A Review of Grassland Ecosystems as Carbon Sinks: Opportunities and Challenges for Climate-Smart Land Use and Agriculture

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ABSTRACT

Grassland ecosystems plays a crucial role as carbon sinks, presenting opportunities for climate-smart land use and agriculture. Through the implementation of sustainable management practices, these ecosystems can enhance carbon sequestration, mitigate climate change, and bolster agricultural productivity. Nevertheless, challenges such as land degradation, overgrazing, and climate variability must be addressed to fully realize the potential of grasslands as carbon sinks. This review elucidates the role of grassland ecosystems in the global carbon cycle, emphasizing their capacity to sequester carbon and mitigate climate change. It explores strategies such as agro-silvo pastoralism, which integrates trees, livestock, and crops, and integrated crop-livestock systems, which optimize resource use and carbon storage. The review aims to provide insights into sustainable land use practices for climate change mitigation and ecosystem health. Despite ongoing research, uncertainties persist regarding the impact of land use patterns on climate change. This review underscores the importance of effective grassland management and land-use patterns that prioritize carbon sinks in mitigating climate change. These systems offer a threefold climate benefit: enhanced carbon sequestration, increased soil organic carbon storage, and reduced anthropogenic CO_2 emissions. The study emphasizes the necessity of integrating land change science into global environmental research and sustainability initiatives, and highlights the significance of vegetative cover restoration, sustainable ecosystem management, and modified land-use patterns in promoting healthier soil carbon stocks and mitigating climate change impacts. By adopting sustainable land use practices, we can enhance biomass yields, increase carbon inputs, and promote environmental resilience, ultimately contributing to climate change mitigation efforts.

Keywords: Grasslands; Agro-Silvo Pastoralism; Crop Livestock Integration; C Sequestration; GHG, Climate Change.

INTRODUCTION

Grasslands cover a significant portion of the world's land, approximately 26%, and a substantial 70% of its agricultural land. These ecosystems play a vital role in carbon sequestration, storing around 20% of global soil carbon (Conant, 2010). To combat global warming, it is crucial to promote sustainable grassland management and land use practices that enhance carbon sinks, thereby reducing atmospheric CO2 levels and contributing to carbon neutrality targets. Land use patterns associated with grasslands and animal agriculture can significantly influence greenhouse gas emissions and carbon accumulation (Gaitán et al., 2016). The effects of animal agriculture on grasslands are multifaceted, impacting local biodiversity, soil composition, nutrient cycles, regional albedo, and hydrology, as well as global greenhouse gas and aerosol levels (Lee et al., 2020). Implementing sustainable grassland management techniques, such as optimized grazing, pasture enhancement, and restoration of degraded pastures, is essential for boosting soil carbon sequestration and preventing further warming from managed grasslands (Weindl et al., 2017). Soil organic carbon (SOC) is a critical component of soil quality and ecosystem services, and its sequestration is increasingly recognized as a potential solution to offset greenhouse gas emissions and climate change effects (Zomer et al., 2017). The rapid depletion of grassland soil carbon due to improper land use necessitates sustainable restoration efforts to increase soil storage capacity (Liu et al., 2023). By adopting sustainable land use practices and promoting effective grassland management, we can enhance soil carbon sequestration, mitigate climate change impacts, and maintain ecosystem service.

Land use and changes are shaped by the complex interplay between human activities and natural systems. The relationship between land cover and greenhouse gas concentrations, as well as the contribution of land use to climate change, has been well-documented (Boddey et al., 2020; Conant et al., 2017; Damian et al., 2021; Gerber et al., 2013; Luo et al., 2017; Powlson et al., 2013; Pretty et al., 2018). Agricultural land use, in particular, has a substantial impact on greenhouse gas emissions, and it has been suggested that land-use systems can play a crucial role in mitigating climate change (O'Mara, 2012). Various land use types are essential for atmospheric carbon sequestration, helping to stabilize carbon in both solid and aqueous forms, and thereby contributing to global warming mitigation (Herrero et al., 2016; Smith et al., 2008). The significance of land-use changes in climate policy cannot be overstated, as highlighted by Searchinger et al. (2018) and Edenhofer et al. (2014), who note the considerable loss of native vegetation and soil carbon storage resulting from land-use changes. The complex relationships between land use, climate change, and carbon sequestration underscore the need for sustainable land use practices that prioritize carbon sinks and mitigate greenhouse gas emissions. By adopting effective land use strategies, we can reduce the environmental impacts of land use and promote a more sustainable future.

Land use practices, such as agroforestry technologies, including agro-silvo pastoralism, are essential for reducing greenhouse gas emissions and enabling animal agriculture to adapt to climate change (Verchot et al., 2007). Silvopastoral systems, which integrate trees and shrubs with forage grasses, have been shown to improve animal nutrition, enhance soil health, and promote carbon sequestration (Murgueitio et al., 2011). By adopting agroforestry methods, carbon storage in animal agriculture lands can be increased, potentially offsetting greenhouse gas emissions and enhancing ecosystem services through the transformation of land into tree-based systems, such as agro-silvo pastoralism. Research has demonstrated the effectiveness of sustainable land management practices in promoting carbon sequestration, with studies showing significant carbon sequestration rates in various land use types (Terefe et al., 2020). The implementation of sustainable land use practices, such as agroforestry and silvopastoral systems, can have numerous benefits, including improved animal nutrition, enhanced soil health, and increased carbon sequestration. By adopting these practices, we can promote ecosystem services, mitigate climate change, and support sustainable agriculture.

Research suggests that agricultural methods, such as crop-livestock or crop-livestock-forestry systems, can significantly impact soil carbon stocks (Oldfeld et al., 2022). Integrated crop-livestock systems (ICLSs) have been shown to produce fewer greenhouse gas emissions, with a reduction of 24-37% compared to grazing systems (Brewer and Gaudin, 2020). These integrated approaches have demonstrated improved productivity, sustainability, and resilience to climate change compared to specialized agricultural methods. Reintroducing ICLSs into cropland has been proposed as a strategy to decrease the greenhouse gas footprint of animal agriculture (Thornton and Herrero, 2015). However, the impact of ICLSs on greenhouse gas fluxes is inconsistent due to the complex nature of emission reduction strategies, and the specific methods involved are not always clear (Sanderson et al., 2013). Further research is needed to understand the mechanisms underlying the benefits of ICLSs and to develop effective strategies for reducing greenhouse gas emissions.

Soil carbon sequestration is a vital strategy for mitigating climate change by reducing greenhouse gas levels and offsetting emissions. The preservation and accumulation of carbon in soil are significantly influenced by climate, as highlighted by the Intergovernmental Panel on Climate Change (IPCC, 2007) and various studies (Fidalgo et al., 2007; Conant et al., 2001). Climate change impacts grassland soil organic carbon storage by altering plant carbon input processes and microbial metabolism, as recently underscored by Bai and Cotrufo (2022). Several strategies have been proposed to enhance soil carbon sequestration rates, including reforestation, afforestation, and conservation practices (Post and Kwon, 2000). Grassland carbon sequestration and sustainable land use patterns can increase soil carbon storage, reduce CO_2 emissions, and protect global environmental security, thereby mitigating the impact of climate change on animal agriculture (Brock et al., 2023; Ruehr et al., 2023). However, animal agriculture and its associated land use management face the challenge of balancing food demand with minimizing carbon release into the atmosphere and sustaining environmental sustainability. Despite the potential of grasslands and animal agriculture land use patterns to contribute to climate change mitigation, knowledge gaps remain. These include quantifying water productivity and improving efficiency in mixed crop systems (Descheemaeker et al., 2010). Moreover, implementing measures to enhance carbon sequestration in forage and grazing and reduce greenhouse gas emissions requires consideration of institutions, policies, and gender roles in animal agriculture-related land use systems.

This review aims to examine the potential of grasslands and animal agriculture land use patterns to reduce greenhouse gas emissions and increase carbon accumulation. Specifically, the study will review existing literature on grassland ecosystems as carbon sinks, identify their potential for mitigating climate change, discuss strategies for managing and restoring these ecosystems, and explore their implications for climate-smart land use and agriculture. By addressing gaps in understanding the complex relationships between grassland ecosystems, carbon sequestration, and climate change, this study aims to contribute to the development of effective strategies for managing grassland ecosystems as carbon sinks and promoting sustainable land use practices.

METHODOLOGY

Literature Search Methodology

A comprehensive literature search was conducted using PubMed, Scopus, and Web of Science databases to identify relevant articles published between 2000 and 2023. The search focused on subjects related to agriculture and environment, and articles were sorted based on their relevance to the study.

Search Strategy and Inclusion Criteria

Peer-reviewed articles were identified using specific keywords, including "carbon sequestration," "climate change mitigation," "grasslands," "agro-silvo pastoralism," "integrated crop livestock systems," "land use patterns," and "sustainable development." The search approach was semi-systematic and integrative, progressing from broad to specific concepts (Snyder, 2019).

Thematic Analysis and Study Selection

The thematic analysis revealed five key themes:

i. Carbon Cycle Dynamics: A key factor in global warming phenomena.

ii. Synergies between Microbial and Plant Diversity: Soil factors in carbon sequestration and cycling.

iii. Grassland-based Livestock Production: Trends and implications for mitigating anthropogenic CO_2 emissions.

Study Screening and Data Extraction

Two reviewers independently screened titles, abstracts, and full texts. Data extraction was performed using a standardized form, and study quality was assessed using the Cochrane risk of bias tool.

Conceptual Framework for Examining Grasslands and Climate-Smart Land Use and Agriculture

The conceptual framework explores the capacity of grasslands and climate-smart land use and agriculture to sequester carbon and mitigate greenhouse gas (GHG) emissions. This framework considers the complex relationships between grassland ecosystems, land use practices, and climate change, with a focus on identifying effective strategies for promoting carbon sequestration and reducing GHG emissions. The framework consists of key components, including grassland ecosystems, climate-smart land use and agriculture, carbon sequestration, and GHG emissions mitigation. Grassland ecosystems cover a significant portion of Earth's surface, while climate-smart land use promotes sustainable agriculture and ecosystem services. Carbon sequestration captures and stores atmospheric carbon dioxide, while GHG emissions mitigation aims to reduce greenhouse gas emissions.

The conceptual framework for analyzing grasslands and Integrated Farming Systems (IFS) in their role in carbon sequestration and greenhouse gas (GHG) emissions mitigation is structured into three components: input factors, process factors, and output factors (Table 1). A feedback loop connects the input and output components. From the input perspective, various land use and management practices influence carbon sequestration and GHG emissions mitigation. These practices encompass afforestation, sustainable forest management, agroforestry, perennial crop production, urban forestry, conservation tillage, no-till farming, cover cropping, crop rotation and intercropping, organic amendments, integrated pest management, grazing management, and soil conservation techniques. Soil type and quality are critical input factors affecting carbon sequestration. Clay soils exhibit higher carbon retention due to increased surface area and reactivity, whereas sandy soils demonstrate lower retention due to reduced surface area and increased leaching. Loamy soils offer a balance between carbon retention and water infiltration, while peat soils possess high carbon storage capacity due to waterlogged conditions.

Table 1 illustrates that aggregated, diverse microbial communities and well-structured soils contribute to carbon sequestration by reducing erosion, enhancing water infiltration, and promoting carbon sequestration. Severe weather conditions can hinder carbon sequestration by causing soil disruption and plant destruction (Oktan et al 2022). Carbon sequestration and photosynthesis are most effective at temperatures ranging from 10 to 25°C (Nayak et al 2022). Plant growth and carbon sequestration are optimal with annual precipitation between 500 and 1,500 mm.

Grazing exerts both positive and negative effects on carbon sequestration. Positive effects include increased soil organic carbon accumulation, above-ground biomass carbon storage, root growth, and improved soil structure (Han et al 2023). Negative effects encompass methane emissions, nitrogen oxide emissions, soil disturbance, and erosion. Optimal grazing practices involve rotational grazing, low-to-moderate stocking rates, mixed grazing, and the incorporation of legumes and forbs (Rouquette, et al 2023).

Optimal tillage practices, including no-till or reduced-till farming, conservation tillage, mulch tillage, and cover cropping, can enhance soil health (Thapa and Dura, 2024), and reduce greenhouse gas emissions (Alasinrin et al. 2024). Tillage negatively impacts carbon sequestration by causing soil disturbance, erosion, and oxidation of soil organic carbon (SOC), while positively affecting it by reducing methane emissions and increasing nitrogen availability for crops.

Integrated Livestock-Crop Systems can maximize the efficiency of nutrient cycling by utilizing manure and crop residues, reducing the need for artificial fertilizers (Sekaran et al 2021). This approach can enhance soil organic carbon (SOC) through the combination of grazing and crop cultivation, while also improving ecosystem services by creating more diverse landscapes.

Agroforestry systems, which combine trees and crops, can improve carbon sequestration, soil health, and biodiversity (Fahad et al 2022; Matos et al 2022). These systems reduce soil disturbance and erosion, while enhancing ecosystem services by storing biomass above-ground, promoting tree roots and litter. By integrating trees into agricultural landscapes, agroforestry systems can also promote more diverse and resilient ecosystems (Reppin et al 2020).

Climate change can impact grassland productivity and carbon sequestration, influencing farming practices

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through policy and economic incentives (Akpensuen, et al 2025; Abrar et al 2025). Additionally, climate change can impact soil health and fertility, which can in turn affect greenhouse gas emissions reduction (Kumar et al 2022).

