higher yields than field-grown lettuce, but also used 13 ± 2.7 times less water on average (when normalized by yield).[114] However, CEA methods ultimately required 82 ± 11 times more energy compared to field-grown lettuce,[114] which may offset any GHG savings with the indirect emissions required for energy generation.

CEA is extremely energy intensive in comparison to traditional agriculture because of its lighting, heating, and cooling needs. In fact, electricity use is the main environmental burden component in hydroponic and aquaponic CEA schemes,[115] contributing to increased system global warming potential. The supplemental CO_2 pumped into greenhouses to increase photosynthesis rates also comes with higher production costs and can introduce complexity into the overall GHG profile of CEA, which based on the lack of published information has not yet been explored.[50,116] This energy burden can be significantly reduced by sourcing electricity from renewable resources, rather than from fossil fuels such as coal and natural gas.[115] However, renewable energy may or may not be able to supply all of the energy needs of a given facility. For example, it would take about 1.5 acres of solar photovoltaics to power a CEA production system producing 25,000 pounds of produce a month.[117] Currently, most CEA adoption does not appear to be taking the place of existing agricultural land or potential land use conversion, but rather to bring food production closer to consumers.[43]

Trade-offs in the environmental performance of CEA technologies are numerous. For example, greenhouses can optimize plant growth and yield via the high amount of sunlight passing through the structure's transmissive rooftop materials (usually glass or plastic), which is well-suited for producing warm-season produce during the winter months. However, in warm seasons when the temperature rises above optimal conditions for plant growth, shading is used to release the heat trapped in the greenhouse, which, in turn, reduces yields unless supplementary light is provided. Moreover, transmissive coverings often have low insulation values, meaning more heat is needed to keep the temperature stabilized during winter.[118] The production of this heat often comes from the combustion of fossil fuels, which releases GHG emissions. The low photosynthetic activity associated with shorter winter days also may need to be compensated by using supplemental artificial light, which introduces even more indirect GHG emissions.[118] Significant amounts of energy for lighting, heating, or cooling therefore may be needed to maximize plant yields in greenhouses.[118]

Lighting in vertical farms can be powered by solar panels but, "...this means capturing sunlight to then recreate the sun, all at a loss in efficiency".[119] Moreover, the input resource use, including energy, water, and nutrients, is constrained by technological limits on monitoring plant nutrient uptake. The authors of one study suggest that this can lead to high nutrient load in CEA systems that can subsequently contaminate soil and water unless one captures or treats the leachate/runoff.[120]

Supply chain proximity can help offset GHG emissions associated with energy inputs for CEA and also reduce food waste. Nearly all produce grown in a controlled environment is harvested near its point of consumption and therefore spends fewer days in transit. To the authors' knowledge, no formal life-cycle analysis of the overall GHG footprint of different CEA systems has been performed, although such information would help inform decisions around sustainability.

IV.ii. Economic Impacts

IV.ii.a. Regenerative Agriculture (RA). Despite the environmental benefits of many of the RA approaches mentioned above, the current adoption can vary significantly by practice. There are several practical economic challenges and barriers such as adoption costs, insufficient technical assistance from the federal government, poor targeting and misalignment of owner/renter incentives, and farmer attitudes and values.[121−123]

The economic benefits of RA are generally tied to the direct and indirect effects of regenerative practices on ecosystem services through changes in crop yields, inputs to production, soil health, water consumption, nitrate leaching, and GHG fluxes.[51] Perceptions about potentially lower yields can cause farmers to be hesitant about adopting RA practices; however, there are situations in which profits can still increase, even if yields are reduced when inputs are lower. For example, LaCanne and Lundgren reported a case in which regenerative corn production had 78% higher profits despite 29% lower grain production due to reduced use of pesticides and fertilizers.[26] A 2011 literature review found that stabilized organic amendment application not only improves yield responses but also the quality of the crops produced.[47] The ability of organic amendments to increase overall soil fertility is tied to crop yield, although the benefits of increased organic matter content differ based on the rate of application, which in turn affects crop nutrition and yield responses. The availability of organic amendments in a particular farming area can limit or promote their adoption. While the application rate of biochar is critical to its GHG reduction potential, the relationship between rate to yield response is not always clear, although it remains fundamental to understanding the investment cost of biochar.[124] A 2022 meta-analysis found that increasing the rate of application of biochar increases the crop yield response; however, if high rates are needed to maintain high yields, the added application cost may offset monetary gains achieved through higher yields.[125] Conservation tillage practices can also affect crop yields, but this is context specific. In a meta-analysis of 678 studies, no-till tended to have a negative impact on yield, especially in the first 1−2 years of no-till, though yields improved in some scenarios; crop type was the most influential factor affecting yield impact, though climate also had a role in the direction of yield response.[126] A review of 106 studies found that cover cropping can increase or decrease grain yield of the primary crops, depending on the cover crop type; yields increased by 13% on average when a mix of legume and nonlegume cover crops were used, but decreased by 4% on average when only legumes or only nonlegumes were used as cover crops.[56]

The cost to maintain GHG-friendly practices can be significant and can affect profitability. Conservation tillage and cover cropping can require the purchase of additional equipment, and cover cropping requires the purchase of seed as well as additional labor and equipment usage to plant and terminate the cover crop. However, conservation tillage can reduce labor and equipment usage due to fewer passes through the field, as well as the use of agrochemicals, such as herbicides and fertilizer (thereby also reducing associated emissions).[127,128] As for soil amendments, a research review by Guenet et al. found that reductions in N_2O emissions after biochar applications only appear significant for the first year, resulting in a need for frequent applications to maintain the effect, which may ultimately limit the cost effectiveness of this strategy to mitigate N_2O emissions.[51] Similarly, the enhanced weathering process of mining, grinding, and spreading rocks over large-scale areas may impose economic costs to the farmer, such as the energy demand associated with pulverizing rocks into powder.[65]

Carbon incentive payments can offer remuneration to farmers for adopting conservation practices. Companies looking to offset their carbon footprint can turn to voluntary carbon markets to purchase these credits, which represent a metric ton of CO_2 removed from the atmosphere. Farmers can opt into programs in which third parties measure and verify soil carbon credits; however, there are costs associated with this testing and verification. Some of these costs could be lowered through innovations in remote, cost-effective sensing technologies used to measure and verify soil carbon concentrations. The feasibility of pursuing carbon credits comes down to the comparison of carbon credit prices to the costs of adopting new agricultural practices. Current carbon offset prices do not always justify these changes. Voluntary carbon credit prices can vary widely from less than a dollar per ton to over $50 per ton, depending on the type of carbon offset project, the carbon standard under which it was developed, and other aspects of the project.[129] Costs for adopting regenerative agricultural practices may be higher than this; adopting cover cropping cost one farmer in Indiana $40 an acre, while carbon credits only generated about $11 an acre.[130,131] Additionally, large concerns still remain about the accuracy of estimates for soil-based carbon sequestration, and there is no regulated standard for what constitutes a credit. Also in question is the longevity of the practice adoption. Offsets are often sold with the understanding that carbon will be stored for decades, but it may be difficult to ensure that a practice is continued for that duration of time. Also, most emissions from agriculture are N_2O from soil management, and mitigation of this GHG may not be adequately considered in current offsetting schemes.

Given that these RA practices can transform the productive capability of agricultural lands, they can potentially be the key to meeting renewable fuel targets in the form of biofuel crops. However, biomass removal (e.g., stover removal or cover crop removal) can reduce SOC, which is important to consider in long-term biofuel supply chain economic and environmental optimization.[132] Other biofuel cropping systems, such as corn for ethanol, offer opportunities for climate-smart agriculture adoption, both improving soil health and lifecycle emissions for biofuel.[133] Additionally, biofuels have the potential to increase long-term prices of commodities which could actually enable farmers to invest in these practices.[134]

IV.ii.b. Digital Agriculture (DA). DA is typically adopted to optimize farm efficiencies, thus leading to improved financial returns for farmers.[135] Perceptions among early users were that DA was technologically intensive and time-consuming but did not necessarily improve output, making it cost prohibitive.[136] However, novel technologies and improved management techniques have made it more profitable since its inception, and there has been an increase in the adoption of several DA technologies.[135]

DA has the potential to improve profitability by reducing inputs such as fertilizer, labor, fungicide, etc. through optimization.[137−139] Digital agriculture technologies can also improve yields through more targeted and responsive field management.[138,140] Yield improvements can lead to higher profits sometimes even if operating costs are higher;[138,140,141] however, profit margins may vary depending on the crop and other farm-specific factors. For example, while Sanches et al. find improved operational costs when DA is applied to expanded bioenergy production (vis a vis better field systematization), the overall production cost of sugar cane was nearly the same as a business-as-usual scenario (about 23.3 USD Mg^{1-}).[100]

Additionally, different combinations of technologies can exhibit different levels of cost savings; for example, Schimmelpfennig and Ebel found that variable rate technologies showed cost savings with soil mapping but not with yield mapping alone.[140] While yield increases and input reductions are generally given as the primary reasons for adopting digital agriculture, Thompson et al. also found that convenience was a key factor for some producers.[142] Commodity prices also affect DA adoption because higher prices mean farmers can invest more in technology and techniques.[136] Technologies such as smart irrigation have the potential to improve the use efficiency of both water and energy, which can improve crop yields or potentially enable switching to higher value crops. Smart irrigation can be achieved through variable rate irrigation, microirrigation systems, soil moisture detection, temperature measurements, and other metrics collected through sensors, and the application of artificial intelligence and automated systems.[143] For example, using a cloud-based decision support system and a sensor-based irrigation management system for greenhouse-produced zucchini, researchers were able to demonstrate a 38.2% reduction in irrigation water needs.[144] However, this increased water use efficiency, while potentially allowing expansion of agricultural production and lower energy costs, does not necessarily lead to water conservation or cost savings for the water itself.[18] This is particularly relevant in locations with “use it or lose it” policies that incentivize the full consumption of water rights.

While optimal fertilizer application can improve farm profits through maximizing yields and minimizing inputs, the marginal differences for optimal nitrogen application are not always large, and farmers rarely face penalties for overapplying fertilizers.[70] This means that unless fertilizer prices and usage are high, they might not be significant economic drivers in the adoption of DA practices.

DA can require large upfront investments as well as significant time to adopt and troubleshoot, which can hinder its adoption.[138,145] Therefore, DA is more often associated with large-scale operations, partially because those operations are more able to afford such technologies and systems.[135,146,147] Additionally, much of the digital agricultural technology available has been developed for larger farms, which means that tools tailored to the needs of small and medium farm enterprises may not be available.[148]

Additional barriers beyond the financial feasibility must be overcome before farmers adopt DA practices.[149] Uncertainty about anticipated yield results and questions about the ease-of-use and longevity of new technologies can affect adoption of such practices.[123] Lack of information and farmer perceptions are also part of the complex array of factors that affect adoption.[145,150,151] To address economic uncertainties, Medici et al. developed a web-based tool to estimate economic performance of adopting digital agriculture technologies, but this tool does not yet analyze regional differences in impacts and may be overly simplistic for farmer business decisions.[146] Farmers also face challenges related to privacy, data ownership, and cybersecurity within DA.[43,152] Broadband Internet needed to connect digital farm management systems to larger networks may not be available in many rural locations.

DA can potentially help identify less profitable areas, allowing farmers to choose alternative cultivation choices for

Table 1. Summary of GHG and economic Impacts of Climate-Smart Agricultural Practices[a]

Type	Practice or Technology	GHG Impact			Economic Impact	Citations (Bibliography)
		CO_2	N_2O	CH_4		
Regenerative Agriculture	Organic amendments	↓ SOC improved, especially with long-term application. Biochar has particularly high carbon sequestration potential.	↓↑ Emissions are highly dependent on soil moisture and soil texture.	↓↑ Emissions are influenced by soil saturation and soil pH.	Need for frequent application to maintain GHG reductions and soil health benefits may limit cost-effectiveness. Can provide monetary benefits through increased yield and produce quality.	44, 47, 48, 51, 71, 73−77, 79, 85, 86, 124, 125
	Cover Cropping	↓ Most SOC retention is likely to occur within the first 20 years of practice. Crop type and rotation affect sequestration	↑ Lifetime emissions can offset SOC gains. Emissions are influenced by the crop used and site climatic conditions. Can reduce indirect emissions through decreased nitrogen leaching.	↓↑ Emissions are highly variable and depend on factors such as crop residues, fertilization, and fertilizer types.	Can provide benefits through reduced erosion and enhanced soil health, requiring less fertilizer and water inputs, but has variable impacts on crop yield.	26, 54−57, 81, 91−94
	Conservation Tillage	? Increases SOC but typically only in the soil surface layer; carbon gains in deeper soil is shown to be inconsistent or reduced compared to full tillage, making it difficult to understand whether there is net carbon gain.	↓↑ Increases N_2O emissions under no-till practices, but no significant effect is observed in reduced until systems.	↓↑ Emissions have been variable among no-till systems (reduced in paddy rice farming, increased in dryland farming).	Can reduce the use of agrochemicals and equipment and therefore reduce associated costs to farmers. Provides indirect benefits through reduced erosion, enhanced nutrient efficiency; however, yields can sometimes be reduced.	26, 40, 59, 60, 62−64, 69, 80, 89−91, 126, 127
	Enhanced Weathering	↓ Improves carbon sequestration in soils and oceans. Life-cycle CO_2 emissions need to be better understood.	? May limit N_2O emissions when basalt is applied to conventionally managed crops, but more research is needed.	? May limit CH_4 emissions when artificial silicate is applied to rice paddies, but more research is needed.	Process of mining, grinding, and spreading rocks over large-scale areas may impose substantial costs. Provides indirect benefits through enhanced ecosystem services.	10, 41, 42, 65−67, 82−84
Digital Agriculture	Includes remote sensing, cloud computing, AI, robotics, microirrigation, and variable rate technologies	↓ Improved efficiencies can lower inputs and their associated emissions. Increased yields also mean increased carbon stock in the crop itself.	↓ Decreases emissions by reducing fertilizer inputs. Can also reduce emissions produced through anaerobic conditions via soil structure improvement.	↓ Decreases emissions by reducing fertilizer inputs (e.g,, manure). Can also reduce emissions produced through anaerobic conditions via soil structure improvement.	Can reduce overapplication of agrochemicals, thereby reducing costs. Can conserve water and energy needs as well, reducing associated costs. Boosts profits by improving farm efficiencies and/or yield. Upfront investment in technology can be cost-prohibitive.	96−101, 107, 123, 133, 137, 138, 140−142, 144−146, 148
Controlled-Environment Agriculture	Includes greenhouses, vertical farming, aquaponics, high tunnels, and container farms	↓↑ May indirectly increase emissions due to energy input sources, but indirectly reduce emissions due to minimized transportation.	? More research is required to determine impact.	? More research is required to determine impact.	Profitability depends on local demand and supply of food, location, population density, facility design, and crops produced. Requires large upfront cost for technology as well as costs of energy needs. Can extend the growing season and reduce water and land needs.	108−110, 113, 114, 132, 155, 158−160, 163

[a] Legend: Down arrow indicates practice generally decreases emissions. Up arrow indicates practice generally increases emissions. Bidirectional arrows indicate practice may increase or decrease emissions depending on system parameters. Question mark indicates that more research is needed.

those areas, thus leading to more biodiversity. For example, one study in Southern Ontario in Canada found that up to 14% of the studied farmland was unprofitable and that setting aside this land could be economically beneficial for the farmer while also allowing for increased biodiversity.[153] In locations where climate incentives reward carbon sequestration on lands taken out of production, DA can help farmers understand whether conversion is economically viable (i.e., whether carbon sequestration with sustainable cultivation is greater than on fallow lands).[154]

IV.iii.c. Controlled Environment Agriculture (CEA). CEA offers greater control over food safety and plant growth; however, profitability typically depends on local demand and supply of food, climate, facility design, and crops produced.[155] While financial research firms have predicted incredible growth in the CEA industry (compound annual growth rates of 10–20% from 2022 to 2030, depending on the country),[156,157] CEA businesses have struggled with profitability, with over $700 M of the U.S. CEA market exiting in 2021 alone.[117] CEA can be more costly in many circumstances but may meet the requirements of certain customers who are willing to pay a premium.[155] Profitability can also be seen in cases such as nursery production, where the most vulnerable part of the growing process happens in a more environmentally monitored agriculture system. O'Sullivan et al. suggest that significant research is needed around crop yield improvement, product diversity, and profitability in order to scale up CEA deployment.[108]

The wide variety of CEA systems and technologies has made it difficult to develop traditional microeconomic analysis, such as assessing optimal production size and maximizing profit. This is compounded by a lack of available costs and data. Some studies have turned to uncertainty quantification and risk analysis to model hypothetical systems.[158−160] However, many economic aspects of CEA have been underexplored. For example, the complex relationship between HVAC systems and costs is typically excluded from techno-economic studies (Baumont de Oliveira et al.).[158] Automated systems are also difficult to incorporate, though Morella et al. give an economic analysis of vertical farm monitoring.[161] Existing economic analyses are often one-off studies that are difficult to compare.[110,114,162,163] As the greatest expenses for CEA greenhouses are labor and management, energy, and structures, accounting for more than 80% of landed costs, Nicholson et al. suggest that it will be difficult to reduce the costs of CEA systems relative to field-production levels, although there may be a profitable angle for CEA in the production of leafy greens (such as microgreens) that command a higher price for their characteristics and quality.[113]

Because energy is a significant cost in CEA operations, vertical farm companies have begun exploring distributed renewable energy generation, such as biogas from manure or solar photovoltaics, to power their operations and reduce their energy costs, which could offer cobenefits like GHG reductions and energy independence or self-sufficiency.[164,165] Likewise, energy-efficient upgrades for CEA systems may be able to pay for themselves over time. Energy efficiency is particularly important when energy prices are volatile; one European CEA company laid off more than half of its workers in 2022 due to high energy prices.[166] More research is needed to determine costs across different CEA technologies and different types of produce, especially as more energy efficiency technologies become available.

V. DISCUSSION

The pathway for decarbonizing agriculture will involve multifaceted solutions; no one practice can mitigate emissions through agriculture. RA, DA, and CEA are not necessarily mutually exclusive approaches and can be implemented in conjunction to maximize environmental and economic outcomes given that these practices vary in the extent to which they deliver on GHG reductions and farmer profitability. However, based on the existing research that has been undertaken as documented in the literature, we can begin to understand where and why certain practices are more conducive to mitigating GHG emissions and identify what research needs to be done to better understand the role these practices can play in advancing GHG-friendly agriculture that benefits both society at large and the farmers implementing them.