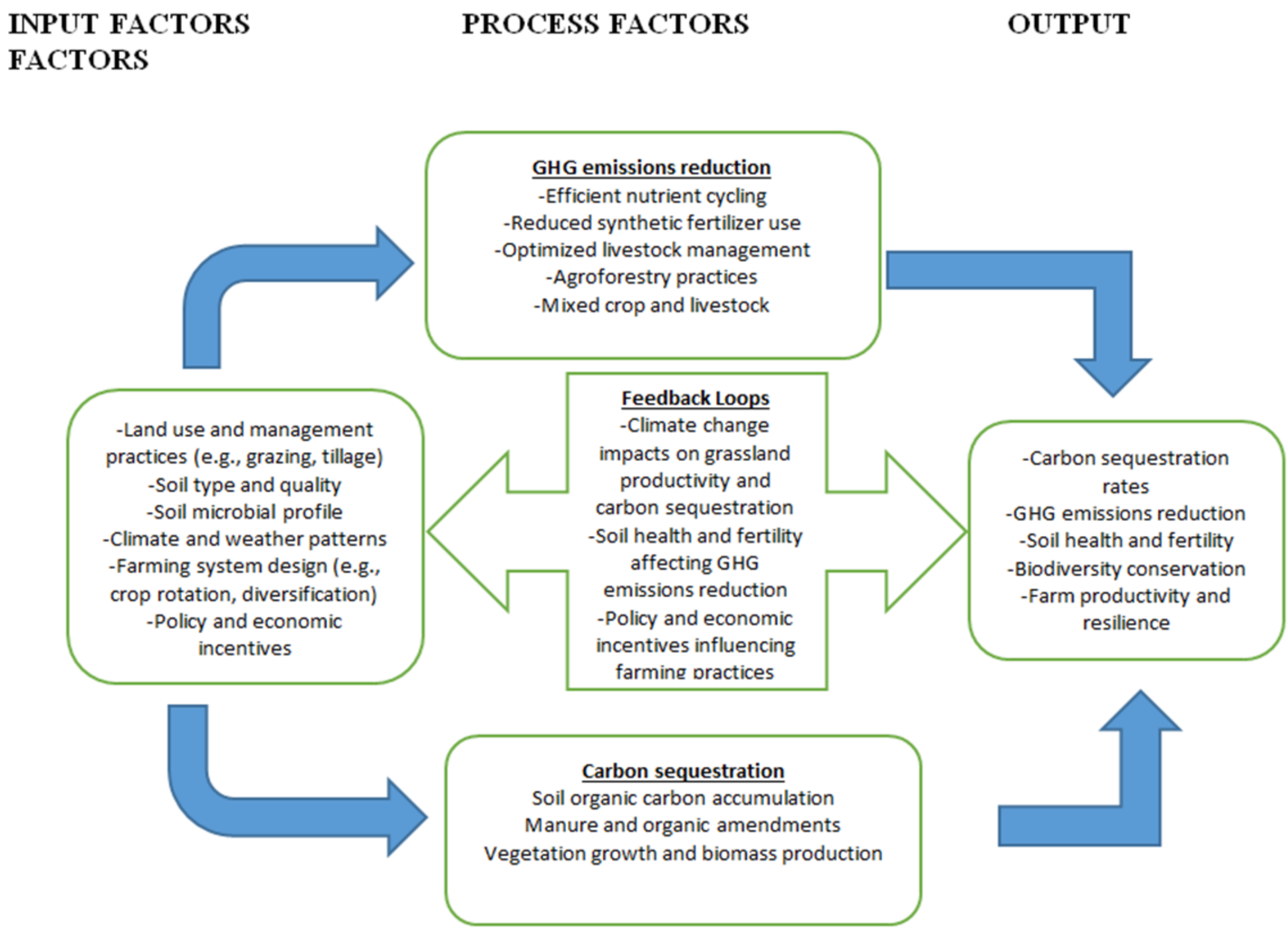

Figure 1 Conceptual Framework for Examining Grasslands and Climate-Smart Land Use and Agriculture in GHG Emission Dynamics.

The framework highlights the interconnections between grassland ecosystems, climate-smart land use and agriculture, carbon sequestration, and GHG emissions mitigation. It includes land use practices like grazing, agriculture, and conservation, ecosystem services like food, fiber, and climate regulation, and climate change impacts like temperature, precipitation, and weather patterns. These interconnections are crucial for sustainable land use and agriculture. The framework can be utilized in various contexts, such as sustainable land use planning, climate change mitigation, and ecosystem-based adaptation, to promote sustainable land use and agriculture, reduce GHG emissions, and promote carbon sequestration, while also addressing the impacts of climate change.

Carbon Cycle Dynamics: A Key Factor in Global Warming Phenomena

Carbon dioxide (CO2) is a potent greenhouse gas that plays a crucial role in regulating the Earth's temperature. By trapping heat from the Earth's surface, CO2 prevents the planet from becoming approximately 32.0°C colder (Mehmood et al., 2020). However, human activities have significantly increased CO2 concentrations in the atmosphere, leading to severe consequences for the Earth's natural environment. Agriculture, forestry, and other land use (AFOLU) are significant contributors to CO2 emissions, accounting for 23% of human-induced CO2, CH4, and N2O emissions between 2007 and 2016 (Jia et al., 2019). Human activities like transportation, industrial processes, and residential energy use contribute to the release of CO2 into the atmosphere. These activities release large amounts of CO2, disrupting the natural carbon cycle and causing global warming.

Rising CO_2 levels lead to climate change, altering temperature and precipitation patterns, altering ecosystems, and impacting biodiversity. The natural carbon cycle is disrupted, leading to changes in carbon storage and release. Current CO_2 emissions from human activities amount to approximately seven billion tons each year, contributing to the increasing concentrations and climate change impacts. Therefore, it is crucial to address these issues to mitigate the negative effects of climate change.

The carbon cycle is a complex process that involves the exchange of carbon between atmospheric, oceanic, and terrestrial reservoirs, and is intricately linked to the Earth's climate (Ciais et al., 2013). The global carbon cycle comprises three key components: atmospheric carbon, oceanic carbon, and terrestrial biosphere. Atmospheric carbon, influenced by human activities like fossil fuel burning and land-use changes, represents the amount of carbon dioxide in the atmosphere. Oceanic carbon, absorbed by the oceans, is influenced by ocean chemistry and circulation patterns. Terrestrial biosphere, stored in plants, soils, and other organic matter, is influenced by land-use changes, climate, and plant physiology. Natural processes, such as afforestation, play a crucial role in maintaining stable surface air temperatures and atmospheric CO_2 levels by balancing carbon emissions and absorption (Li et al., 2022). Natural carbon sinks, including forests, oceans, and soils, are critical in mitigating climate change by absorbing more than half of human-generated CO_2 emissions (Royal Society, 2018). These sinks help to regulate the Earth's climate by reducing the amount of CO_2 in the atmosphere, which in turn helps to slow down global warming. However, the unprecedented scale of human carbon production is disrupting the carbon cycle, potentially leading to severe climatic impacts.

Human activities, such as burning fossil fuels, deforestation, and land-use changes, are releasing large amounts of CO_2 into the atmosphere, which is altering the natural balance of the carbon cycle. The global carbon cycle is closely tied to the greenhouse effect and involves the continuous movement of carbon among various sources. The carbon cycle is a dynamic process that is constantly evolving, with new information being documented regularly (IPCC, 2018). This provides extensive references for students and researchers studying the carbon cycle and its connection to climate change. Understanding the carbon cycle and its connection to climate change is critical for developing effective strategies to mitigate and adapt to the impacts of climate change. By reducing greenhouse gas emissions and promoting carbon sequestration, we can help to stabilize the Earth's climate and reduce the risks associated with climate change.

Scientists have made significant progress in quantifying human-induced CO_2 emissions and oceanic carbon content. Research has improved our understanding of the increase in atmospheric CO_2 since 1750, particularly in relation to land-use changes and the terrestrial biosphere's response to climate shifts (IPCC, 2007). Global advancements have also been made in identifying key CO_2 flows, enabling more accurate assessments of carbon exchange (IPCC, 2013, 2014). The concept of "carbon-climate feedbacks" refers to the indirect effects that influence carbon exchange through ecosystem responses to climate change (Kaushik et al., 2020). Climate factors, such as temperature and precipitation patterns, modify the metabolism and productivity of land-based ecosystems, affecting their involvement in CO_2 exchange with the atmosphere (Andrew et al., 2018).

Researchers have gained a better understanding of the impact of land-use changes on atmospheric CO_2 levels since 1750, as well as the terrestrial biosphere's response to a changing climate (Jia et al., 2019). Globally, advancements in technology have improved the identification of major CO_2 flows, enabling more accurate assessments of carbon exchange and its relationship to climate change (Harris et al., 2022). These advances in understanding the carbon cycle and its relationship to climate change have significant implications for climate change research and policy. By improving our understanding of the complex interactions between the carbon cycle, climate change, and ecosystems, we can develop more effective strategies for mitigating and adapting to the impacts of climate change.

Biodiversity plays a significant role in the global carbon cycle and climate by influencing processes at the interface between the biosphere and atmosphere. Many Earth system models now incorporate a dynamic vegetation component, focusing on climate, plant physiology, and the efficiency of carbon assimilation (Buscardo et al., 2021). The global carbon cycle has been studied extensively, with notable representations provided by Bolin et al. (1979) and Wigley and Schimel's edited work in 2000. Post et al. (1990) presented a mathematical inventory of global carbon reservoirs and fluxes, while Hansen et al. (2007) summarized current knowledge regarding active carbon reservoirs on Earth. The global carbon cycle involves the exchange of carbon stocks in the atmosphere, ocean, and terrestrial biosphere, which is affected by various biological and geochemical processes (Rackey, 2023). This cycle is critical for understanding the impacts of rising atmospheric CO2 levels, climate change, and the eventual removal of CO2 through extensive implementation of negative emission technologies.

Stabilizing CO2 levels in the atmosphere is crucial for addressing climate change, and this can only be achieved through significant reductions in global CO2 emissions (Le Quéré et al., 2009). Moreover, the unpredictable effects of changes in CO2 sinks on future atmospheric CO2 concentrations highlight the importance of reducing uncertainties. Artificial methods for CO2 extraction include reforestation, mangrove restoration, kelp farming, sustainable agricultural practices, and cutting-edge technologies. These methods effectively absorb CO2 from the air through photosynthesis, promote carbon sequestration, and utilize sustainable agricultural practices. They also involve the development and deployment of advanced technologies to capture and utilize CO2.

Human activities have dramatically increased atmospheric levels of CO2 and other greenhouse gases. For a period spanning 20 million years, CO2 concentrations remained below 280 parts per million (ppm). However, human activities such as burning fossil fuels, deforestation, and land-use changes have led to a significant increase in atmospheric CO2 levels, contributing to climate change. Reducing CO2 emissions and promoting carbon sequestration are critical for mitigating climate change. By implementing artificial methods for CO2 extraction and reducing greenhouse gas emissions, we can help to stabilize the Earth's climate and reduce the risks associated with climate change.

The global carbon cycle is experiencing substantial alterations due to anthropogenic activities, with the escalation of carbon dioxide and methane emissions contributing to climate change (Guariguata, 2009). The equilibrium among the surface ocean, terrestrial biosphere, and atmosphere is being disrupted by the utilization of fossil fuels, human-induced land disturbances such as deforestation and urbanization, and indirect effects of climate warming, which impact permafrost, soils, and oceans, thereby altering carbon storage and release. Natural ecosystems, both terrestrial and marine, function as buffers, absorbing and storing nearly half of all CO2 emissions (Regnier et al., 2022). The research underscores the importance of comprehending the impact of extreme climate events on the terrestrial biosphere, noting that droughts and heatwaves can diminish regional ecosystem carbon reserves and modify terrestrial carbon uptake.

Despite the increase in anthropogenic greenhouse gas emissions, the natural carbon cycle has not kept pace, which has mitigated climate change and limited global temperature increases (Abellan et al., 2017). This underscores the necessity of understanding the intricate interactions between the carbon cycle, climate change, and ecosystems. Comprehending the impact of human activities on the global carbon cycle is crucial for devising effective strategies to mitigate climate change. By reducing greenhouse gas emissions and promoting carbon sequestration, we can contribute to stabilizing the Earth's climate and mitigating the risks associated with climate change.

Synergies between Microbial and Plant Diversity and Soil Factors in Carbon Sequestration and Cycling

Soil Microbial Communities: Key Players in the Carbon Cycle

Soil microbes play a vital role in carbon cycling within soil ecosystems by breaking down and transforming organic matter through various metabolic pathways, ultimately affecting soil carbon storage and turnover (Wu et al., 2024). This process is further facilitated by microbial carbon pumps, which enable carbon turnover in plants, soil, and microorganisms. Despite their importance, the ability of soil microbes to withstand and adapt to climate change remains poorly understood, even as the impacts of land use on soil ecosystems are well-documented (de Vries et al., 2012). The study of environmental microorganisms has led to the development of numerous biologically based agricultural methods and products (Kremer, 2017). Microorganisms are incredibly diverse, with a wide range of metabolisms and habitats, including soil, water, and even human beings (Onen et al., 2020). They are essential for maintaining Earth's biogeochemical cycles, yet the intricacies of their relationships with ecosystem processes remain understudied, despite the growing exploration of complex environmental microbial communities (Graham et al., 2016). Further research is needed to understand the role of soil microbes in carbon cycling and ecosystem processes. This includes investigating climate change's effects on soil microbial communities, developing sustainable agricultural practices that utilize beneficial microorganisms, and exploring the intricate connections between microorganisms and ecosystem processes. This knowledge can lead to more effective strategies for mitigating climate change and promoting sustainable ecosystem management.

Soil microorganisms are crucial for biodiversity and ecological processes such as carbon and nutrient cycling (Delgado-Baquerizo et al 2018). Microbial biomass carbon, a measure of soil organic carbon (SOC), increases in plant mixtures, but its proportion of SOC is lower and is consistent across forest, grassland, and cropland systems and is independent of climate (Chen et al 2019). Liang et al. (2017) explained soil carbon dynamics through two pathways, ex vivo modification and in vivo turnover, which are influenced by microbial growth and activity. These pathways, driven by microbial catabolism or anabolism, contribute to the magnitude of the organic carbon reservoir in soils. Thakur et al. (2015) reported that plant diversity increased soil microbial biomass in various terrestrial ecosystems, extending previous findings from twelve grassland studies. Because diversity in plants increases the availability of carbon to belowground plant matter and encourages microbial mass contributions, it enhances soil organic carbon retention.

The natural carbon cycle involves the degradation of soil organic carbon (SOC) by microbes and chemical reactions, releasing CO2 into the atmosphere. However, the decline in soil organic carbon leads to a significant release of CO2, causing severe impacts on humans, plants, and wildlife. Wu et al. (2024) confirmed that the structure, activity, and assembly mechanisms of soil microorganisms are crucial to the soil carbon cycle. Microbial energetics play a crucial role in the biogeochemical cycle of carbon and nitrogen, affecting the bioavailability of phosphorus in the mycorrhizosphere (Varma and Buscot, 2005). However, understanding the interactions between environmental variables and microbial community structure is essential for accurately predicting their role in ecosystem carbon and nitrogen cycling (Junkins et al. 2022). Microbial ecology aims to understand inter- and intraspecies interactions in microbial communities, but challenges arise due to the complexity, dynamic nature, and unique interactions within a community (Kodera et al 2022). Graham et al. (2016) suggested that a deeper understanding of microbial communities, based on ecological principles, could improve our capacity to predict ecosystem processes compared to environmental variables and microbial physiology. The combination of these factors can provide a comprehensive explanation for the rates of carbon and nitrogen cycling processes. Recent studies suggest that microbial biomass can enhance ecosystem carbon cycling models, suggesting that understanding microbial community structure can also improve our understanding (Schimel and Weintraub, 2003).

Microbial-derived compounds make up a significant portion of stable SOC (Kallenbach et al., 2016). However, questions remain about interactions, microbial community structure, physiology, and impacts on carbon conversion into microbial biomass versus soil carbon release. The soil microbial carbon pump (MCP) concept highlights the active role of soil microbes in storing soil organic carbon (SOC) through continuous microbial transformation from labile to persistent anabolic forms but has not been evaluated with data (Zhu et al 2020). This study highlights the significance of microbial substrate efficiency, C and N allocation in regulating plant-derived C and N incorporation into soil organic matter (SOM), and soil matrix interactions in SOM stabilization. Soil microorganisms have a substantial influence on soil organic carbon (SOC) reserves because they not only release carbon dioxide into the atmosphere through decomposition but also take up carbon, grow their bodies, and finally die. (Cotrufo, et al 2013; Liang, et al 2019; Liang, et al 2017; Schimel and Schaeffer, 2012). Microbial residues can be "pumped" into organic matter structures that can persist in soils for decades or even millennia. These processes of continual carbon turnover include absorption, biomass building, cell death, and metabolic products.

The Intersection of Soil Organic Carbon and the Carbon Cycle

Soil plays a critical role in the global carbon cycle, serving as the second-largest carbon store on Earth with approximately 2000 Pg C in soil organic carbon (SOC) (Janzen, 2004). The production and degradation processes of these enormous carbon pools significantly impact CO2 sequestration and release, influencing short-term climate control and climate change mitigation (Davidson and Janssens, 2006; Lal, 2008). Soil carbon is a crucial component of ecosystem capacity and the global carbon cycle, contributing to biogeochemistry and climate change mitigation. Stable soil aggregates play a vital role in promoting and stabilizing soil organic carbon (Wu et al., 2024). However, human activities, such as fires, have significantly reduced soil organic carbon, leading to soil oxidation and loss. Soils serve as a vital carbon sink, buffering against the growth of atmospheric CO2, with 58% of soil composition being organic carbon (Trivedi et al., 2018). In addition to food production, soils provide essential ecological services, including: biodiversity conservation, water purification, climate regulation and human legacy. To prevent environmental degradation and ensure food security in a changing climate, sustainable agriculture techniques focus on managing soil organic carbon. Adopting practices like effective soil carbon management can mitigate climate change, promote ecosystem health, and ensure long-term food security, while also maintaining ecosystem balance and addressing climate change challenges.

The total soil carbon stock consists of both soil organic carbon (SOC) and soil inorganic carbon (SIC) components (Lorenz and Lal, 2018). SIC and SOC interact, with carbon sequestered in the SOC stock through vegetation fixation, deposition, and charred biomass. Net primary production (NPP) is the main C input, as a significant fraction of CO2 fixed during photosynthesis is respired. Cropland, temperate grassland/shrubland, and tropical grassland/savannah may store up to 716 Pg of SOC at a soil depth of 1 m. Furthermore, the soil carbon stock is influenced primarily by climate, geology, and land management techniques, as these factors influence soil and plant type. Soil processes are crucial for plant growth and productivity, but their representation in Earth system models is often unsupported by empirical evidence (Buscardo et al 2021). Understanding belowground community diversity, function, and biotic interactions is essential, as is understanding the impacts of belowground life on aboveground community dynamics and biosphere-atmosphere feedbacks.

Soil respiration, a significant global carbon cycle flux, is often assumed to equalize CO2 efflux, but this study challenges this assumption by integrating CO2 and O2 measurements (Angert et al 2015). Soil respiration comprises heterotrophic respiration by microorganisms such as bacteria and fungi and autotrophic respiration by living roots, estimated by measuring CO2 flux or based on soil profile gradients (Davidson et al., 2002; Davidson and Trumbore, 1995). The concentration of soil organo-mineral particles decreases with increasing density across diverse soils due to a decrease in the organic to mineral phase mass ratio and variations in the mineral phase density, affecting soil texture, mineralogy, location, and management (Sollins et al. 1994). This implies that soils play a critical role in carbon sequestration; hence, understanding the impact of underground life on aboveground community dynamics can enhance carbon storage in land use management. Soils stabilize carbon through various processes, including physical protection against decomposers, organomineral complexes, and biochemically recalcitrant BC (Lorenz and Lal, 2018). Because of its relatively high hydrophobicity, organic matter (OM) either reduces its biodegradability or increases its aggregate stability, stabilizing soil organic carbon (Bachmann et al 2008). Soil aggregation and complex formation are crucial in agroecosystems, with climate, physicochemical characteristics, and vegetation management influencing input and loss.

Plant Diversity's Impact on Carbon Storage and Flux

Plant diversity plays a crucial role in shaping grassland ecosystems, with significant impacts on productivity and soil carbon stocks. Research has shown that plant diversity has a positive effect on natural grasslands and grassland biodiversity, leading to enhanced ecosystem functioning and carbon sequestration (Bai and Cotrufo, 2023). The effects of plant diversity on soil carbon accumulation become more pronounced over time, mirroring the effects on biomass productivity. The increase in belowground carbon inputs, enhanced microbiological development and turnover, and greater entombment of necrotic material are contributing factors.

To promote soil organic carbon (SOC) storage and persistence in grasslands, continuous high levels of diversification and root carbon inputs are necessary (Chen et al., 2018; Lange et al., 2015). This is critical for maintaining ecosystem health and mitigating climate change. Despite the importance of plant diversity, global plant diversity loss is occurring at an alarming rate. Plant diversity is crucial for improving litter inputs and reducing microbial respiration, which significantly impacts the storage and persistence of SOCs. The impact of plant diversity on SOC remains a critical area of research, with important implications for ecosystem management and climate change mitigation (Chen et al., 2023).

Functional diversity enhances biomass accumulation and productivity, positively impacting carbon storage (Hisano and Chen's 2020). Therefore, understanding the impact of plant diversity on net biomass change under different abiotic settings is crucial for understanding human environmental change and soil organic carbon dynamics (Chapin et al 2000). The reduction in plant diversity raises concerns about the potential negative impact on terrestrial ecosystem ecological services (Naeem et al. 2000; Loreau et al. 2001; Hooper et al. 2005). This could make it more difficult for long-lived carbon pools to function as carbon sinks, potentially reducing the ability of terrestrial ecosystems to absorb CO2 from the atmosphere. This topic has been extensively discussed and researched, with numerous studies indicating potential negative effects on ecosystems (Fan et al. 1998; Pacala et al. 2001).

Grassland-based livestock production and animal product consumption trends and implications for mitigating anthropogenic CO2 emissions

Grasslands, comprising 20-40% of the world's land area, account for 80% of agricultural land and play a crucial role in the global food system (Steinfeld et al., 2006). Despite 20% of natural grasslands being farmed, grasslands contribute 27% and 23% of milk and meat production, respectively, supporting one billion of the world's poorest people and accounting for one-third of worldwide protein intake (FAO 2006). Livestock systems are vital for poverty alleviation, food security, and agricultural growth and contribute to reducing global warming emissions (World Bank 2021; Shrestha et al. 2020). However, animal agriculture can potentially contribute to addressing global warming by reducing the associated greenhouse gas emissions (Grossi et al. 2018).

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Livestock products are crucial for global food security, providing 33% of the world's protein and 17% of its calories (Rosegrant et al., 2009). Livestock output is predicted to increase in emerging nations, with 2.6 and 2.7 billion cattle, buffaloes, and small ruminants by 2050, respectively (FAO, 2006). The livestock industry employs 1.1 billion people and supports one billion of the world's poorest people (Hurst et al 2005). Livestock are essential for agriculture, providing more than 13% of the world's calories and 28% of its protein needs. The global demand for milk, beef, and eggs is expected to increase by 30%, 60%, and 80%, respectively, by 2050, posing a dilemma: more livestock or intensified production (Melkan 2019). The "livestock revolution" is accelerating in developing nations, with global meat production predicted to double and milk production predicted to rise (Thornton, 2010; Wright et al., 2012). However, climate change, land and water competition, and food security challenges may negatively impact livestock production (Thornton, 2010).

The increasing human population demand for livestock-related goods can be addressed through climate-smart livestock systems, which minimize CH4 intensity and sustain livestock output (Grossi et al., 2019). Population growth, urbanization, and increasing income levels are expected to increase the demand for animal-related goods, potentially overworking grazing systems (Mahtta et al. 2022). The growing global population, projected to surpass 10 billion by 2050, is causing a surge in the demand for protein-rich dietary sources (FAO 2009; van Dijk et al. 2021. Climate change exacerbates the demand for protein-rich food, as the growing population's desire magnifies the negative consequences of climate change and variability (Henchion et al. 2017; Pimentel et al. 2004). The demand for animal products is expected to quadruple by 2050 due to urbanization, population growth, and rising wages (Sejian et al. 2016). The reduction of food-linked emissions can be achieved by minimizing the intensity of livestock production emissions and from the land use forms associated with livestock production (Montes et al 2013; Hristove et al 2013).

Climate change is putting pressure on global agriculture, which is expected to contribute 13.5% of the world's anthropogenic GHG emissions (IPCC, 2007). GHG emissions from livestock-related activities cause the atmosphere to warm, making pasture and livestock development a serious issue (World Bank, 2010). The IPPC (2014) suggests considering socioeconomic processes and climate threats due to livestock's contribution to the carbon level. The amount of GHGs from agriculture is 17318-1675 TgCO2eq per year, with 57% coming from animal-based foods, 29% from plant-based foods, and 14% from other uses. Resource-constrained livestock systems, particularly in sub-Saharan Africa and South Asia, contribute significantly to GHG and CO2-eq. (FAOSTAT, 2021). Paying attention to C stocks and GHG emissions from livestock should be a priority (Shi et al., 2022).

Animal-related land use patterns can reduce greenhouse gas emissions and enhance food security. A paradigm shift in land use management is necessary to sequester and lower CH4 release from livestock. Two ways to achieve this goal include reviewing adaptation and mitigation methods, reviewing animal farming systems, and implementing policies that support these efforts (World Bank 2021). Grasslands and grazing strategies such as adaptive multipadock grazing effectively capture CH4 from the environment, promoting net C sequestration and storage and thus mitigating climate change effects (Mossier et al 2021). Global studies have examined the effects of rising demand for livestock products on land use and GHG emissions (Steinfeld and Wassenaar 2007; Wassenara et al., 2007; Calpine et al., 2009). Human activities such as biomass removal, excessive stocking, and inadequate grazing management have negatively impacted grassland productivity and depleted soil carbon reserves (Ghosh and Mahanta, 2014).

Research on the decomposition, transformation, and stability of soil organic matter has significantly increased as a result of the increasing interest in understanding the relationship between climate change and the global carbon cycle (Yng et al. 2022; Hisano and Chen, 2020; Thakur, et al. 2015). Soil organic carbon (SOC) is crucial for mitigating climate change and ensuring food production Bai and Cotrufo, 2023). Chen et al. (2023) suggested that increasing soil carbon and nitrogen storage can effectively combat climate change. Furthermore, functional diversity increased soil carbon in the mineral layer by 32%, while expanding species evenness increased it by 30% in the organic horizon. These results imply that enhancing soil carbon storage can be achieved by protecting and enhancing functionally diversified forests. Climate and land-use changes could alter the grassland carbon balance by altering the water budget, nutrient cycling, and plant and soil processes (Liu et al. 2023).

Grasslands and their implications for C sequestration and mitigating anthropogenic CO2 emissions in animal agriculture.

Grasslands may function as soil carbon sinks and store one-third of all terrestrial carbon stocks worldwide (Bai and Cotrufo, 2023). Furthermore, grasslands can offer low-cost or high-carbon-gain ecological alternatives worldwide through better grazing management and biodiversity restoration. The SOC sequestration potential is between 2.3 and 7.3 billion tons of CO^2e per year. Plant carbon storage and microbial catabolism and anabolism processes are altered by climate change, which impacts grassland SOC storage. The interaction of temperature, rainfall, and grazing intensity in grassland soil stores leads to increased greenhouse gas emissions (Whitehead, 2020).

Grasslands have been found to serve as carbon sinks, potentially reducing the rise in atmospheric carbon dioxide levels and contributing to climate change (Heath et al 2005). Recent advancements in soil carbon dynamics have revealed that 20-40% of the 1,500 Pg of C stored in upper soils has turnover times of centuries or less and is primarily composed of undecomposed plant material and hydrolyzable components from mineral surfaces (Trumbore, 1997). Research shows that managing grassland agroecosystems can significantly reduce carbon emissions by decreasing CH4 uptake and increasing N2O emissions (Retallack, 2013).