In Table 1, we show a summary of our findings regarding GHG emissions from different agricultural practices. Of note are the varied results that have been found in different studies regarding GHG emissions, especially relating to system-specific parameters. This underscores the importance of improved modeling of the various factors that influence the CO_2, N_2O, and CH_4 emissions in agricultural soils. We also show a need for more research into N_2O, and CH_4 emissions in agriculture.

While all the RA practices reviewed here can improve SOC, organic amendments, such as biochar and enhanced weathering, show particularly high carbon sequestration potential. Many research questions still remain about the duration of and regional variation in carbon sequestration achieved through these agricultural practices as well as their life-cycle emissions and impacts on yields. Digital technologies can reduce CO_2, N_2O, and CH_4 emissions, mainly through the precision application of farming inputs that also changes the overall growth and performance of crop species. For example, DA technologies can reduce N_2O emissions via precision monitoring systems that can predict plant nitrogen responses and appropriately match nitrogen fertilizer rates. Overall, DA is still an emerging field, and more research is needed in the measurement of soil carbon using digital agricultural technologies, such as remote sensing and artificial intelligence, to better verify carbon sequestration for carbon offsetting programs.[167] Similarly, more research is needed to understand the GHG footprint of CEA, which can vary significantly depending on the technology, location, crop type, climate, and other factors. While the localized nature of CEA can eliminate GHG emissions that would otherwise be involved in the transport of food, energy usage and its associated GHG emissions can be significant for these CEA systems, especially for nongreenhouse systems that require artificial lighting.

The economic feasibility of RA, DA, and CEA also shapes the ability of these practices to decarbonize agriculture. Improving the financial bottom line of farmers is important as it provides motivation for growers to adopt climate-smart practices. The potential economic benefits of RA are tied to its impacts on ecosystem health and services, particularly through changes in crop yields, soil health, water consumption, nitrate leaching, and GHG fluxes. While DA technologies tend to cater to larger farms, the efficiencies and targeted decision-making that DA offers can be a win-win both environmentally and financially. The semicontrolled production environment of CEA technologies makes it possible to produce food throughout the year and to higher quality and safety standards, which can increase growers' profitability margins, but as such, comes at the cost of greater energy use.

Ultimately, plausible decarbonization pathways that also address economic (i.e., the financial bottom line) and social (i.e., food and fuel) considerations may involve the integration of multiple approaches in ways that the strengths of one overcome the weaknesses of the other(s), making it critical to understand trade-offs between practices. As an example, a regenerative practice, such as enhanced weathering, can be paired with digital agriculture technologies, such as remote sensors, to optimize the timing and rate of material applications for maximum yield and cost-effectiveness. Where conventional field production may not be an option, such as in urban environments (where high-value crops may also be economically feasible), CEA approaches can be deployed in conjunction with sensors and other digital technologies to optimize heating, cooling, lighting, nutrient, and other input requirements; these systems could also be powered by renewable energy to further mitigate GHG impacts. Combining these emerging and existing approaches in novel ways can ultimately help improve the sustainability of the water-energy-food nexus.[168]

Many of the approaches studied here have the potential to increase carbon sequestration in soils and in the process, reduce CO_2 emissions, but the net GHG balance of these practices is obscured by inadequate accounting and/or simulation of non-CO_2 GHG emissions, namely N_2O and CH_4, as well as uncertainties about actual CO_2 sequestration over the long-term. In applying these climate-smart practices, there also is potential for increased yields and decreased input requirements (i.e., fertilizers, water, etc.), which can enhance the bottom lines of farmers. Through increased yields and added in situ environmental benefits (such as better soil health), these practices directly impact the quantity and quality of products in agriculture-dependent supply chains

Regardless of the agricultural approach—be it RA, DA, or CEA—incentive pricing, ease of implementation, and timelines influence farmer adoption. Similarly, the practices themselves can influence yield outcomes for both food and biofuel crops, which in turn also affect a farmer's bottom line. These yield impacts also relate to the per-kilogram GHG emission reduction potential posed by each practice. More research into per-kilogram emission reductions in food production could highlight which practices are more effective for meeting both global food needs and GHG reduction goals.

VI. CONCLUSION

In this Review, we summarize the GHG and economic impacts of existing and emerging agricultural practices. With global initiatives to reduce GHG emissions, agriculture's sequestration and mitigation potential have been increasingly important to understand.

Recently, there has been increasing focus on three main categories of agricultural approaches and farming systems for GHG mitigation: (1) RA, (2) DA, and (3) CEA, although their effectiveness in mitigating GHG emissions is still in the exploratory phase. For these practices to reach greater adoption levels, it is vital to characterize their economics and practical impacts to farmers. Also, as renewable fuel targets are pursued as a path toward decarbonization, especially in hard-to-decarbonize transportation sectors, we must understand the impact of different agricultural practices on biomass production and biofuel processing.

In the process of reviewing the literature, several knowledge gaps were identified. These knowledge gaps need to be explored more deeply to advance our understanding of the complex environmental interactions within the agricultural supply chain as they pertain to reducing GHG emissions. For example, more research is needed on CH_4, N_2O, and CO_2 fluxes that considers regional variations in soil type, precipitation, climate, and crop type to understand decarbonization potential more broadly. There is also a need to incorporate these findings into current models of agricultural GHG emissions, making them more realistic and capable of finer detail.

To facilitate the gathering of big data on soil GHG emissions, more research is needed in the development of sensitive microsensors and nanosensors that are resistant to harsh environmental conditions while being operationally cost-effective. This will enable more affordable and accurate GHG accounting for carbon offsetting schemes, thus, allowing for more farmer participation. There also is a need to better understand how to meaningfully integrate artificial intelligence and machine learning in agriculture to positively impact ecosystem services and farmer returns. For CEA schemes, more research is needed into the potential GHG impacts and landed costs of crop production, in comparison both to one another and to conventional in-field production.

For us to solve our pressing climate problems while feeding a growing population, it will be important to continue to innovate in these agricultural practice categories and address these research gaps, especially so that the economics of these practices can be more favorable for farmers, leading to their sustained adoption.

AUTHOR INFORMATION

Corresponding Authors

Kamila Kazimierczuk – *Pacific Northwest National Laboratory, Richland, Washington 99352, United States*; orcid.org/0000-0002-0568-1410; Phone: 509-371-6109; Email: kamila.kazimierczuk@pnnl.gov

Sarah E. Barrows – *Pacific Northwest National Laboratory, Richland, Washington 99352, United States*; Phone: 509-375-2815; Email: sarah.barrows@pnnl.gov

Authors

Mariefel V. Olarte – *Pacific Northwest National Laboratory, Richland, Washington 99352, United States*; orcid.org/0000-0003-2989-1110

Nikolla P. Qafoku – *Pacific Northwest National Laboratory, Richland, Washington 99352, United States; Department of Civil and Environmental Engineering, University of Washington, Seattle, Washington 99195, United States*; orcid.org/0000-0002-3258-5379

Complete contact information is available at: https://pubs.acs.org/10.1021/acsengineeringau.3c00031

Funding

Pacific Northwest National Laboratory is operated for the U.S. Department of Energy by Battelle under contract DE-AC05–76RL01830. The views and opinions of the authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

We would like to thank our reviewers whose feedback significantly improved this manuscript. We would also like to thank T.J. Heibel, Corinne Drennan, and our Chief Science Technology Officer, Cindy Powell, for their institutional support of the writing of this manuscript.

■ REFERENCES

(1) Poore, J.; Nemecek, T. Reducing food's environmental impacts through producers and consumers. *Science* **2018**, *360* (6392), 987−992.

(2) Tubiello, F. N.; Karl, K.; Flammini, A.; Gütschow, J.; Obli-Laryea, G.; Conchedda, G.; Pan, X.; Qi, S. Y.; Halldórudóttir Heiðarsdóttir, H.; Wanner, N.; Quadrelli, R.; Rocha Souza, L.; Benoit, P.; Hayek, M.; Sandalow, D.; Mencos Contreras, E.; Rosenzweig, C.; Rosero Moncayo, J.; Conforti, P.; Torero, M. Pre- and post-production processes increasingly dominate greenhouse gas emissions from agri-food systems. *Earth Syst. Sci. Data* **2022**, *14* (4), 1795−1809.

(3) U.S. EPA *Understanding Global Warming Potentials*. https://www.epa.gov/ghgemissions/understanding-global-warming-potentials (accessed 2023-07-12).

(4) FAO *Emissions due to agriculture. Global, regional and country trends 2000−2018*; Food and Agriculture Organization of the United Nations: Rome, 2020.

(5) Smith, P.; Martino, D.; Cai, Z.; Gwary, D.; Janzen, H.; Kumar, P.; McCarl, B.; Ogle, S.; O'Mara, F.; Rice, C.; Scholes, B.; Sirotenko, O.; Howden, M.; McAllister, T.; Pan, G.; Romanenkov, V.; Schneider, U.; Towprayoon, S.; Wattenbach, M.; Smith, J. Greenhouse gas mitigation in agriculture. *Philosophical Transactions of the Royal Society B: Biological Sciences* **2008**, *363* (1492), 789−813.