Grassland-based animal production measures are crucial for improving ecosystem performance and reducing greenhouse gas emissions in animals (Wolf et al 2021). Improved grazing management and biodiversity restoration can provide low-cost and/or high-carbon-gain options for natural climate solutions in global grasslands (Bai and Cotrufo, 2022). Grasslands can store soil carbon and mitigate atmospheric GHG buildup, with the primary sources being livestock excrement and urine. Pastures emit approximately 22 g of N20–N, 74% of which comes from anthropogenic sources (Dangal et al. 2019). They can store up to 0.5 parts per millions of carbon annually and up to a meter in depth. Grazing lands cover 525 million km2, covering 40% of land surfaces (Gerber et al. 2013; Lorenz and Lal 2018). SOC pools in grassland soils can constitute up to 30% of terrestrial SOC (Lal, 2002; Follett et al 2000), and the balance of soil C stocks is influenced by plant photosynthesis and respiration (Schlesinger and Bernhardt, 2013). Contemporary livestock management may lead to changes in grassland community assemblages and plant productivity (Mlchunas and Lauenroth, 1993).

Grazing land and their implications for C sequestration and mitigating anthropogenic CO2 emissions in animal agriculture.

Grazing lands are integral to carbon (C) sequestration and the mitigation of anthropogenic CO2 emissions within animal agriculture (Table 2). These lands possess a substantial buffering capacity for soil maintenance and restoration, encompassing 40% of the terrestrial area and sequestering up to 05 Pg C annually to a depth of 1 m (Lorenz and Lal 2018). The management of grazing lands can profoundly influence soil carbon storage, greenhouse gas emissions, and overall ecosystem health. Implementing effective grazing land management strategies can enhance carbon sequestration, reduce emissions, and promote sustainable animal agriculture practices. Consequently, managing grazed areas to augment soil carbon stocks may be crucial for reducing greenhouse gas emissions and mitigating global warming. Barrdgett et al. (2021) propose that improved grazing management and biodiversity restoration can provide cost-effective and high-carbon climate solutions in global grasslands. One-third of arable land comprises pastures and agricultural cropping systems, which can significantly reduce atmospheric CO2 by storing it as soil organic carbon (Jansson et al. 2021). This process enhances the soil carbon budget, benefiting crop productivity and soil health, and facilitates the long-term storage of carbon in resistant forms, which is vital for decelerating global warming.

Effective grazing system management in animal agriculture minimizes the land footprint, C sequestration, C opportunity cost, and N2O emissions (Hong et al. 2021; Sekaran et al. 2021; Brewer and Gaudin,2020; Lu et al. 2021; Teague and Kreuter 2020). Improving soil quality indicators and storage in grassland agroecosystems involves using soil organic matter (SOM), preserving soil stability, and protecting SOCS pools by reducing C-loss pathways (Abdalla et al. 2018), and it has been reported that enhancing soil quality indicators and storage in grazing land or grassland agroecosystems can be achieved by utilizing soil organic matter, preserving soil stability, and protecting SOCS pools.

Good grazing management allows perennial plants to live and reproduce for years, promoting an ongoing cycle of pruning, root sloughing, and regeneration and contributing indefinitely to soil carbon. Carbon sinks, such as grasslands, forests, and agroecosystems, absorb more carbon than released, storing 34% of the global terrestrial carbon stock, with most stored in soil, unlike forests. (World Resources Institute, 2000). The management of grazed areas is crucial for increasing soil carbon stocks, as highlighted by Soussana and Lemaire (2014) and Dalamini et al. (2016). The utilization of grazing land for establishing agroecosystems enhances soil optimization, promotes ecological diversity, and decreases greenhouse gas emissions (Aguilera et al., 2013).

Properly managed grazing management can enhance ecosystem function, leading to the creation of robust, long-lasting, and cost-effective agroecosystems (Teague and Kreuter 2020). As the intensity of ruminant grazing in rangelands and extensive grasslands increases, livestock production in humid and subhumid grazing systems is expected to increase (Thornton, 2010). Changes in ruminant-based production systems can also lead to net carbon sinks by improving soil health. However, the benefits of grazing and grassland enhancement on carbon sequestration have been inconsistently documented globally (Soussana and Lemaire, 2014; Dalamini et al. 2016) and in Zhou et al. 2016).

Grazing land absorbs carbon as it develops, while animals consume carbon-containing feed, acting as a carbon sink. However, this carbon is converted into CO2 and methane, contributing to greenhouse gas emissions from livestock activities (Abdalla et al. 2018). Tropical and subtropical climate zones have longer growing seasons and milder winters, allowing forage species to be added as cover crops or for extended grazing seasons (Cook and Vizy, 2012). Higher soil organic carbon stocks enhance nutrient retention and water holding capacity, promoting microbiological diversity and resilience to climate change (Philippot et al 2001). The care and maintenance of pasture biomass and bovine grazing play a significant role in reducing greenhouse gas emissions and combating global warming (Gerber et al. 2013). The sequence of biological processes involved

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in grazing management includes carbon inputs, biomass export, carbon retention, and soil organic matter breakdown.

The amount of carbon absorbed from plant debris, such as fallen litter and dying roots, also varies. Ghosh and Mahanta (2014) reported that grazing management, forage sowing, fertilizer application, and restoration may all enhance grassland carbon sequestration. Persistent degradation, a changing climate, a lack of knowledge about the carbon stock of grasslands, disagreements over long-term carbon stock documentation methods, and difficulties implementing policies are some of the difficulties. For the management of grasslands to be sustainable, these problems must be resolved.

When biomass is eliminated by grazing or cutting, inputs from aboveground biomass can be reduced by 60% (Soussana et al., 2010). Soil carbon storage can be influenced by the grazing regime itself, with excessive compensatory plant growth potentially leading to soil carbon gain (Tanentzap et al. 2012). Conversely, excessive grazing can result in soil carbon loss due to erosion or lower plant production and litter inputs (Klumpp et al. 2009). This leads to complex management effects on soil carbon storage (Zhou et al. 2016). The contradictory effects of liming, fertilizer application, and grazing regime on soil carbon stock, as well as reported increases, decreases, and no change in stock in grassland ecosystems with unique climatic and soil conditions, are not surprising (Mcsherry and Ritchie, 2013). The integration of improved crops, native fauna, and climatic and economic factors is essential for diversified forest-grassland strategies (Marsden et al 2020) and Mugwe and Otieno 2021).

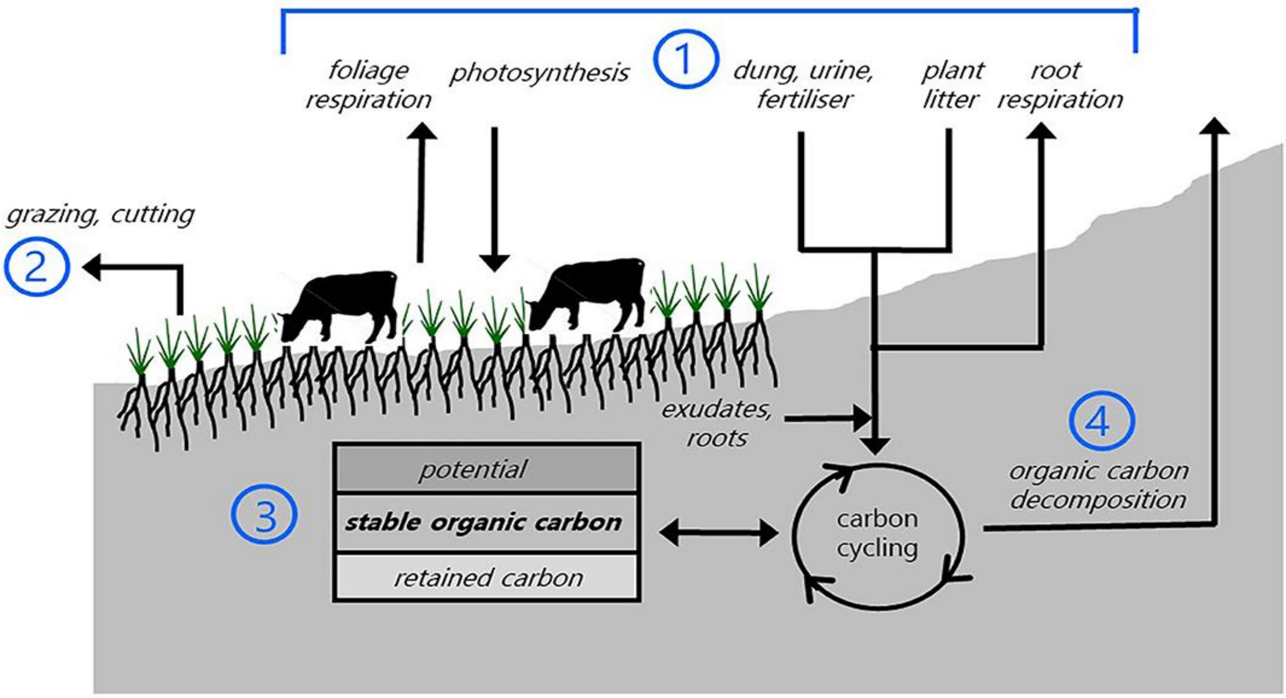

Figure 2: Grazing landscape management to boost soil carbon (C) stores (Source: Whitehead 2020).

Whitehead (2020) study highlights the importance of grazing landscape management in enhancing soil carbon (C) stores (Figure 2). Forage and grazing management practices are crucial for soil C sequestration and reducing greenhouse gas emissions, which are essential for addressing global warming (Teague and Kreuter, 2020). Wang et al (2021) reported that grazing lands offer numerous goods and ecosystem services, including forage, livestock, soil carbon storage, biodiversity, and recreational opportunities. To ensure long-term sustainability, optimal management is needed to balance livestock productivity while reducing environmental impacts like greenhouse gas emissions and soil degradation. Cattle, sheep, and goats can provide permanent soil protection, reduce soil erosion, and enhance biogeochemical net storage (Smith et al. 2020. Using forage and ruminant species in agricultural systems improves soil ecology and performance. Soil C uptake is influenced by biomass removal frequency and intensity, with cutting, grazing, and restoration methods used.

The loss of foliage through grazing affects plant photosynthesis, limiting C inputs but increasing post grazing growth and causing unpleasant broad-leaved plants. (Gilbert et al. 2020).

Perennial forages can enhance soil organic carbon (SOC) levels and lower greenhouse gas emissions in grasslands or rangelands where livestock graze (Godde et al. (2020)). Studies have shown that CH4 absorption is lower in grasslands with a long agricultural history, but seasonal mean CO2 emissions increase with increasing cattle stocking rates (Ma et al. (2021). Future management strategies should consider the unique environmental conditions and soil properties of each grassland ecosystem (Teague and Kreuter 2020; Ma et al. 2021). Permanent forage plant protection is crucial for cattle, sheep, and goats that graze on forages to prevent soil erosion and increase C absorption (Stanley et al., 2018). Studying gas emissions from grasslands, fodder, and grazing management systems involves examining processes for increasing soil organic matter (SOC) stocks, stabilizing SOM into recalcitrant SOC pools, and conserving SOC pools by minimizing C loss pathways (Sarkar et al. 2020). Additionally, examining animal factor gas missions and managing them to minimize digestive gas emissions are essential.

Animal elements during grazing contribute to sequestration, reducing digestive gas emissions and atmospheric gas emissions (Teague and Kreuter 2020). Poor grazing land management can increase greenhouse gas emissions while reducing carbon sequestration, which can increase photosynthesis and soil microorganism survival and reduce soil carbon discharge, thereby contributing to warming (Delgado et al. 2011). Improving land use patterns, plant photosynthesis duration, and the conversion of carbon into stable soil organic carbon can help reduce greenhouse gas emissions and protect ecosystems. Grazing impacts soil carbon and cropland net primary productivity, with managerial zeal and declining animal populations impacting environmental greenhouse gas (GHG) and grassland drains worldwide (Meier et al 2019). Soil properties, environmental factors, and grazing intensity can cause conflicting responses of soil microbial communities (Chang et al. [167] (2021). Perennial cropland grazing increases active labile and soluble carbon in soils, while grazed cropland soils have greater microbial carbon use efficiency (Brewer et al. 2023).

Agro-silvo-pasture systems (ASPSs) promote carbon sequestration and mitigate anthropogenic CO2 emissions in animal agriculture

Nair (1989) described agro-silvo pastoralism as "the integration of woody perennials, livestock, pastures, and crops into the same farming system." Agroforestry technologies are increasingly recognized as a crucial strategy for combating global warming, particularly due to the rise of greenhouse gases, particularly carbon dioxide (Niar 2015). Carbon sequestration can be achieved by storing carbon in soil and vegetation, with soil-based atmospheric CO2 storage being a crucial strategy for addressing climate change (Lal 2004). The global soil carbon reservoir, approximately 1500 Gt of carbon, is sensitive to climate and human disturbances, and agricultural soils can either source or sink atmospheric CO2 depending on their management practices and land use patterns (Amundson, 2001).

Silvopastoral systems are expected to store more carbon than pure grassland systems through two main mechanisms: increased C storage in the biomass of trees and increased soil organic carbon (SOC) storage through C inputs to the soil (Matteucci et al. 2000). The litterfall rate varied from 0.42 (silvopastoral system) to 0.89 Mg C ha^{-1} yr^{-1} (primary forest). The higher C input in the form of litterfall in ecosystems with trees probably creates favourable conditions for soil microorganisms, leading to enhanced microbial activity and CO2 evolution or greater tree root respiration.

Compared with traditional farming, agro-silvo pastoralism (ASPS) is an agroforestry technology that has the potential to help mitigate climate change by sequestering more atmospheric carbon in plant parts and soil (Penn State, 2018). Silvopastoral systems have significant potential for carbon storage due to their ability to absorb carbon from tree woody biomass, input it through litterfall, and convert it into below-ground carbon (Fabiola et al. 2022). Understanding the carbon (C) dynamics of silvopastoral systems can help mitigate greenhouse gas emissions. ASPS is considered the most attractive strategy for climate change mitigation and adaptation in agriculture, contributing significantly to meeting climate objectives for emission-free animal production (Hart et al. 2017). ASPS helps in decreasing or eliminating significant amounts of GHGs through increased carbon sequestration in above- and belowground biomass, as well as soil organic carbon (Aertsens et al. (2013). These systems can increase carbon sequestration, offset GHG emissions, and reduce the carbon footprint generated by animal production. Aryal et al. (2022) demonstrated that silvopastoral systems improve carbon storage in areas dominated by livestock.

Trees in agroforestry systems can increase net carbon storage, potentially reducing the carbon footprint of livestock, especially in developing countries (Haile et al.2008) and Palm et al. 2004). Plant diversity regulates productivity, biomass allocation, and SOC inputs through root exudates and litter. Microbial in vivo transformation is crucial for the synthesis of MAOM, while microbial ex vivo modification leads to POM production. Climate change affects SOC sequestration through microbial and plant processes, and other factors, such as plant and animal waste C inputs, compaction, grazing, and fire, influence SOC storage (Beillouim et al. 2023). Compared with single-species crop or pasture systems, ASPSs have greater potential to sequester carbon (C) due to their apparent capacity to catch and exploit growth resources more effectively (Nair, 2010). Furthermore, C storage is anticipated to range from 0.29 to 15.21 Mg ha−1 yr−1 aboveground and 30 to 300 Mg C ha−1 up to a depth of 1 m in the soil.

Mixed crop livestock promote C sequestration and mitigate anthropogenic CO2 emissions in animal agriculture

Mixed crop-livestock systems have been identified as a promising approach to promote carbon (C) sequestration and mitigate anthropogenic CO2 emissions in animal agriculture (Table 3). By integrating crops and livestock, these systems can enhance soil carbon storage, reduce greenhouse gas emissions, and promote more efficient use of resources. This approach has significant potential to contribute to climate change mitigation and sustainable agriculture practices. The use of mixed livestock crops is a method that promotes carbon sequestration and reduces anthropogenic CO2 emissions in animal agriculture (Choquette-Levy et al., 2021). Crop and livestock integration systems are crucial for combating global warming by ensuring ecological balance and sustainable animal agricultural production, according to various studies (Reay et al., 2020; Liu and Yuan, 2021). The UN Sustainable Development Goals mandate the reorganization of current mixed crop practices towards environmentally friendly agriculture (Eisenstein's 2020). Classical mixed-crop and livestock farming systems, particularly for resource-constrained smallholder farmers, provide nearly two-thirds of the world's population support (Clark and Tilma, 2017; Vermeulen et al 2012).

Systems combining crops and livestock exhibit superior carbon sequencing performance, a crucial factor influencing global climate change trends (Peterson et al. 2019). Livestock crop integration enhances carbon sequestration and nutrient cycling, with comanagement elements such as nitrogen and phosphorus significantly impacting these effects (Acosta-Martnez et al. 2010; Archer and Schmeins 1991). However, no-till planting is a highly effective method for achieving high levels of SOC and high nitrogen fertilization in mixed crop and livestock systems. Crop-livestock integration enhances crop yield and soil quality by utilizing multiple agroecosystem elements and increasing the complexity of grazing animals (Mazzincini et al. 2011). Soil quality is associated with improved carbon sequestration.

The integration of crops and livestock relies on technologically advanced production and efficiency-enhancing strategies, along with innovative organizational, policy, and market strategies, particularly in the context of agricultural value chains (Tarawali et al. (2011). Xu et al. (2023) suggested that integrating crops and animals can reduce greenhouse gas emissions by 17.67%, primarily by allowing manure and feed to return to the field, and that system reorganization can achieve a 28.09%–41.32% reduction. The impact of integrated crop-livestock systems on greenhouse gas fluxes is variable, with management strategies crucial for limiting emissions (Duru and Therond, 2015). Studies show that integrating livestock into cropland can enhance semiarid agroecosystems, particularly carbon sequestration, and may improve the functioning of these systems (Sanderson et al 2013).

The integration of grazed forage crops can enhance soil organic carbon, promoting the accumulation and retention of nitrogen and phosphorus (Carvalho et al. 2010; Palmer et al. 2021). Crops and livestock components are crucial for maintaining biogeochemical processes, increasing biological diversity, creating an organized environmental mosaic, and strengthening the system's adaptability to potential threats and catastrophes (Lemaire et al. (201). Bonaudo et al. (2014) and Amadori et al. (2022) reported that crop-livestock integration can be planned with varying degrees of diversity. Compared with isolated livestock rearing systems, integrated systems reduced N20 emissions by 27-40%, and crops such as maize and cover crops had 40% lower emissions.

The study by Russell (2007) explores the relationship between mixed crop livestock and greenhouse gas emissions (Figure 3). Integrated crop-livestock production improves nutrient cycling and energy efficiency, leading to increased farm productivity and ecosystem benefits such as carbon management. Crop-livestock integrated systems have a substantial effect on the chemical, physical, and biological characteristics of soil that support carbon sequestration. The integration of crops and livestock in forage and grazing systems has led to increased pasture acreage and animal population, causing environmental change in grazing areas and necessitating more effective measures to promote soil carbon increases, affecting the biophysical and chemical characteristics of soils (Carvalho et al. 2018). Sekaran et al. (2021) reported that ICLSs aim to revive a functional agricultural system based on sustainable intensification and agroecological principles. However, mixed crop farms face higher energy costs, while grassland-based farms offer more flexibility in adjusting farming practices to minimize income decline.

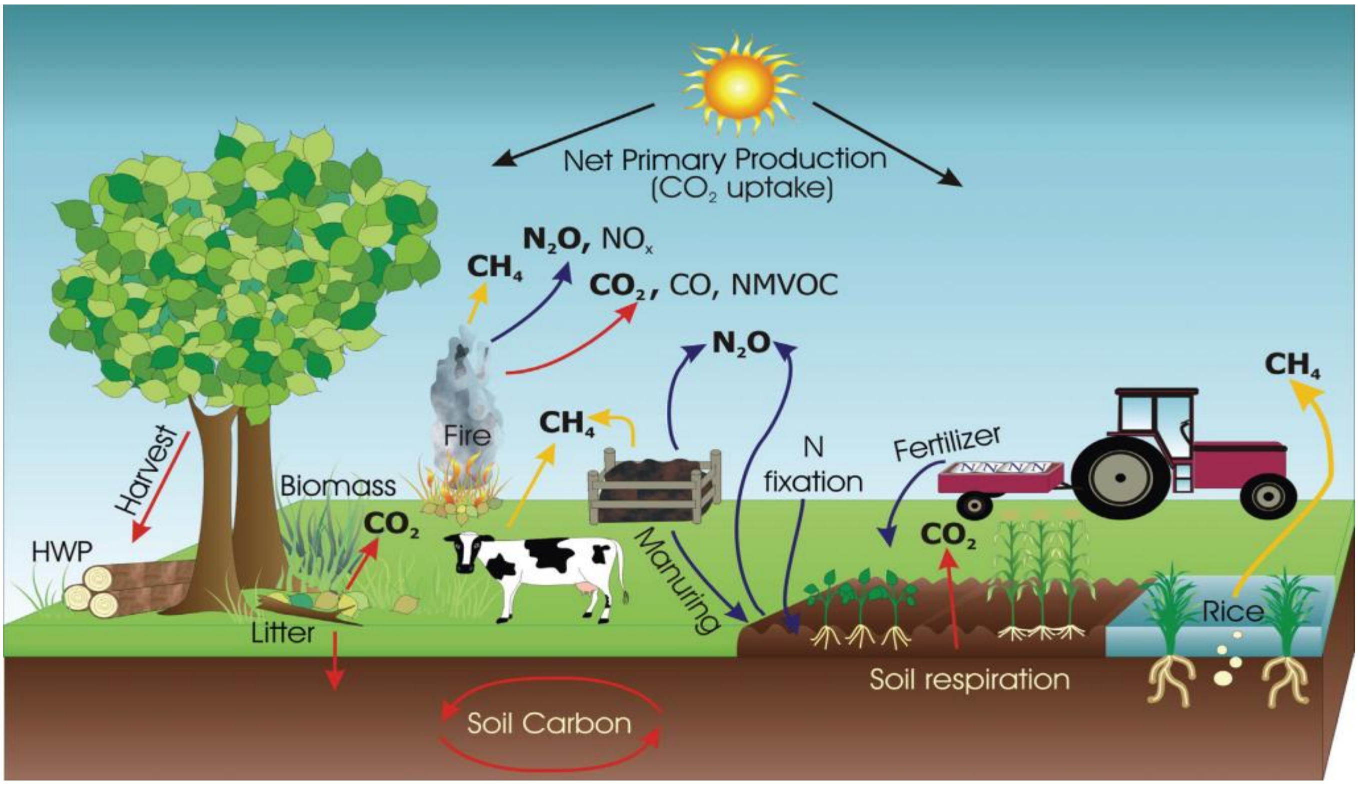

Figure 3. Mixed crop livestock and GHG emissions (Russel, 2007).

Land use change and its implications for C sequestration and GHG anthropogenic gas emissions

Land-use changes, like deforestation, increase carbon dioxide emissions by releasing stored carbon and creating new sources (Turner et al. 2007). This is a major contributor to global environmental change, primarily causing global warming. The conversion of tropical forests to agricultural land releases stored carbon in soil and biomass, causing significant environmental impacts (Van der Werf et al. (2009). Human activities like inefficient agricultural practices, deforestation, and desertification are major contributors to greenhouse gas emissions (Guariguata, 2009). Deforestation, a process where plants cannot absorb carbon dioxide, leads to increased global warming (Amoakwah et al 2022). Climate extremes can decrease regional ecosystem carbon stocks, potentially negating the expected increase in terrestrial carbon uptake, as highlighted by Reichstein et al. (2013).

Land use change, particularly agricultural land, is a major concern in natural ecosystems, with over 50% of newly created agricultural land in tropical regions coming from damaged forests (Gibbs et al. (2010). This raises questions about ecological services and biotic diversity. Land use change is crucial for climate policy, as native vegetation and soils store significant carbon, and losses from agricultural expansion account for 20-25% of greenhouse gas emissions (Searchinger et al. 2018). Climate policies aim to discourage land use change while meeting food demands, which are predicted to increase by over 50% by 2050 (Edenhofer et al. 2014).

Land use changes significantly affect carbon sources, sinks, habitat loss, and food production, causing habitat loss and undermining food production (Le Quéré, et al 2013; Arneth et al 2014; Popp et al 2014). Forestry activities have a greater impact on carbon sequestration and storage than livestock production (Marques et al., 2019). Proper land management strategies can prevent biodiversity loss and enhance carbon storage. However, land-use change deficits in biological diversity and ecological services are expected to worsen as the global population demands more agricultural goods (Sha et al. 2022). The replacement of land use patterns will determine biodiversity and ecosystem service losses. Land-use and land-management changes significantly affect grassland soil carbon, with effects varying regionally and climate zonewise (Roy et al. 2022; Bonan, 2008; Dolman et al. 2003; Dale, 1997). There is no consensus between operational and global perspectives on land management and land-use change Wiesmeier et al. (2020). Converting arable land to grassland is an effective method for increasing carbon stocks, enhancing humus production, and storing CO_2 in soil.

Dumortier et al. (2010) highlighted land-use dynamics, C stock change, and land-use change as the primary challenges in estimating GHG emissions from agriculture. Remote sensing is the sole method for measuring land-use change, but its quantification is challenging due to the lack of consistent time-series data globally. The soil microbial component is sensitive to soil changes due to land use changes or management before other soil properties are detected (Gregorich et al., 2006, Acosta-Martínez et al., 2007; Ingram et al. (2008). Land-use change plays a crucial role in addressing global environmental challenges and promoting sustainable development, making it essential to understand its impact on global warming. Improved GHG gas observation networks and in situ measurements will enable the development of country-specific emission factors (IPPCs, 2006). Roman-Cuesta et al. (2016) proposed replacing land use-specific greenhouse emissions quantification and management with alternative methods to reduce uncertainties in emissions inventory data on agriculture, forestry, and other land uses.

CONCLUSION

In conclusion, the effective management of grasslands, grazing systems, and land use patterns is crucial for soil organic carbon management, which is vital for enhancing global environmental security and mitigating climate change impacts. By adopting practices such as agro-silvo pastoralism and mixed-livestock systems, we can increase carbon sequestration, promote soil organic carbon storage, and reduce anthropogenic CO_2 emissions. Given the significant impact of land use changes on the environment, "land change science" should be a critical focus in global environmental research and sustainability efforts. Strategic land use transitions, including vegetative cover restoration, can help minimize carbon loss and enhance carbon accumulation. By prioritizing sustainable land management practices, we can improve soil carbon stocks, boost biomass production, and contribute to global efforts to address climate change. Future research should focus on quantifying carbon sequestration potential in grassland ecosystems, investigating effective management strategies for optimizing carbon sequestration, and examining the impacts of climate change on grassland ecosystems. Accurate measurements of carbon sequestration rates are crucial for informed land use decisions. Effective management practices, such as grazing, fire management, and restoration techniques, are also essential for optimizing carbon sequestration in grasslands. Research should explore the scalability of grassland carbon sequestration strategies and their policy implications, including incentives for landowners and managers. Investigations should focus on integrating grassland carbon sequestration with agricultural systems, including livestock production and crop rotation. By addressing these research gaps and the proposed future research directions, we can strengthen our understanding of grassland ecosystems as carbon sinks and their role in climate-smart land use and agriculture. This will enable policymakers, land managers, and practitioners to make informed decisions about managing grasslands for carbon sequestration and climate change mitigation.