(6) U.S. EPA *Global Non-CO2 Greenhouse Gas Emission Projections & Mitigation: 2015−2050*; Office of Atmospheric Programs: Washington, DC, 2019; pp 53−62.

(7) Smith, P., Martino, D.; Cai, Z.; Gwary, D.; Janzen, H.; Kumar, P.; McCarl, B.; Ogle, S.; O'Mara, F.; Rice, C.; Scholes, B.; Sirotenko, O. Agriculture. In *Climate Change 2007 - Mitigation of Climate Change: Working Group III contribution to the Fourth Assessment Report of the IPCC*; Intergovernmental Panel on Climate Change, Ed.; Cambridge University Press: Cambridge, 2007; pp 497−540.

(8) Clark, M. A.; Domingo, N. G. G.; Colgan, K.; Thakrar, S. K.; Tilman, D.; Lynch, J.; Azevedo, I. L.; Hill, J. D. Global food system emissions could preclude achieving the 1.5 and 2 C climate change targets. *Science* **2020**, *370* (6517), 705−708.

(9) Chambers, A.; Lal, R.; Paustian, K. Soil carbon sequestration potential of US croplands and grasslands: Implementing the 4 per Thousand Initiative. *Journal of Soil and Water Conservation* **2016**, *71* (3), 68A−74A.

(10) Qafoku, N. P. Climate-Change Effects on Soils: Accelerated Weathering, Soil Carbon, and Elemental Cycling. In *Advances in Agronomy*; Sparks, D. L., Ed.; Academic Press: 2015; Vol. *131*, pp 111−172.

(11) Lal, R.; Monger, C.; Nave, L.; Smith, P. The role of soil in regulation of climate. *Philos. Trans R Soc. Lond B Biol. Sci.* **2021**, *376* (1834), 20210084.

(12) Paustian, K.; Larson, E.; Kent, J.; Marx, E.; Swan, A. Soil C Sequestration as a Biological Negative Emission Strategy. *Frontiers in Climate* **2019**, *1*, 8.

(13) American University. *Fact Sheet: Soil Carbon Sequestration. School of International Service, Institute for Carbon Removal Law & Policy*, 2020. https://www.american.edu/sis/centers/carbon-removal/fact-sheet-soil-carbon-sequestration.cfm#:~:text=Potential%20Scale%20and%20Costs&text=A%20recent%20expert%20assessment%20estimates,per%20ton%20of%20CO2. (accessed 2023-03-24).

(14) Cook-Patton, S. C.; Drever, C. R.; Griscom, B. W.; Hamrick, K.; Hardman, H.; Kroeger, T.; Pacheco, P.; Raghav, S.; Stevenson, M.; Webb, C.; Yeo, S.; Ellis, P. W. Protect, manage and then restore lands for climate mitigation. *Nature Climate Change* **2021**, *11* (12), 1027−1034.

(15) Mbow, C., Rosenzweig, C.; Barioni, L. G.; Benton, T. G.; Herrero, M.; Krishnapillai, M.; Liwenga, E.; Pradhan, P.; Rivera-Ferre, M. G., Sapkota, T.; Tubiello, F. N.; Xu, Y. Food Security. In *Climate Change and Land: IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems*, Shukla, P. R., Calvo Buendia, E., Masson-Delmotte, V., Pörtner, H.-O., Roberts, D. C., Zhai, P., Slade, R., Connors, S., van Diemen, R., Ferrat, M., Haughey, E., Luz, S., Neogi, S., Pathak, M., Petzold, J., Portugal Pereira, J., Vyas, P., Huntley, E., Kissick, K., Belkacemi, M., Malley, J., Eds.; Cambridge University Press: 2022; pp 437−550.

(16) Rosenzweig, C.; Mbow, C.; Barioni, L. G.; Benton, T. G.; Herrero, M.; Krishnapillai, M.; Liwenga, E. T.; Pradhan, P.; Rivera-Ferre, M. G.; Sapkota, T.; Tubiello, F. N.; Xu, Y.; Mencos Contreras, E.; Portugal-Pereira, J. Climate change responses benefit from a global food system approach. *Nature Food* **2020**, *1* (2), 94−97.

(17) Zurek, M.; Hebinck, A.; Selomane, O. Climate change and the urgency to transform food systems. *Science* **2022**, *376* (6600), 1416−1421.

(18) Pérez-Blanco, C. D.; Loch, A.; Ward, F.; Perry, C.; Adamson, D. Agricultural water saving through technologies: a zombie idea. *Environmental Research Letters* **2021**, *16* (11), No. 114032.

(19) Pia Oberč, B.; Schnell, A. A. *Approaches to sustainable agriculture*; International Union for Conservation of Nature (IUCN): 2020.

(20) Giller, K. E.; Hijbeek, R.; Andersson, J. A.; Sumberg, J. Regenerative Agriculture: An agronomic perspective. *Outlook on Agriculture* **2021**, *50* (1), 13−25.

(21) Goodman, W.; Minner, J. Will the urban agricultural revolution be vertical and soilless? A case study of controlled environment agriculture in New York City. *Land Use Policy* **2019**, *83*, 160−173.

(22) Ingram, J.; Maye, D. What Are the Implications of Digitalisation for Agricultural Knowledge. *Frontiers in Sustainable Food Systems* **2020**, *4*, 66.

(23) McGuire, A. *Regenerative Agriculture: Solid Principles, Extraordinary Claims*. https://csanr.wsu.edu/regen-ag-solid-principles-extraordinary-claims/ (accessed 2022-07-18).

(24) Saiz-Rubio, V.; Rovira-Más, F. From Smart Farming towards Agriculture 5.0: A Review on Crop Data Management. *Agronomy* **2020**, *10* (2), 207.

(25) Elevitch, C. R.; Mazaroli, D. N.; Ragone, D. Agroforestry Standards for Regenerative Agriculture. *Sustainability* **2018**, *10* (9), 3337.

(26) LaCanne, C.; Lundgren, J. Regenerative agriculture: Merging farming and natural resource conservation profitably. *PeerJ.* **2018**, *6*, No. e4428.

(27) Kremen, C. Ecological intensification and diversification approaches to maintain biodiversity, ecosystem services and food production in a changing world. *Emerg Top Life Sci.* **2020**, *4* (2), 229−240.

(28) MacLaren, C.; Mead, A.; Balen, D.; Claessens, L.; Etana, A.; Haan, J.; Haagsma, W.; Jäck, O.; Keller, T.; Labuschagne, J.; Myrbeck, Å.; Necpalova, M.; Nziguheba, G.; Six, J.; Strauss, J.; Swanepoel, P.; Thierfelder, C.; Topp, K.; Tshuma, F.; Storkey, J.; et al. Long-term evidence for ecological intensification as a pathway to sustainable agriculture. *Nature Sustainability* **2022**, *5*, 770.

(29) Bertoglio, R.; Corbo, C.; Renga, F. M.; Matteucci, M. The Digital Agricultural Revolution: A Bibliometric Analysis Literature Review. *IEEE Access* **2021**, *9*, 134762−134782.

(30) Engler, N.; Krarti, M. Review of energy efficiency in controlled environment agriculture. *Renewable and Sustainable Energy Reviews* **2021**, *141*, No. 110786.

(31) Gan, C. I.; Soukoutou, R.; Conroy, D. M. Sustainability Framing of Controlled Environment Agriculture and Consumer Perceptions: A Review. *Sustainability* **2023**, *15* (1), 304.

(32) Pretty, J. Intensification for redesigned and sustainable agricultural systems. *Science* **2018**, *362* (6417), eaav0294.

(33) Sahu, N.; Vasu, D.; Sahu, A.; Lal, N.; Singh, S., Strength of Microbes in Nutrient Cycling: A Key to Soil Health. In *Agriculturally Important Microbes for Sustainable Agriculture*; Meena, V. S., Mishra, P. K., Bisht, J. K., Pattanayak, A., Eds.; Springer: Singapore, 2017; Vol. *I*, pp 69−86.

(34) Kallenbach, C. M.; Frey, S. D.; Grandy, A. S. Direct evidence for microbial-derived soil organic matter formation and its ecophysiological controls. *Nat. Commun.* **2016**, *7* (1), 13630.

(35) Lewandowski, A. *Organic Matter Management*; Minnesota Institute for Sustainable Agriculture: 2000.

(36) U.S. DOE. U.S. Department of Energy Issues a Request for Information for Enhanced Weathering Research Opportunities. *Energy.gov*; U.S. Department of Energy, Office of Fossil Energy and Carbon Management: 2020.

(37) Newton, P.; Civita, N.; Frankel-Goldwater, L.; Bartel, K.; Johns, C. What Is Regenerative Agriculture? A Review of Scholar and Practitioner Definitions Based on Processes and Outcomes. *Frontiers in Sustainable Food Systems* **2020**, *4*, 577723.

(38) Garnett, T.; Godde, C.; Müller, A.; Röös, E.; Smith, P.; Boer, I. J. M.; zu Ermgassen, E.; Herrero, M.; Middelaar, C.; Schader, C.; Zanten, H. Grazed and confused? Ruminating on cattle, grazing systems, methane, nitrous oxide, the soil carbon sequestration question − and what it all means for greenhouse gas emissions. *LEAP*; University of Oxford: 2017

(39) Basche, A.; Miguez, F.; Kaspar, T.; Castellano, M. Do cover crops increase or decrease nitrous oxide emissions? A meta-analysis. *Journal of Soil and Water Conservation* **2014**, *69*, 471.