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Author Contribution:

All authors made equal contributions to the conception, design, and writing of this study. The final manuscript was reviewed and approved by all authors, ensuring a collaborative and comprehensive approach to the research.

REFERENCES

1. Abalos, D., De Deyn, G.B., Kuyper, T.W. and Van Groenigen, J.W. (2014) Plant species identity surpasses species richness as a key driver of N2O emissions from grassland. Global Change Biology, 20(1), 265-275. doi: 10.1111/gcb.12350.
2. Abalos, D., De Deyn, G.B., Philippot, L., Oram, N.J., Oudová, B., Pantelis, I., Clark, C., Fiorini, A., Bru, D., Mariscal-Sancho, I. and van Groenigen, J.W. (2020) Manipulating plant community composition to steer efficient N-cycling in intensively managed grasslands. Dryad Digital Repository. doi: 10.5061/dryad.9p8cz8wf0.
3. Abalos, D., van Groenigen, J.W. and De Deyn, G.B. (2018) What plant functional traits can reduce nitrous oxide emissions from intensively managed grasslands? Global Change Biology, 24(1), e248-e258. doi: 10.1111/gcb.13827.
4. Abdalla, M., Espenberg, M., Zavattaro, L., Lellei-Kovacs, E. et al. (2022) Does liming grasslands increase biomass productivity without causing detrimental impacts on net greenhouse gas emissions? Environmental Pollution, 300, 118999. doi: 10.1016/j.envpol.2022.118999.
5. Abdalla, M.A., Hastings, D.R., Chadwick, D.L., Jones, C.D. et al. (2018) Critical review of the impacts of grazing intensity on soil organic carbon storage and other soil quality indicators in extensively managed grasslands. Agriculture, Ecosystems & Environment, 253, 62-81. doi: 10.1016/j.agee.2017.10.023.
6. Abecia, L., Toral, P.G., Martin-Garcia, A.I., Martinez, G., Tomkins, N.W., Molina-Alcaide, E., Newbold, C. and Yanez-Rui, A. (2012) Effect of bromochloromethane on methane emission, rumen fermentation pattern, milk yield, and fatty acid profile in lactating dairy goats. Journal of Dairy Science, 95, 2027-2036.
7. Abellán, E., McGregor, S. and England, M.H. (2017) Analysis of the southwards wind shift of ENSO in CMIP5 models. Journal of Climate, 30(7), 2415-2435. doi: 10.1175/JCLI-D-16-0326.1.
8. Acosta-Martínez, V., Bell, C.W., Morris, B.E.L., Zak, J. and Allen, V.G. (2010) Long-term soil microbial community and enzyme activity responses to an integrated cropping-livestock system in a semiarid region. Agriculture, Ecosystems & Environment, 137(3-4), 231-240.
9. Adeyeri, O.E., Zhou, W., Laux, P., Wang, X. et al. (2023) Land use and land cover dynamics: Implications for thermal stress and energy demands. Renewable and Sustainable Energy Reviews.
10. Aertsens, J., Nocker, L. and De Gobin, A. (2013) Valuing the carbon sequestration potential for European agriculture. Land Use Policy, 31, 584-594. doi: 10.1016/j.landusepol.2012.09.003.
11. Aguilera, E., Lassaletta, L., Gattinger, A. and Gimeno, B.S. (2013) Managing soil carbon for climate change mitigation and adaptation in mediterranean cropping systems: a meta-analysis. Agriculture, Ecosystems & Environment, 168, 25-36. doi: 10.1016/j.agee.2013.02.003.
12. Akpensuen, T.T., Cartmill, A.D., Pérez-Márquez, S. et al. (2025) 'Make African grasslands climate-change resilient', Communications Earth & Environment, 6, p. 111. doi: 10.1038/s43247-025-02109-3.
13. Alasinrin, S.Y., Salako, F.K., Busari, M.A., Sainju, U.M., Badmus, B.S. and Isimikalu, T.O. (2025) 'Greenhouse gas emissions in response to tillage, nitrogen fertilization, and manure application in the tropics', Soil and Tillage Research. doi: 10.1016/j.still.2024.106296.

14. Albrecht, A. and Kandji, S.T. (2003) Carbon sequestration in tropical agroforestry systems. Agriculture, Ecosystems & Environment, 99, 15-27.
15. Alexandratos, N. and Bruinsma, J. (2012) World agriculture towards 2030/2050: the 2012 revision. ESA Working Paper No. 12–03. Rome: FAO.
16. Altieri, M.A. (1999) The ecological role of biodiversity in agroecosystems. Agriculture, Ecosystems & Environment, 74, 19-31. doi: 10.1016/B978-0-444-50019-9.50005-4.
17. Alvarez, R., Berhongaray, G. and Gimenez, A. (2021) Are Grassland Soils of the Pampas Sequestering Carbon? Science of the Total Environment, 763, 142978.
18. Alvarez, R., Gimenez, A., Caffaro, M., Pagnanini, F., Gangi, D. and Berhongaray, G. (2022) 'Land Use Effects on Soil Organic Carbon Fractions in the Pampas of Argentina Determined via Inverse Analysis of Carbon Mineralization Data', Communications in Soil Science and Plant Analysis. doi: 10.1080/00103624.2022.2070629.
19. Álvaro-Fuentes, J., Morell, F.J., Plaza-Bonilla, D., Arrúe, J.L. and Cantero-Martínez, C. (2012) Modelling tillage and nitrogen fertilization effects on soil organic carbon dynamics. Soil and Tillage Research, 120, 32-39. doi: 10.1016/j.still.2012.01.009.
20. Amadori, C., Dieckow, J., Zanatta, J.A., de Moraes, A. et al. (2022) Nitrous oxide and methane emissions from soil under integrated farming systems in southern Brazil. Science of the Total Environment, 828. doi: 10.1016/j.scitotenv.2022.154555.
21. Amoakwah, E., Lucas, S.T., Didenko, N.A., Rahman, M.A. and Islam, K.R. (2022) Impact of deforestation and temporal land-use change on soil organic carbon storage, quality, and lability. PLoS ONE, 17(8), e0263205. doi: 10.1371/journal.pone.0263205.
22. Amundson, R. (2001) The Carbon Budget in Soils. Annual Review of Earth and Planetary Sciences, 29, 535-562. doi: 10.1146/annurev.earth.29.1.535.
23. Andrews, T. et al. (2018) Accounting for Changing Temperature Patterns Increases Historical Estimates of Climate Sensitivity. Geophysical Research Letters, 45(16). doi: 10.1029/2018GL078887.
24. Angert, A., Yakir, D., Rodeghiero, M., Preisler, Y., Davidson, E.A. and Weiner, T. (2015) O2 was used to study the relationships between soil CO2 efflux and soil respiration. Biogeosciences, 12, 2089-2099. doi: 10.5194/bg-12-2089-2015.
25. Archer, D. (2010) The Global Carbon Cycle. Princeton University Press, Princeton, NJ, 205. Available at: (link unavailable).
26. Archer, S. and Smeins, F.E. (1991) Ecosystem-level processes. In: Grazing Management: Ecological Perspectives. Timber Press, Portland, OR, 109-139.
27. Arjona-Jaime, P. and Rangel-Mendez, R. (2023) Catching Excess CO2 from the Atmosphere. Frontiers for Young Minds, 11, 1227960. doi: 10.3389/frym.2023.1227960.
28. Arneth, A., Brown, C. and Rounsevell, M. (2014) Global models of human decision-making for land-based mitigation and adaptation assessment. Nature Climate Change, 4, 550-557. doi: 10.1038/nclimate2250.
29. Aryal, D.R., Morales-Ruiz, D.E., López-Cruz, S., Tondopó-Marroquín, C.N., Lara-Nucamendi, A., Jiménez-Trujillo, J.A., Pérez-Sánchez, E., Betanzos-Simon, J.E., Casasola-Coto, F., Martínez-Salinas, A., Sepúlveda-López, C.J., Ramírez-Díaz, R., La O Arias, M.A., Guevara-Hernández, F., Pinto-Ruiz, R. and Ibrahim, M. (2022) Silvopastoral systems and remnant forests enhance carbon storage in livestock-dominated landscapes in Mexico. Scientific Reports, 12(1), 16769. doi: 10.1038/s41598-022-21089-4.
30. Asner, G.P., Elmore, A.J., Olander, L.P., Martin, R.E. and Harris, A.T. (n.d.) Grazing systems, ecosystem responses, and global change.
31. Assmann, J.M., Anghinoni, I., Martins, A.P., Diego Cecagno, S.E.V., Carlos, F.S. (2014) Soil carbon and nitrogen stocks and fractions in a long-term integrated crop–livestock system under no-tillage in southern Brazil. Agriculture, Ecosystems & Environment, 190, 52-59.
32. Bachmann, J., Guggenberger, G., Baumgart, T., Ellerbrock, R.H. et al. (2008) Physical carbon-sequestration mechanisms under special consideration of soil wettability. 171(1), 14-26.
33. Bai, Y. and Cotrufo, M.F. (2022) Grassland soil carbon sequestration: Current understanding, challenges, and solutions. Science, 377(6606), 603-608. doi: 10.1126/science. abo2380.
34. Bansal, S., Chakraborty, P. and Kumar, S. (2022) Crop–livestock integration enhanced soil aggregate-associated carbon and nitrogen, and phospholipid fatty acid. Scientific Reports, 12, 2781. doi:

10.1038/s41598-022-06560-6.

35. Bardgett, R.D., Bullock, J.M., Lavorel, S., Manning, P., Schaffner, U., Ostle, N., Chomel, M., Durigan, G., Fry, E.L., Johnson, D., Lavallee, J.M., Le Provost, G., Luo, S., Png, K., Sankaran, M., Hou, X., Zhou, H., Ma, L., Ren, W., Li, X., Ding, Y., Li, Y. and Shi, H. (2021) Combatting global grassland degradation. Nature Reviews Earth & Environment, 2, 720-735.
36. Barneze, A.S., Abdalla, M., Whitaker, J., McNamara, N.P. and Ostle, N.J. (2022) Predicted Soil Greenhouse Gas Emissions from Climate × Management Interactions in Temperate Grassland. Agronomy, 12(12). doi: 10.3390/agronomy12123055.
37. Barneze, A.S., Whitaker, J., McNamara, N.P. and Ostle, N.J. (2022b) Interactions between climate warming and land management regulate greenhouse gas fluxes in a temperate grassland ecosystem. Science of the Total Environment, 833, 155212. doi: 10.1016/j.scitotenv.2022.155212.
38. Barona, E., Ramankutty, N., Hyman, G. and Coomes, O. (2010) The role of pasture and soybean in deforestation of the Brazilian Amazon. Environmental Research Letters, 5, 024002.
39. Barton, D.N. (2016) Assessing ecosystem services from multifunctional trees in pastures using Bayesian belief networks. Ecosystem Services, 18, 165-174. doi: 10.1016/j.ecoser.2016.03.002.
40. Beillouin, D., Corbeels, M., Demenois, J. et al. (2023) A global meta-analysis of soil organic carbon in the Anthropocene. Nature Communications, 14, 3700. doi: 10.1038/s41467-023-39338-z.
41. Bellarby, J., Tirado, R., Leip, A., Weiss, F., Lesschen, J.P. and Smith, P. (2013) Livestock greenhouse gas emissions and mitigation potential in Europe. Global Change Biology, 19, 3-18. doi: 10.1111/j.1365-2486.2012.02786. x.
42. Berry, P.M., Stockdale, E., Sylvester-Bradley, R., Philipps, L. et al. (2003) N, P and K budgets for crop rotations on nine organic farms in the UK. Soil Use and Management, 19(2), 112-118.
43. Blaschke, P. (2020) Integrated land use options for the Aotearoa New Zealand low-emissions ‘careful revolution’. Policy Quarterly, 16, 26-34. doi: 10.26686/pq. v16i2.6479.
44. Blattner, C. (2020) Just transition for agriculture? A critical step in tackling climate change. Journal of Agriculture, Food Systems, and Community Development, 9, 53-58. doi: 10.5304/jafscd.2020.093.006.
45. Boddey, R.M. et al. (2004) 'Nitrogen cycling in Brachiaria pastures: the key to understanding the process of pasture decline', Agriculture, Ecosystems & Environment.
46. Bolin, B. (1970) The carbon cycle. Scientific American, 23, 124-132. doi: 10.1038/scientificamerican0970.
47. Bonan, G. (2008) Land use and land-cover change. In: Ecological Climatology: Concepts and Applications. Cambridge University Press, 432-469. doi: 10.1017/CBO9780511805530.028.
48. Bonaudo, T., Bendahan, A.B., Sabatier, R., Ryschawy, J. et al. (2014) Agroecological principles for the redesign of integrated crop-livestock systems. European Journal of Agronomy, 57, 43-51. doi: 10.1016/j.eja.2013.09.010.
49. Bossio, D.A., Cook-Patton, S.C., Ellis, P.W. et al. (2020) The role of soil carbon in natural climate solutions. Nature Sustainability, 3, 391-398. doi: 10.1038/s41893-020-0491-z.
50. Brewer, K.M. and Gaudin, A.C.M. (2020) Potential of crop-livestock integration to enhance carbon sequestration and agroecosystem functioning in semiarid croplands. Soil Biology and Biochemistry, 149, 107936. doi: 10.1016/j.soilbio.2020.107936.
51. Brewer, K.M., Muñoz-Araya, M., Martinez, I., Marshall, K.N. and Gaudin, A.C.M. (2023) Long-term integrated crop-livestock grazing stimulates soil ecosystem carbon flux, increasing subsoil carbon storage in California perennial agroecosystems. Geoderma, 438. doi: 10.1016/j.geoderma.2023.116598.
52. Britannica (2021) Carbon sequestration summary. Encyclopedia Britannica. Available at: (link unavailable) (Accessed: 19 March 2025).
53. Brock, C., Franko, U. and Wiesmeier, M. (2023) Soil management for carbon sequestration. In: Goss, M.J. and Oliver, M. (eds.) Encyclopedia of Soils in the Environment (Second Edition). Academic Press, 424-432. doi: 10.1016/B978-0-12-822974-3.00124-5.
54. Buck, H.J., Carton, W., Lund, J.F. and Markusson, N. (2023) Why residual emissions matter right now. Nature Climate Change, 13, 351-358. doi: 10.1038/s41558-022-01592-2.
55. Bunthoeun, P., Saoleng, L. and Chetra, S. (2011) Biodigesters development to ensure sustainable agriculture and mitigate greenhouse gas emissions in Cambodia. In: Strategies and Challenges for Sustainable Animal Agriculture-Crop Systems, Volume III: Full Papers. Proceedings of the 3rd International Conference on Sustainable Animal Agriculture for Developing Countries; 2011 July 26–