(40) Soane, B. D.; Ball, B. C.; Arvidsson, J.; Basch, G.; Moreno, F.; Roger-Estrade, J. No-till in northern, western and south-western Europe: A review of problems and opportunities for crop production and the environment. *Soil & Tillage Research* **2012**, *118*, 66−87.

(41) Kantola, I. B.; Masters, M. D.; Beerling, D. J.; Long, S. P.; DeLucia, E. H. Potential of global croplands and bioenergy crops for climate change mitigation through deployment for enhanced weathering. *Biology Letters* **2017**, *13* (4), No. 20160714.

(42) Strefler, J.; Amann, T.; Bauer, N.; Kriegler, E.; Hartmann, J. Potential and costs of carbon dioxide removal by enhanced weathering of rocks. *Environmental Research Letters* **2018**, *13*, 034010.

(43) Green, A. G.; Abdulai, A.-R.; Duncan, E.; Glaros, A.; Campbell, M.; Newell, R.; Quarshie, P.; KC, K. B.; Newman, L.; Nost, E.; Fraser, E. D. G. A scoping review of the digital agricultural revolution and ecosystem services: implications for Canadian policy and research agendas. *FACETS* **2021**, *6*, 1955−1985.

(44) Minasny, B.; Malone, B. P.; McBratney, A. B.; Angers, D. A.; Arrouays, D.; Chambers, A.; Chaplot, V.; Chen, Z.-S.; Cheng, K.; Das, B. S.; Field, D. J.; Gimona, A.; Hedley, C. B.; Hong, S. Y.; Mandal, B.; Marchant, B. P.; Martin, M.; McConkey, B. G.; Mulder, V. L.; O'Rourke, S.; Richer-de-Forges, A. C.; Odeh, I.; Padarian, J.; Paustian, K.; Pan, G.; Poggio, L.; Savin, I.; Stolbovoy, V.; Stockmann, U.; Sulaeman, Y.; Tsui, C.-C.; Vågen, T.-G.; van Wesemael, B.; Winowiecki, L. Soil carbon 4 per mille. *Geoderma* **2017**, *292*, 59−86.

(45) Schlesinger, W. H.; Amundson, R. Managing for soil carbon sequestration: Let's get realistic. *Global Change Biology* **2019**, *25* (2), 386−389.

(46) Gilchrist, J. *The Promise of Regenerative Agriculture: The Science-Backed Business Case and Mechanisms to Drive Adoption; E2*; National Resources Defenses Council: 2021; p 152.

(47) Diacono, M.; Montemurro, F. Long-term effects of organic amendments on soil fertility. *Sustainable Agriculture* **2011**, *2*, 761−786.

(48) Gravuer, K.; Gennet, S.; Throop, H. L. Organic amendment additions to rangelands: A meta-analysis of multiple ecosystem outcomes. *Global Change Biology* **2019**, *25* (3), 1152−1170.

(49) Owen, J.; Kebreab, E.; Silver, W. *Greenhouse Gas Mitigation Opportunities in California Agriculture: Review of Emissions and Mitigation Potential of Animal Manure Management and Land Application of Manure*; Nicholas Institute: Duke University, 2014.

(50) Singh, H.; Poudel, M. R.; Dunn, B.; Fontanier, C.; Kakani, G. Greenhouse Carbon Dioxide Supplementation with Irrigation and Fertilization Management of Geranium and Fountain Grass. *HortScience horts* **2020**, *55* (11), 1772−1780.

(51) Guenet, B.; Gabrielle, B.; Chenu, C.; Arrouays, D.; Balesdent, J.; Bernoux, M.; Bruni, E.; Caliman, J.-P.; Cardinael, R.; Chen, S.; Ciais, P.; Desbois, D.; Fouche, J.; Frank, S.; Henault, C.; Lugato, E.; Naipal, V.; Nesme, T.; Obersteiner, M.; Pellerin, S.; Powlson, D. S.; Rasse, D. P.; Rees, F.; Soussana, J.-F.; Su, Y.; Tian, H.; Valin, H.; Zhou, F. Can N2O emissions offset the benefits from soil organic carbon storage? *Global Change Biology* **2021**, *27* (2), 237−256.

(52) Zhang, Q.; Xiao, J.; Xue, J.; Zhang, L. Quantifying the Effects of Biochar Application on Greenhouse Gas Emissions from Agricultural Soils: A Global Meta-Analysis. *Sustainability* **2020**, *12* (8), 3436.

(53) Averill, C.; Waring, B. Nitrogen limitation of decomposition and decay: How can it occur? *Global Change Biology* **2018**, *24* (4), 1417−1427.

(54) Lugato, E.; Leip, A.; Jones, A. Mitigation potential of soil carbon management overestimated by neglecting N2O emissions. *Nature Climate Change* **2018**, *8* (3), 219−223.

(55) Poeplau, C.; Don, A. Carbon sequestration in agricultural soils via cultivation of cover crops − A meta-analysis. *Agriculture, Ecosystems & Environment* **2015**, *200*, 33−41.

(56) Abdalla, M.; Hastings, A.; Cheng, K.; Yue, Q.; Chadwick, D.; Espenberg, M.; Truu, J.; Rees, R. M.; Smith, P. A critical review of the impacts of cover crops on nitrogen leaching, net greenhouse gas balance and crop productivity. *Global Change Biology* **2019**, *25* (8), 2530−2543.

(57) Muhammad, I.; Sainju, U. M.; Zhao, F.; Khan, A.; Ghimire, R.; Fu, X.; Wang, J. Regulation of soil CO2 and N2O emissions by cover crops: A meta-analysis. *Soil and Tillage Research* **2019**, *192*, 103−112.

(58) Cai, A.; Han, T.; Ren, T.; Sanderman, J.; Rui, Y.; Wang, B.; Smith, P.; Xu, M.; Li, Y. e. Declines in soil carbon storage under no tillage can be alleviated in the long run. *Geoderma* **2022**, *425*, No. 116028.

(59) Ogle, S. M.; Alsaker, C.; Baldock, J.; Bernoux, M.; Breidt, F. J.; McConkey, B.; Regina, K.; Vazquez-Amabile, G. G. Climate and Soil Characteristics Determine Where No-Till Management Can Store Carbon in Soils and Mitigate Greenhouse Gas Emissions. *Sci. Rep.* **2019**, *9* (1), 11665.

(60) Feng, J.; Li, F.; Zhou, X.; Xu, C.; Ji, L.; Chen, Z.; Fang, F. Impact of agronomy practices on the effects of reduced tillage systems on CH4 and N2O emissions from agricultural fields: A global meta-analysis. *PLoS One* **2018**, *13* (5), e0196703−e0196703.

(61) Baker, J. M.; Ochsner, T. E.; Venterea, R. T.; Griffis, T. J. Tillage and soil carbon sequestration—What do we really know? *Agriculture, Ecosystems & Environment* **2007**, *118* (1), 1−5.

(62) Maucieri, C.; Tolomio, M.; McDaniel, M.; Zhang, Y.; Robatjazi, J.; Borin, M. No-tillage effects on soil CH4 fluxes: A meta-analysis. *Soil and Tillage Research* **2021**, *212*, No. 105042.

(63) Al-Kaisi, M.; Licht, M. A. *Impact of Tillage and Crop Rotation Systems on Carbon Sequestration*; Iowa State University: 2001.

(64) Powlson, D. S.; Stirling, C. M.; Jat, M. L.; Gerard, B. G.; Palm, C. A.; Sanchez, P. A.; Cassman, K. G. Limited potential of no-till agriculture for climate change mitigation. *Nature Climate Change* **2014**, *4* (8), 678−683.

(65) Beerling, D. J.; Leake, J. R.; Long, S. P.; Scholes, J. D.; Ton, J.; Nelson, P. N.; Bird, M.; Kantzas, E.; Taylor, L. L.; Sarkar, B.; Kelland, M.; DeLucia, E.; Kantola, I.; Müller, C.; Rau, G.; Hansen, J. Farming with crops and rocks to address global climate, food and soil security. *Nature Plants* **2018**, *4* (3), 138−147.

(66) Israeli, Y.; Emmanuel, S. Impact of grain size and rock composition on simulated rock weathering. *Earth Surface Dynamics Discussions* **2018**, *6*, 319.

(67) Edelmann, B.; Menker, C. *Enhanced weathering: When climate research takes unexpected turns*; Northwestern University, Medill School of Journalism, Media, and Integrated Marketing Communications, 2021. https://news.medill.northwestern.edu/chicago/enhanced-weathering-when-climate-research-takes-unexpected-turns/#:~:text=Enhanced%20weathering%20is%20a%20process,which%20breaks%20down%20the%20rock (accessed 2022-04-01).

(68) EASAC. *Negative emission technologies: What role in meeting Paris Agreement targets?* European Academies' Science Advisory Council: European Academies' Science Advisory Council, 2018.

(69) Olson, K. R.; Ebelhar, S. A.; Lang, J. M. Effects of 24 Years of Conservation Tillage Systems on Soil Organic Carbon and Soil Productivity. *Applied and Environmental Soil Science* **2013**, *2013*, 617504.

(70) Thamo, T.; Pannell, D. J.; Kragt, M. E.; Robertson, M. J.; Polyakov, M. Dynamics and the economics of carbon sequestration: common oversights and their implications. *Mitigation and Adaptation Strategies for Global Change* **2017**, *22* (7), 1095−1111.

(71) Lehmann, J.; Kleber, M. The contentious nature of soil organic matter. *Nature* **2015**, *528* (7580), 60−68.

(72) Guo, Y.; Wang, X.; Li, X.; Wang, J.; Xu, M.; Li, D. Dynamics of soil organic and inorganic carbon in the cropland of upper Yellow River Delta, China. *Sci. Rep.* **2016**, *6* (1), 36105.

(73) Tian, Y.; Wang, Q.; Gao, W.; Luo, Y.; Wu, L.; Rui, Y.; Huang, Y.; Xiao, Q.; Li, X.; Zhang, W. Organic amendments facilitate soil carbon sequestration via organic carbon accumulation and mitigation of inorganic carbon loss. *Land Degradation & Development* **2022**, *33* (9), 1423−1433.

(74) Charles, A.; Rochette, P.; Whalen, J. K.; Angers, D. A.; Chantigny, M. H.; Bertrand, N. Global nitrous oxide emission factors from agricultural soils after addition of organic amendments: A meta-analysis. *Agriculture, Ecosystems & Environment* **2017**, *236*, 88−98.

(75) Chen, H.; Li, X.; Hu, F.; Shi, W. Soil nitrous oxide emissions following crop residue addition: a meta-analysis. *Global Change Biology* **2013**, *19* (10), 2956−2964.

(76) Pilecco, G. E.; Chantigny, M. H.; Weiler, D. A.; Aita, C.; Thivierge, M.-N.; Schmatz, R.; Chaves, B.; Giacomini, S. J. Greenhouse gas emissions and global warming potential from biofuel cropping systems fertilized with mineral and organic nitrogen sources. *Science of The Total Environment* **2020**, *729*, No. 138767.

(77) Brenzinger, K.; Drost, S. M.; Korthals, G.; Bodelier, P. L. E. Organic Residue Amendments to Modulate Greenhouse Gas Emissions From Agricultural Soils. *Frontiers in Microbiology* **2018**, *9*, 3035.

(78) Borchard, N.; Schirrmann, M.; Cayuela, M. L.; Kammann, C.; Wrage-Mönnig, N.; Estavillo, J. M.; Fuertes-Mendizábal, T.; Sigua, G.; Spokas, K.; Ippolito, J. A.; Novak, J. Biochar, soil and land-use interactions that reduce nitrate leaching and N2O emissions: A meta-analysis. *Science of The Total Environment* **2019**, *651*, 2354−2364.

(79) Song, Y.; Li, Y.; Cai, Y.; Fu, S.; Luo, Y.; Wang, H.; Liang, C.; Lin, Z.; Hu, S.; Li, Y.; Chang, S. X. Biochar decreases soil N2O emissions in Moso bamboo plantations through decreasing labile N concentrations, N-cycling enzyme activities and nitrification/denitrification rates. *Geoderma* **2019**, *348*, 135−145.

(80) Mei, K.; Wang, Z.; Huang, H.; Zhang, C.; Shang, X.; Dahlgren, R. A.; Zhang, M.; Xia, F. Stimulation of N2O emission by conservation tillage management in agricultural lands: A meta-analysis. *Soil and Tillage Research* **2018**, *182*, 86−93.

(81) Behnke, G. D.; Villamil, M. B. Cover crop rotations affect greenhouse gas emissions and crop production in Illinois, USA. *Field Crops Research* **2019**, *241*, No. 107580.

(82) Amann, T.; Hartmann, J.; Struyf, E.; de Oliveira Garcia, W.; Fischer, E. K.; Janssens, I.; Meire, P.; Schoelynck, J. Enhanced Weathering and related element fluxes − a cropland mesocosm approach. *Biogeosciences* **2020**, *17* (1), 103−119.

(83) Kantzas, E. P.; Val Martin, M.; Lomas, M. R.; Eufrasio, R. M.; Renforth, P.; Lewis, A. L.; Taylor, L. L.; Mecure, J.-F.; Pollitt, H.; Vercoulen, P. V.; Vakilifard, N.; Holden, P. B.; Edwards, N. R.; Koh, L.; Pidgeon, N. F.; Banwart, S. A.; Beerling, D. J. Substantial carbon drawdown potential from enhanced rock weathering in the United Kingdom. *Nature Geoscience* **2022**, *15* (5), 382−389.

(84) Blanc-Betes, E.; Kantola, I. B.; Gomez-Casanovas, N.; Hartman, M. D.; Parton, W. J.; Lewis, A. L.; Beerling, D. J.; DeLucia, E. H. In silico assessment of the potential of basalt amendments to reduce N2O emissions from bioenergy crops. *GCB Bioenergy* **2021**, *13* (1), 224−241.

(85) Zhou, G.; Gao, S.; Xu, C.; Dou, F.; Shimizu, K.-y.; Cao, W. Rational utilization of leguminous green manure to mitigate methane emissions by influencing methanogenic and methanotrophic communities. *Geoderma* **2020**, *361*, No. 114071.

(86) Spokas, K. A.; Cantrell, K. B.; Novak, J. M.; Archer, D. W.; Ippolito, J. A.; Collins, H. P.; Boateng, A. A.; Lima, I. M.; Lamb, M. C.; McAloon, A. J.; Lentz, R. D.; Nichols, K. A. Biochar: a synthesis of its agronomic impact beyond carbon sequestration. *J. Environ. Qual* **2012**, *41* (4), 973−89.

(87) Joseph, S.; Cowie, A. L.; Van Zwieten, L.; Bolan, N.; Budai, A.; Buss, W.; Cayuela, M. L.; Graber, E. R.; Ippolito, J. A.; Kuzyakov, Y.; Luo, Y.; Ok, Y. S.; Palansooriya, K. N.; Shepherd, J.; Stephens, S.; Weng, Z.; Lehmann, J. How biochar works, and when it doesn't: A review of mechanisms controlling soil and plant responses to biochar. *GCB Bioenergy* **2021**, *13* (11), 1731−1764.

(88) Ahmad, S.; Li, C.; Dai, G.; Zhan, M.; Wang, J.; Pan, S.; Cao, C. Greenhouse gas emission from direct seeding paddy field under different rice tillage systems in central China. *Soil and Tillage Research* **2009**, *106* (1), 54−61.

(89) Harada, H.; Kobayashi, H.; Shindo, H. Reduction in greenhouse gas emissions by no-tilling rice cultivation in Hachirogata polder, northern Japan: Life-cycle inventory analysis. *Soil Science and Plant Nutrition* **2007**, *53* (5), 668−677.

(90) Hao, Q.; Jiang, C.; Chai, X.; Huang, Z.; Fan, Z.; Xie, D.; He, X. Drainage, no-tillage and crop rotation decreases annual cumulative emissions of methane and nitrous oxide from a rice field in Southwest China. *Agriculture, Ecosystems & Environment* **2016**, *233*, 270−281.

(91) Gong, Y.; Li, P.; Sakagami, N.; Komatsuzaki, M. No-tillage with rye cover crop can reduce net global warming potential and yield-scaled global warming potential in the long-term organic soybean field. *Soil and Tillage Research* **2021**, *205*, No. 104747.

(92) Li, J.; Wang, S.; Shi, Y.; Zhang, L.; Wu, Z. Do Fallow Season Cover Crops Increase N2O or CH4 Emission from Paddy Soils in the Mono-Rice Cropping System? *Agronomy* **2021**, *11* (2), 199.

(93) Sanz-Cobena, A.; García-Marco, S.; Quemada, M.; Gabriel, J. L.; Almendros, P.; Vallejo, A. Do cover crops enhance N2O, CO2 or CH4 emissions from soil in Mediterranean arable systems? *Science of The Total Environment* **2014**, *466−467*, 164−174.

(94) Wang, Y.; Saikawa, E.; Avramov, A.; Hill, N. S. Agricultural Greenhouse Gas Fluxes Under Different Cover Crop Systems. *Frontiers in Climate* **2022**, *3*, 742320.

(95) Beerling, D. J.; Kantzas, E. P.; Lomas, M. R.; Wade, P.; Eufrasio, R. M.; Renforth, P.; Sarkar, B.; Andrews, M. G.; James, R. H.; Pearce, C. R.; Mercure, J.-F.; Pollitt, H.; Holden, P. B.; Edwards, N. R.; Khanna, M.; Koh, L.; Quegan, S.; Pidgeon, N. F.; Janssens, I. A.; Hansen, J.; Banwart, S. A. Potential for large-scale CO2 removal via enhanced rock weathering with croplands. *Nature* **2020**, *583* (7815), 242−248.

(96) Balafoutis, A.; Beck, B.; Fountas, S.; Vangeyte, J.; van der Wal, T.; Soto, I.; Gómez-Barbero, M.; Barnes, A.; Eory, V. Precision Agriculture Technologies Positively Contributing to GHG Emissions Mitigation, Farm Productivity and Economics. *Sustainability* **2017**, *9*, 1339.

(97) Rees, R. M.; Maire, J.; Florence, A.; Cowan, N.; Skiba, U.; van der Weerden, T.; Ju, X. Mitigating nitrous oxide emissions from agricultural soils by precision management. *Front. Agr. Sci. Eng.* **2020**, *7* (1), 75−80.