29; Nakhon Ratchasima, Thailand. Nakhon Ratchasima: Suranaree University of Technology, 706-710.
56. Buscardo, E., Forkuor, G., Rubino, A. et al. (2021) Land and people. Communications Earth & Environment, 2, 178. doi: 10.1038/s43247-021-00240-5.
57. Cacho, O., Hean, R. and Karanja, F. (2008) Accounting for carbon sequestration and its implications for land-use change and forestry projects. CAB Reviews: Perspectives in Agriculture, Veterinary Science, Nutrition and Natural Resources, 3, 1-17. doi: 10.1079/PAVSNNR20083077.
58. Cai, Y.J., Chang, S.X. and Cheng, Y. (2017) Greenhouse gas emissions from excreta patches of grazing animals and their mitigation strategies. Earth-Science Reviews, 171, 44-57. doi: 10.1016/j.earscirev.2017.05.013.
59. Camacho, P.A.G., Pinto, C.E., Lopes, C.F., Tomazelli, D., Werner, S.S., Garagorry, F.C., Baldissera, T.C., Schirmann, J. and Sbrissia, A.F. (2023) Intensification of pasture-based animal production system has little short-term effect on soil carbon stock in the southern Brazilian highland. Agronomy, 13, 850. doi: 10.3390/agronomy13030850.
60. Cardinael, R., Umulisa, V., Toudert, A., Olivier, A., Bockel, L. and Bernoux, M. (2018) Revisiting IPCC Tier 1 coefficients for soil organic and biomass carbon storage in agroforestry systems. Environmental Research Letters, 13, 1-20. doi: 10.1088/1748-9326/aaeb5f.
61. Carvalho, J.L.N., Raucci, G.S., Cerri, C.E.P., Bernoux, M., Feigl, B.J., Wruck, F.J. and Cerri, C.C. (2010) Impact of pasture, agriculture and crop-livestock systems on soil C stocks in Brazil. Soil and Tillage Research, 110, 175-186. doi: 10.1016/j.still.2010.07.011.
62. Carvalho, P.C.F., Peterson, C.A., Nunes, P.A.A., Martins, A.P. et al. (2018) Animal production and soil characteristics from integrated crop-livestock systems: toward sustainable intensification. Journal of Animal Science, 96, 3513-3525. doi: 10.1093/jas/sky085.
63. Castillo, M.S. (2020) Tree species effects on understorey forage productivity and microclimate in a silvopasture of the Southeastern USA. Agriculture, Ecosystems & Environment, 295, 106917. doi: 10.1016/j.agee.2020.106917.
64. Cederberg, C., Persson, U.M., Neovius, K., Molander, S. and Clift, R. (2011) Including carbon emissions from deforestation in the carbon footprint of Brazilian beef. Environmental Science & Technology, 45(5), 1773-1779. doi: 10.1021/es103240z.
65. Chahal, I., Vyn, R.J., Mayers, D. et al. (2020) Cumulative impact of cover crops on soil carbon sequestration and profitability in a temperate humid climate. Scientific Reports, 10, 13381. doi: 10.1038/s41598-020-70224-6.
66. Chalco Vera, J., Curti, R.N. and Acreche, M.M. (2020) Integrating critical values of soil drivers for mitigating GHGs: An assessment in a sugarcane cropping system. Science of the Total Environment, 704, 135420. doi: 10.1016/j.scitotenv.2019.135420.
67. Chang, J., Ciais, P., Gasser, T., Smith, P. et al. (2021) Climate warming from managed grasslands cancels the cooling effect of carbon sinks in sparsely grazed and natural grasslands. Nature Communications, 12, 118. doi: 10.1038/s41467-020-20406-7.
68. Chang, J., Viovy, N., Vuichard, N., Ciais, P., Campioli, M., Klumpp, K., Martin, R., Leip, A. and Soussana, J.F. (2016) Modelled changes in potential grassland productivity and in grass-fed ruminant livestock density in Europe over 1961-2010. Global Change Biology, 22, 338-350.
69. Chapin, F.S. III, Zavaleta, E.S., Eviner, V.T., Naylor, R.L., Vitousek, P.M., Reynolds, H.L. et al. (2000) Functional and societal consequences of changing biotic diversity. Nature, 405, 234–242.
70. Chen, S. et al. (2018) Proceedings of the National Academy of Sciences of the United States of America, 115, pp. 4027-4032.
71. Chen, X., Chen, H.Y.H., Chen, C. and Ma, Z. (2019) Effects of plant diversity on soil carbon in diverse ecosystems: a global meta-analysis. Biological Reviews of the Cambridge Philosophical Society. doi: 10.1111/brv.12554.
72. Chen, X., Taylor, A., Reich, P., Hisano, M. and Chang, S. (2023) Tree diversity increases decadal forest soil carbon and nitrogen accrual. Nature, 618. doi: 10.1038/s41586-023-05941-9.
73. Chivenge, P., Murwira, H., Giller, K., Mapfumo, P. and Six, J. (2007) Long-term impact of reduced tillage and residue management on soil carbon stabilization: implications for conservation agriculture on contrasting soils. Soil and Tillage Research, 94, 328–337.
74. Choquette-Levy, N., Wildemeersch, M., Oppenheimer, M. and Levin, S.A. (2021) Risk transfer policies and climate-induced immobility among smallholder farmers. Nature Climate Change, 11,

1046–1054.
75. Choudhary, V.K., Singh, S.L., Anil Dixit, A. and Bhagawati, R. (2014) Biomass and carbon sequestration potential of agroforestry trees in Arunachal Pradesh, North East India. Climate Change and Environmental Sustainability, 2(1), 48-54.
76. Ciais, P. et al. (2013) Carbon and other biogeochemical cycles. In: Stocker, T.F. et al. (eds.) Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.
77. Clark, M. and Tilman, D. (2017) Comparative analysis of environmental impacts of agricultural production systems, agricultural input efficiency, and food choice. Environmental Research Letters, 12, 064016.
78. Coble, A.P., Contosta, A.R., Smith, R.G., Siegert, N.W. et al. (2020) Influence of forest-to-silvopasture conversion and drought on components of evapotranspiration. Agriculture, Ecosystems & Environment, 295, 106916.
79. Conant, R.T., Cerri, C.E., Osborne, B.B. and Paustian, K. (2017) Grassland management impacts on soil carbon stocks: a new synthesis. Ecological Applications, 27, 662–668.
80. Conant, R.T., Paustian, K. and Elliott, E.T. (2001) Grassland management and conversion into grasslands: effects on soil carbon. Ecological Applications, 11, 343–355.
81. Congio, G.F.S., Bannink, A., Mayorga, O.L., Rodrigues, J.P.P. et al. (2023) Improving the accuracy of beef cattle methane inventories in Latin America and Caribbean countries. Science of the Total Environment, 856, 159128.
82. Cook, K.H. and Vizy, E.K. (2012) Impact of climate change on mid-twenty-first century growing seasons in Africa. Climate Dynamics, 39, 2937–2955.
83. Cotrufo, M.F., Wallenstein, M.D., Boot, C.M., Denef, K. and Paul, E. (2013) The Microbial Efficiency-Matrix Stabilization (MEMS) framework integrates plant litter decomposition with soil organic matter stabilization: do labile plant inputs form stable soil organic matter? 19(4), 988-995.
84. Crippa, M., Solazzo, E., Guizzardi, D., Monforti-Ferrario, F. et al. (2021) Food systems are responsible for a third of global anthropogenic GHG emissions. Nature Food, 2, 198-209. doi: 10.1038/s43016-021-00225-9.
85. Cubillos, A.M., Vallejo, V., Arbeli, Z., Teran, W. et al. (2016) Effect of the conversion of conventional pasture to intensive silvopastoral systems on edaphic bacterial and ammonia oxidizer communities in Colombia. European Journal of Soil Biology, 72, 42-50. doi: 10.1016/j.ejsobi.2015.12.003.
86. da Silva Oliveira, D.M., Tavares, R.L.M., Loss, A., Madari, B.E., Cerri, C.E.P., Alves, B.J.R., Pereira, M.G. and Cherubin, M.R. (2023) Climate-Smart Agriculture and Soil C Sequestration in Brazilian Cerrado: A Systematic Review. Revista Brasileira de Ciência do Solo, 47.
87. Dale, V.H. (1997) The relationship between land-use changes and climate change. Ecological Applications, 7, 753-769. doi: 10.1890/1051-0761(1997)007[0753: TRBLUC](link unavailable);2.
88. Damian, J.M. et al. (2021) Predicting soil C changes after pasture intensification and diversification in Brazil. Catena.
89. Dangal, S., Sanderman, J., Wills, S. and Ramirez-Lopez, L. (2019) Accurate and precise prediction of soil properties from a large mid-infrared spectral library. Soil Systems, 3, 11. doi: 10.3390/soilsystems3010011.
90. Davidson, E. and Janssens, I. (2006) Temperature sensitivity of soil carbon decomposition and feedbacks to climate change. Nature, 440, 165-173. doi: 10.1038/nature04514.
91. de Carvalho, A.M., de Jesus, D.R., de Sousa, T.R., Ramos, M.L.G., de Figueiredo, C.C., de Oliveira, A.D., Marchão, R.L., Ribeiro, F.P., Dantas, R.d.A. and Borges, L.d.A.B. (2023) Soil Carbon Stocks and Greenhouse Gas Mitigation of Agriculture in the Brazilian Cerrado—A Review. Plants, 12, 2449. doi: 10.3390/plants12132449.
92. de Vries, F., Liiri, M., Bjørnlund, L. et al. (2012) Land use alters the resistance and resilience of soil food webs to drought. Nature Climate Change, 2, 276-280. doi: 10.1038/nclimate1368.
93. Delgado, J.A., Groffman, P.M., Nearing, M.A., Goddard, T., Reicosky, D., Lal, R. et al. (2011) Conservation practices to mitigate and adapt to climate change. Journal of Soil and Water Conservation, 66, 118A-129A. doi: 10.2489/jswc.66.4.118A.
94. Delgado-Baquerizo, M. et al. (2018) A global atlas of the dominant bacteria found in soil. Science, 359, 320-325.

95. Descheemaeker, K., Amede, T. and Haileslassie, A. (2010) Improving water productivity in mixed crop–livestock farming systems of sub-Saharan Africa. Agricultural Water Management, 97(5), 579-586. doi: 10.1016/j.agwat.2009.11.012.
96. Dlamini, P., Chivenge, P. and Chaplot, V. (2016) Overgrazing decreases soil organic carbon stocks the most under dry climates and low soil pH: A meta-analysis shows. Agriculture, Ecosystems & Environment, 221, 258-269. doi: 10.1016/j.agee.2016.01.026.
97. Dolman, A.J. and Verhagen, A. (2003) Land use and global environmental change. In: Dolman, A.J. (ed.) Global Environmental Change and Land Use. Kluwer Academic Publishers, 3-13.
98. Don, A., Schumacher, J. and Freibauer, A. (2011) Impact of tropical land-use change on soil organic carbon stocks—A meta-analysis. Global Change Biology, 17(4), 1658-1670. doi: 10.1111/j.1365-2486.2010.02336. x.
99. Dowhower, S.L., Teague, W.R., Casey, K.D. and Daniel, R. (2019) Soil greenhouse gas emissions as impacted by soil moisture and temperature under continuous and holistic planned grazing in native tallgrass prairie. Agriculture, Ecosystems & Environment, 286, 106647. doi: 10.1016/j.agee.2019.106647.
100. Drinkwater, L.E., Wagoner, P. and Sarrantonio, M. (1998) Legume-based cropping systems have reduced carbon and nitrogen losses. Nature, 396, 262-265.
101. Duin, E.C., Wagner, T., Shima, S., Prakash, D., Cronin, B., Yáñez-Ruiz, D.R., Duval, S., Rümbeli, R., Stemmler, R.T., Thauer, R.K. and Kindermann, M. (2016) Proceedings of the National Academy of Sciences, Early Edition. doi: 10.1073/pnas.1600298113.
102. Duru, M. and Therond, O. (2015) Livestock system sustainability and resilience in intensive production zones: which form of ecological modernization? Regional Environmental Change, 15(8), 1651-1665.
103. Duru, M., Moraine, M. and Therond, O. (2015) An analytical framework for structuring analysis and design of sustainable ruminant livestock systems. Animal Frontiers, 5(4), 6-13.
104. Duveiller, G. et al. (2020) Local biophysical effects of land use and land cover change: towards an assessment tool for policy makers. Land Use Policy.
105. Edenhofer, O. et al. (2014) Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, 1-30.
106. Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Minx, J.C. et al. (2014) Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, 1-30.
107. Eisenstein, M. (2020) Natural solutions for agricultural productivity. Nature, 588, S58-S59. doi: 10.1038/d41586-020-03445-4.
108. Etminan, M., Myhre, G., Highwood, E.J. and Shine, K.P. (2016) Radiative forcing of carbon dioxide, methane, and nitrous oxide: a significant revision of the methane radiative forcing. Geophysical Research Letters, 43(12), 612-623. doi: 10.1002/2016GL071930.
109. Fahad, S., Chavan, S.B., Chichaghare, A.R., Uthappa, A.R., Kumar, M., Kakade, V., Pradhan, A., Jinger, D., Rawale, G., Yadav, D.K., Kumar, V., Farooq, T.H., Ali, B., Sawant, A.V., Saud, S., Chen, S. and Poczai, P. (2022) 'Agroforestry Systems for Soil Health Improvement and Maintenance', Sustainability, 14(22), p. 14877. doi: 10.3390/su142214877.
110. FAO (2006) Livestock’s Long Shadow: Environmental Issues and Options. Food and Agriculture Organization of the United Nations.
111. FAO (2009) How to Feed the World in 2050. High-Level Expert Forum.
112. FAO (2020) Emissions due to agriculture. Global, regional and country trends 2000–2018. FAOSTAT Analytical Brief Series No 18. FAO, Rome.
113. FAO, IFAD, UNICEF, WFP and WHO (2019) The State of Food Security and Nutrition in the World 2019. Safeguarding against economic slowdowns and downturns. FAO, Rome, Italy.
114. Feliciano, D., Ledo, A., Hillier, J. and Nayak, D.R. (2018) Which agroforestry options give the greatest soil and above ground carbon benefits in different world regions? Agriculture, Ecosystems & Environment, 254, 117-129. doi: 10.1016/j.agee.2017.11.032.
115. Flysjö, A., Henriksson, M., Cederberg, C., Ledgard, S. and Englund, J.E. (2011) The impact of various parameters on the carbon footprint of milk production in New Zealand and Sweden. Agricultural Systems, 104, 459-469. doi: 10.1016/j.agsy.2011.03.003.