(98) Woods, J.; Williams, A.; Hughes, J. K.; Black, M.; Murphy, R. Energy and the food system. *Philosophical Transactions of the Royal Society B: Biological Sciences* **2010**, *365* (1554), 2991−3006.

(99) Zhang, K.; Liang, X.; Zhang, Y.; Liu, X.; Cao, Q.; Zhu, Y.; Cao, W.; Chen, D.; Tian, Y. Unveiling the environmental and socio-economic benefits of precision nitrogen management for paddy fields in subtropical China. *European Journal of Agronomy* **2023**, *142*, No. 126663.

(100) Sanches, G. M.; Bordonal, R. d. O.; Magalhães, P. S. G.; Otto, R.; Chagas, M. F.; Cardoso, T. d. F.; Luciano, A. C. d. S. Towards greater sustainability of sugarcane production by precision agriculture to meet ethanol demands in south-central Brazil based on a life cycle assessment. *Biosystems Engineering* **2023**, *229*, 57−68.

(101) Medel-Jiménez, F.; Piringer, G.; Gronauer, A.; Barta, N.; Neugschwandtner, R. W.; Krexner, T.; Kral, I. Modelling soil emissions and precision agriculture in fertilization life cycle assessment - A case study of wheat production in Austria. *Journal of Cleaner Production* **2022**, *380*, No. 134841.

(102) Lapidus, D.; Salem, M. E.; Beach, R. H.; Zayed, S.; Ortiz-Monasterio, I. Greenhouse gas mitigation benefits and profitability of the GreenSeeker Handheld NDVI sensor: evidence from Mexico. *Precision Agriculture* **2022**, *23* (6), 2388−2406.

(103) Liu, C.; Wang, X.; Bai, Z.; Wang, H.; Li, C. Does Digital Technology Application Promote Carbon Emission Efficiency in Dairy Farms? Evidence from China. *Agriculture* **2023**, *13* (4), 904.

(104) Md. Rayhan, S.; Ayesha, S.; Scott, A. S. Precision Agriculture for Sustainable Soil and Crop Management. In *Soil Science*; Michael, A.; Indi, B., Eds.; IntechOpen: Rijeka, 2022; p Ch. 4.

(105) National Academies of Sciences, Engineering and Medicine. *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda*; The National Academies Press: Washington, DC, 2019; p 510.

(106) Cisternas, I.; Velásquez, I.; Caro, A.; Rodríguez, A. Systematic literature review of implementations of precision agriculture. *Computers and Electronics in Agriculture* **2020**, *176*, No. 105626.

(107) Kim, M.-Y.; Lee, K. H. Electrochemical Sensors for Sustainable Precision Agriculture—A Review. *Frontiers in Chemistry* **2022**, *10*, 848320.

(108) O'Sullivan, C. A.; Bonnett, G. D.; McIntyre, C. L.; Hochman, Z.; Wasson, A. P. Strategies to improve the productivity, product diversity and profitability of urban agriculture. *Agricultural Systems* **2019**, *174*, 133−144.

(109) Benis, K.; Ferrão, P. Commercial farming within the urban built environment − Taking stock of an evolving field in northern countries. *Global Food Security* **2018**, *17*, 30−37.

(110) Goldstein, B.; Hauschild, M.; Fernández, J.; Birkved, M. Urban versus conventional agriculture, taxonomy of resource profiles: a review. *Agronomy for Sustainable Development* **2016**, *36* (1), 9.

(111) Martin, M.; Molin, E. Environmental Assessment of an Urban Vertical Hydroponic Farming System in Sweden. *Sustainability* **2019**, *11* (15), 4124.

(112) Romeo, D.; Vea, E. B.; Thomsen, M. Environmental Impacts of Urban Hydroponics in Europe: A Case Study in Lyon. *Procedia CIRP* **2018**, *69*, 540−545.

(113) Nicholson, C. F.; Harbick, K.; Gómez, M. I.; Mattson, N. S. An economic and environmental comparison of conventional and controlled environment agriculture (CEA) supply chains for leaf lettuce to US cities. In *Food Supply Chains in Cities*; Palgrave Macmillan: Cham, 2020; pp 33−68.

(114) Barbosa, G. L.; Gadelha, F. D.; Kublik, N.; Proctor, A.; Reichelm, L.; Weissinger, E.; Wohlleb, G. M.; Halden, R. U. Comparison of Land, Water, and Energy Requirements of Lettuce Grown Using Hydroponic vs. Conventional Agricultural Methods. *Int. J. Environ. Res. Public Health* **2015**, *12* (6), 6879−91.

(115) Chen, P.; Zhu, G.; Kim, H.-J.; Brown, P. B.; Huang, J.-Y. Comparative life cycle assessment of aquaponics and hydroponics in the Midwestern United States. *Journal of Cleaner Production* **2020**, *275*, No. 122888.

(116) Poudel, M. R.; Dunn, B. *Greenhouse Carbon Dioxide Supplementation*; Oklahoma State University: 2017.

(117) Ehmke, T., Zuckerberg, K. S. *Vertical Farms Must Trim Costs, Hone Business Models to Achieve Profitability*; CoBank: 2022.

(118) Auburn University. *Are controlled environments the future of food production?* http://sustain.auburn.edu/are-controlled-environments-the-future-of-food-production/ (accessed 2023-07-12).

(119) Greig, R. *Apples to Apples: Are Vertical Farms Better for the Environment?* https://robinsongreig.medium.com/apples-to-apples-are-vertical-farms-better-for-the-environment-b80304ffa8cc (accessed 2023-03-22).

(120) Cohen, A. R.; Chen, G.; Berger, E. M.; Warrier, S.; Lan, G.; Grubert, E.; Dellaert, F.; Chen, Y. Dynamically Controlled Environment Agriculture: Integrating Machine Learning and Mechanistic and Physiological Models for Sustainable Food Cultivation. *ACS ES&T Engineering* **2022**, *2* (1), 3−19.

(121) Amundson, R.; Biardeau, L. Soil carbon sequestration is an elusive climate mitigation tool. *Proc. Natl. Acad. Sci. U. S. A.* **2018**, *115* (46), 11652−11656.

(122) Biardeau, L., Crebbin-Coates, R., Keerati, R., Litke, S., Rodríguez, H. *Soil health and carbon sequestration in US croplands: a policy analysis*; United States Department of Agriculture and the Berkeley Food Institute: 2016.

(123) Dessart, F. J.; Barreiro-Hurlé, J.; van Bavel, R. Behavioural factors affecting the adoption of sustainable farming practices: a policy-oriented review. *European Review of Agricultural Economics* **2019**, *46* (3), 417−471.

(124) Dickinson, D.; Balduccio, L.; Buysse, J.; Ronsse, F.; van Huylenbroeck, G.; Prins, W. Cost-benefit analysis of using biochar to improve cereals agriculture. *GCB Bioenergy* **2015**, *7* (4), 850−864.

(125) Bai, S. H.; Omidvar, N.; Gallart, M.; Kämper, W.; Tahmasbian, I.; Farrar, M. B.; Singh, K.; Zhou, G.; Muqadass, B.; Xu, C.-Y.; Koech, R.; Li, Y.; Nguyen, T. T. N.; van Zwieten, L. Combined effects of biochar and fertilizer applications on yield: A review and meta-analysis. *Science of The Total Environment* **2022**, *808*, No. 152073.

(126) Pittelkow, C. M.; Liang, X.; Linquist, B. A.; van Groenigen, K. J.; Lee, J.; Lundy, M. E.; van Gestel, N.; Six, J.; Venterea, R. T.; van Kessel, C. Productivity limits and potentials of the principles of conservation agriculture. *Nature* **2015**, *517* (7534), 365−368.

(127) Rowen, E. K.; Pearsons, K. A.; Smith, R. G.; Wickings, K.; Tooker, J. F. Early-season plant cover supports more effective pest control than insecticide applications. *Ecological Applications* **2022**, *32* (5), No. e2598.

(128) SARE. *Managing Cover Crops Profitably*, 3rd ed.; Clark, A., Ed.; Sustainable Agriculture Research and Education, 2012. https://www.sare.org/wp-content/uploads/Managing-Cover-Crops-Profitably.pdf.

(129) Purchasing Carbon Offsets FAQs. https://secondnature.org/climate-action-guidance/purchasing-carbon-offsets-faqs/#:~:text=How%20much%20do%20carbon%20offsets,project%2C%20and%20the%20vintage%20year. (accessed 2023-03-22).

(130) Dunn, E. G., The Latest Farm Product: Carbon Credits. *The New York Times*, 2021.

(131) *IndigoAg Paths to Profitability*. https://www.indigoag.com/paths-to-profitability (accessed 2023-07-15).

(132) Zhang, B.; Guo, C.; Lin, T.; Faaij, A. P. C. Economic optimization for a dual-feedstock lignocellulosic-based sustainable biofuel supply chain considering greenhouse gas emission and soil carbon stock. *Biofuels, Bioproducts and Biorefining* **2022**, *16* (3), 653−670.

(133) Liu, X.; Kwon, H.; Northrup, D.; Wang, M. Shifting agricultural practices to produce sustainable, low carbon intensity feedstocks for biofuel production. *Environmental Research Letters* **2020**, *15* (8), No. 084014.

(134) De La Torre Ugarte, D.; Hellwinckel, C. *Problem is the Solution: the Role of Biofuels in the Transition to a Regenerative Agriculture* **2010**, *66*, 365−384.

(135) Lowenberg-DeBoer, J.; Erickson, B. Setting the Record Straight on Precision Agriculture Adoption. *Agronomy Journal* **2019**, *111* (4), 1552−1569.

(136) Mulla, D.; Khosla, R. *Historical Evolution and Recent Advances in Precision Farming*; CRC Press: Boca Raton, FL; 2015; pp 1−36.

(137) Casa, R.; Cavalieri, A.; Lo Cascio, B. Nitrogen fertilisation management in precision agriculture: A preliminary application example on maize. *Italian Journal of Agronomy* **2011**, *6*, 5.

(138) Koutsos, T.; Menexes, G. Economic, Agronomic, and Environmental Benefits From the Adoption of Precision Agriculture Technologies: A Systematic Review. *International Journal of Agricultural and Environmental Information Systems (IJAEIS)* **2019**, *10* (1), 40−56.

(139) Liu, Y.; Langemeier, M. R.; Small, I. M.; Joseph, L.; Fry, W. E. Risk Management Strategies using Precision Agriculture Technology to Manage Potato Late Blight. *Agronomy Journal* **2017**, *109* (2), 562−575.

(140) Schimmelpfennig, D.; Ebel, R. Sequential Adoption and Cost Savings from Precision Agriculture. *Journal of Agricultural and Resource Economics* **2016**, *41* (1), 97−115.

(141) Nawar, S.; Corstanje, R.; Halcro, G.; Mulla, D.; Mouazen, A. M. Chapter Four - Delineation of Soil Management Zones for Variable-Rate Fertilization: A Review. In *Advances in Agronomy*; Sparks, D. L., Ed.; Academic Press: 2017; Vol. *143*, pp 175−245.

(142) Thompson, N. M.; Bir, C.; Widmar, D. A.; Mintert, J. R. FARMER PERCEPTIONS OF PRECISION AGRICULTURE TECHNOLOGY BENEFITS. *Journal of Agricultural and Applied Economics* **2019**, *51* (1), 142−163.

(143) García, L.; Parra, L.; Jimenez, J. M.; Lloret, J.; Lorenz, P. IoT-Based Smart Irrigation Systems: An Overview on the Recent Trends on Sensors and IoT Systems for Irrigation in Precision Agriculture. *Sensors* **2020**, *20* (4), 1042.

(144) Canaj, K.; Parente, A.; D'Imperio, M.; Boari, F.; Buono, V.; Toriello, M.; Mehmeti, A.; Montesano, F. F. Can Precise Irrigation Support the Sustainability of Protected Cultivation? A Life-Cycle Assessment and Life-Cycle Cost Analysis. *Water* **2022**, *14* (1), 6.

(145) Troiano, S.; Carzedda, M.; Marangon, F. Better richer than environmentally friendly? Describing preferences toward and factors affecting precision agriculture adoption in Italy. *Agricultural and Food Economics* **2023**, *11* (1), 16.

(146) Medici, M.; Pedersen, S. M.; Canavari, M.; Anken, T.; Stamatelopoulos, P.; Tsiropoulos, Z.; Zotos, A.; Tohidloo, G. A web-tool for calculating the economic performance of precision agriculture technology. *Computers and Electronics in Agriculture* **2021**, *181*, No. 105930.

(147) Mizik, T. How can precision farming work on a small scale? A systematic literature review. *Precision Agriculture* **2023**, *24* (1), 384−406.

(148) Birner, R.; Daum, T.; Pray, C. Who drives the digital revolution in agriculture? A review of supply-side trends, players and challenges. *Applied Economic Perspectives and Policy* **2021**, *43* (4), 1260−1285.

(149) Pathak, H. S.; Brown, P.; Best, T. A systematic literature review of the factors affecting the precision agriculture adoption process. *Precision Agriculture* **2019**, *20* (6), 1292−1316.

(150) Pignatti, E.; Carli, G.; Canavari, M. What really matters? A qualitative analysis on the adoption of innovations in agriculture. *Journal of Agricultural Informatics* **2015**, DOI: 10.17700/jai.2015.6.4.212.

(151) Tey, Y. S.; Brindal, M. Factors influencing the adoption of precision agricultural technologies: a review for policy implications. *Precision Agriculture* **2012**, *13* (6), 713−730.

(152) Barreto, L.; Amaral, A. In *Smart Farming: Cyber Security Challenges*, 2018 International Conference on Intelligent Systems (IS), 25−27 Sept 2018; 2018; pp 870−876.

(153) Capmourteres, V.; Adams, J.; Berg, A.; Fraser, E.; Swanton, C.; Anand, M. Precision conservation meets precision agriculture: A case study from southern Ontario. *Agricultural Systems* **2018**, *167*, 176−185.

(154) USDA. *USDA Expands and Renews Conservation Reserve Program in Effort to Boost Enrollment and Address Climate Change*; United States Department of Agriculture: Natural Resources Conservation Service, 2021.

(155) Gómez, C.; Currey, C. J.; Dickson, R. W.; Kim, H.-J.; Hernández, R.; Sabeh, N. C.; Raudales, R. E.; Brumfield, R. G.; Laury-Shaw, A.; Wilke, A. K.; Lopez, R. G.; Burnett, S. E. Controlled Environment Food Production for Urban Agriculture. *HortScience horts* **2019**, *54* (9), 1448−1458.

(156) *Vertical Farming Market Analysis By Structure, By Component (Hardware, Software, Services), By Growing Mechanism (Aeroponics, Hydroponics), By Crop Category (Fruits Vegetables, & Herbs, Flowers & Ornamentals) And Segment Forecasts, 2023*−*2030*; Grand View Research, 2022.

(157) Businesswire Europe Indoor Farming Market Size, Share & Industry Trends Analysis Report 2022−2028. https://www.businesswire.com/news/home/20220615005838/en/Europe-Indoor-Farming-Market-Size-Share-Industry-Trends-Analysis-Report-2022-2028---ResearchAndMarkets.com (accessed 2023-04-13).

(158) Baumont de Oliveira, F. J.; Ferson, S.; Dyer, R. A. D.; Thomas, J. M. H.; Myers, P. D.; Gray, N. G. How High Is High Enough? Assessing Financial Risk for Vertical Farms Using Imprecise Probability. *Sustainability* **2022**, *14* (9), 5676.

(159) Liaros, S.; Botsis, K.; Xydis, G. Technoeconomic evaluation of urban plant factories: The case of basil (Ocimum basilicum). *Science of The Total Environment* **2016**, *554*−*555*, 218−227.

(160) Zhang, H.; Asutosh, A.; Hu, W. Implementing Vertical Farming at University Scale to Promote Sustainable Communities: A Feasibility Analysis. *Sustainability* **2018**, *10* (12), 4429.

(161) Morella, P.; Lambán, M. P.; Royo, J.; Sánchez, J. C. Vertical Farming Monitoring: How Does It Work and How Much Does It Cost? *Sensors (Basel)* **2023**, *23* (7), 3502.

(162) Benis, K.; Reinhart, C.; Ferrão, P. Building-Integrated Agriculture (BIA) In Urban Contexts: Testing A Simulation-Based Decision Support Workflow. *Proceedings of Buidling Simulation 2017: 15th Conference of IBPSA* **2017**.

(163) Eaves, J.; Eaves, S. Comparing the Profitability of a Greenhouse to a Vertical Farm in Quebec. *Canadian Journal of Agricultural Economics/Revue canadienne d'agroeconomie* **2018**, *66* (1), 43−54.

(164) Moshari, A.; Aslani, A.; Entezari, A.; Ghanbari, K. Performance assessment of the integration of semitransparent solar cells with different geometry of greenhouses under different climate regions. *Environ. Sci. Pollut Res. Int.* **2023**, *30* (22), 62281−62294.

(165) Semuels, A. Dinner As We Know it Is Hurting the Planet. But What If We Radically Rethink How We Make Food?. *Time*, 2020

(166) Marsten, J. Brief: Vertical farm network InFarm to lay off 'more than half' of workforce, downsize operations. *AgFunderNews*, 2022

(167) Guan, K.; Jin, Z.; DeLucia, E. H.; Paul, W.; Peng, B.; Tang, J.; Jiang, C.; Wang, S.; Kim, T.; Zhou, W.; Griffis, T.; Liu, L.; Qin, Z.; Margenot, A. J.; Kumar, V.; Bernacchi, C. J.; Yang, W. H.; Lee, D.; Coppess, J. W.; Gerber, J. G.; Jahn, M.; Khanna, M.; Yang, S.-J. A framework for scalably quantifying field-level agricultural carbon outcomes. *Earth ArXiv*, October 25, 2022, ver. 4. https://eartharxiv.org/repository/view/2905/.

(168) Parihar, C. M.; Meena, B. R.; Nayak, H. S.; Patra, K.; Sena, D. R.; Singh, R.; Jat, S. L.; Sharma, D. K.; Mahala, D. M.; Patra, S.; Rupesh; Rathi, N.; Choudhary, M.; Jat, M. L.; Abdallah, A. M. Co-implementation of precision nutrient management in long-term conservation agriculture-based systems: A step towards sustainable energy-water-food nexus. *Energy* **2022**, *254*, 124243.