116. Follett, R.F. and Reed, D.A. (2010) Soil carbon sequestration in grazing lands: societal benefits and policy implications. Rangeland Ecology & Management, 63, 4-15. doi: 10.2111/08-225.1.
117. Food and Agriculture Organization of the United Nations (FAO) (2006) Livestock a Major Threat to the Environment: Remedies Urgently Needed. Retrieved from: (link unavailable).
118. Fornara, D. and Tilman, D. (2008) Plant functional composition influences rates of soil carbon and nitrogen accumulation. Journal of Ecology, 96(2), 314-322. doi: 10.1111/j.1365-2745.2007.01345. x.
119. Frank, A.B., Tanaka, D.L., Hofmann, L. and Follett, B.F. (1995) Soil carbon and nitrogen of northern great plains grasslands as influenced by long-term grazing. Journal of Range Management, 48, 470-474. doi: 10.2307/4002255.
120. Freibauer, A., Rounsevell, M.D.A., Smith, P. and Verhagen, J. (2004) Carbon sequestration in the agricultural soils of Europe. Geoderma, 122, 1-23. doi: 10.1016/j.geoderma.2004.01.021.
121. Friedlingstein, P. (2015) Carbon cycle feedbacks and future climate change. Philosophical Transactions of the Royal Society A, 373, 20140421. doi: 10.1098/rsta.2014.0421.
122. Friedlingstein, P. et al. (2020) Global Carbon Budget 2020. Earth System Science Data, 12, 3269-3340. doi: 10.5194/essd-12-3269-2020.
123. Gaitán, L., Läderach, P., Graefe, S., Rao, I. and van der Hoek, R. (2016) Climate-Smart Livestock Systems: An Assessment of Carbon Stocks and GHG Emissions in Nicaragua. PLoS ONE, 11(12), e0167949. doi: 10.1371/journal.pone.0167949.
124. Gangwar, B. and Ravisankar, N. (2014) Farming systems approach for managing soil, water and crop in coastal areas. Journal of the Indian Society of Coastal Agricultural Research, 32(1), 1-6.
125. Ganjegunte, G.K. et al. (2005) Soil organic carbon composition in a northern mixed-grass prairie. Soil Science Society of America Journal, 69(6), 1746-1756.
126. García-Marco, S., Ravella, S.R., Chadwick, D., Vallejo, A., Gregory, A.S. and Cárdenas, L.M. (2014) Ranking factors affecting emissions of GHG from incubated agricultural soils. European Journal of Soil Science, 65(4), 573-583. doi: 10.1111/ejss.12143.
127. Garnett, T. (2009) Livestock-related greenhouse gas emissions: impacts and options for policymakers. Environmental Science & Policy, 12, 491-503.
128. Garrett, R.D. et al. (2017) 'Social and ecological analysis of commercial integrated crop livestock systems: current knowledge and remaining uncertainty', Agricultural Systems.
129. Garrett, R.D., Niles, M.T., Gil, J.D., Gaudin, A., Chaplin-Kramer, R., Assmann, A. et al. (2017) Social and ecological analysis of commercial integrated crop livestock systems: current knowledge and remaining uncertainty. Agricultural Systems, 155, 136-146.
130. George, S., Wright, D.L. and Marois, J.J. (2013) Impact of grazing on soil properties and cotton yield in an integrated crop–livestock system. Soil & Tillage Research, 132, 47-55.
131. Gerber, P.J., Steinfeld, H., Henderson, B., Mottet, A. et al. (2013) Tackling climate change through livestock—a global assessment of emissions and mitigation opportunities.
132. Ghosh, K. and Mahanta, S.K. (2014) Carbon sequestration in grassland systems. Range Management & Agroforestry, 35(2), 173-181.
133. Gibbs, H.K., Ruesch, A.S., Achard, F., Clayton, M.K., Holmgren, P., Ramankutty, N. and Foley, J.A. (2010) Tropical forests were the primary sources of new agricultural land in the 1980s and 1990s. Proceedings of the National Academy of Sciences, 107(38), 16732-16737. doi: 10.1073/pnas.0910275107.
134. Godde, C.M., de Boer, I.J.M., Ermgassen, E.Z. and Herrero, M. et al. (2020) Soil carbon sequestration in grazing systems: managing expectations. Climatic Change, 161, 385-391. doi: 10.1007/s10584-020-02673-x.
135. Golchin, A., Oades, J.M., Skjemstad, J.O. and Clarke, P. (1994) Soil structure and carbon cycling. Australian Journal of Soil Research, 32(5), 1043-1068.
136. Goodland, R. (2014) A fresh look at livestock greenhouse gas emissions and mitigation potential in Europe. Global Change Biology, 20(7), 2042-2044. doi: 10.1111/gcb.12454.
137. Graham, E.B., Knelman, J.E., Schindlbacher, A., Siciliano, S., Breulmann, M. et al. (2016) Microbes as engines of ecosystem function: when does community structure enhance predictions of ecosystem processes? Frontiers in Microbiology, 7, 214. doi: 10.3389/fmicb.2016.00214.
138. Grossi, G., Goglio, P., Vitali, A. and Williams, A.G. (2018) Livestock and climate change: impact of livestock on climate and mitigation strategies. Animal Frontiers, 9(1), 69-76. doi: 10.1093/af/vfy034.

139. Guariguata, M. (2009) El manejo forestal en el contexto de la adaptación al cambio climático. Revista de Estudios Sociales, 32, 98-112.
140. Haider, A., Bashir, A. and Husnain, M.I.U. (2020) Impact of agricultural land use and economic growth on nitrous oxide emissions: evidence from developed and developing countries. Science of the Total Environment, 741, 140421. doi: 10.1016/j.scitotenv.2020.140421.
141. Han, H., Li, C., Liu, R., Jian, J., Abulimiti, M., Yuan, P. (2023) Warming promotes accumulation of microbial- and plant-derived carbon in terrestrial ecosystems. Science of the Total Environment, 905, 166977. doi: 10.1016/j.scitotenv.2023.166977.
142. Hanson, J.D. and Franzluebbers, A. (2008) Principles of integrated agricultural systems. Renewable Agriculture and Food Systems, 23(4), 263-264.
143. Harper, A.B., Powell, T., Cox, P.M. et al. (2018) Land-use emissions play a critical role in land-based mitigation for Paris climate targets. Nature Communications, 9, 2938. doi: 10.1038/s41467-018-05340-z.
144. Harris, N.L., Gibbs, D.A., Baccini, A. et al. (2021) Global maps of twenty-first century forest carbon fluxes. Nature Climate Change, 11, 234-240. doi: 10.1038/s41558-020-00976-6.
145. Hart, K., Allen, B., Keenleyside, C., Nanni, S., Maréchal, A., Paquel, K., Nesbit, M. and Ziemann, J. (2017) Research for agri committee - the consequences of climate change for EU agriculture. Follow-up to the COP21 - UN Paris Climate Change Conference. doi: 10.2861/295025.
146. Hartmann, M. and Six, J. (2023) Soil structure and microbiome functions in agroecosystems. Nature Reviews Earth & Environment, 4, 4-18. doi: 10.1038/s43017-022-00366-w.
147. Hasegawa, T., Fujimori, S., Ito, A., Takahashi, K. and Masui, T. (2017) Global land-use allocation model linked to an integrated assessment model. Science of the Total Environment, 580.
148. Hassan, M.U., Aamer, M., Mahmood, A., Awan, M.I., Barbanti, L., Seleiman, M.F., Bakhsh, G., Alkharabsheh, H.M., Babur, E., Shao, J., Rasheed, A. and Huang, G. (2022) Management strategies to mitigate N2O emissions in agriculture. Life, 12(3), 439. doi: 10.3390/life12030439.
149. Hayek, M.N., Harwatt, H., Ripple, W.J. and Mueller, N.D. (2021) The carbon opportunity cost of animal-sourced food production on land. Nature Sustainability, 4, 21-24.
150. He, Y., Zhang, T., Zhao, Q., Gao, X., He, T. and Yang, S. (2022) Response of GHG emissions to interactions of temperature and drying in the karst wetland of the Yunnan Guizhou Plateau. Frontiers in Environmental Science, 10, 973900. doi: 10.3389/fenvs.2022.973900.
151. Heath, J., Ayres, E., Possell, M., Bardgett, R.D., Black, H.I.J. et al. (2005) Rising atmospheric CO2 reduces sequestration of root-derived soil carbon. Science, 309(5741), 1711-1713. doi: 10.1126/science.1110700.
152. Henchion, M., Hayes, M., Mullen, A.M., Fenelon, M. and Tiwari, B. (2017) Future protein supply and demand: strategies and factors influencing a sustainable equilibrium. Foods, 6(7), 53. doi: 10.3390/foods6070053.
153. Herrero, M. et al. (2013) Biomass use, production, feed efficiencies, and greenhouse gas emissions from global livestock systems. Proceedings of the National Academy of Sciences, 110, 20888-20893.
154. Herrero, M. et al. (2016) Greenhouse gas mitigation potentials in the livestock sector. Nature Climate Change, 6, 452-461.
155. Herrero, M., Grace, D., Njuki, J., Johnson, N., Enahoro, D., Silvestri, S. and Rufino, M.C. (2013) The roles of livestock in developing countries. Animal, 1, 3-18. doi: 10.1017/S1751731112001954.
156. Herrero, M., Thornton, P.K., Notenbaert, A.M., Wood, S. et al. (2010) Smart investments in sustainable food production: revisiting mixed crop-livestock systems. Science, 327, 822-825. doi: 10.1126/science.1183725.
157. Hewins, D.B. et al. (2018) Grazing and climate effects on soil organic carbon concentration and particle-size association in northern grasslands. Scientific Reports, 8, 1336.
158. Hilimire, K. (2011) Integrated crop/livestock agriculture in the United States: a review. Journal of Sustainable Agriculture, 35, 376-393.
159. Hisano, M. and Chen, H.Y.H. (2020) Spatial variation in climate modifies effects of functional diversity on biomass dynamics in natural forests across Canada. Global Ecology and Biogeography, 00, 1-14. doi: 10.1111/geb.13060.
160. Holmes, C.D. (2018) Methane feedback on atmospheric chemistry: methods, models, and mechanisms. Journal of Advances in Modeling Earth Systems, 10, 1087-1099. doi: 10.1002/2017MS001196.

161. Hong, W.Y., Perera, S.P. and Burrows, A.D. (2020) Comparison of MIL-101(Cr) metal-organic framework and 13X zeolite monoliths for CO2 capture. Microporous and Mesoporous Materials, 308, 110525.
162. Hooper, D.U., Chapin, F.S., Ewel, J.J., Hector, A., Inchausti, P., Lavorel, S. et al. (2005) Effects of biodiversity on ecosystem functioning: a consensus of current knowledge and needs for future research. Ecological Monographs, 75, 3-35.
163. Houghton, R.A., House, J.I., Pongratz, J., van der Werf, G.R. et al. (2012) Carbon emissions from land use and land-cover change. Biogeosciences, 9, 5125-5142. doi: 10.5194/bg-9-5125-2012.
164. Hristov, A.N., Oh, J., Firkins, J.L., Dijkstra, J., Kebreab, E., Waghorn, G. et al. (2013) Special topics—Mitigation of methane and nitrous oxide emissions from animal operations: I. A review of enteric methane mitigation options. Journal of Animal Science, 91, 5045-5069. doi: 10.2527/jas.2013-6585.
165. Hülsbergen, K.J. and Rahmann, G. (2015) Klimawirkungen und Nachhaltigkeit ökologischer und konventioneller Betriebssysteme – Untersuchungen in einem Netzwerk von Pilotbetrieben: Forschungsergebnisse 2013-2014. Johann Heinrich von Thünen-Institut. doi: 10.3220/REP_29_2015.
166. Huppmann, D., Rogelj, J., Kriegler, E., Krey, V. and Riahi, K. (2018) A new scenario resource for integrated 1.5°C research. Nature Climate Change, 8, 1027-1030. doi: 10.1038/s41558-018-0317-4.
167. Hurst, P., Termine, P. and Karl, M. (2005) Agricultural workers and their contribution to sustainable agriculture and rural development. FAO.
168. Ibidhi, R. and Calsamiglia, S. (2020) Carbon footprint assessment of Spanish dairy cattle farms: effectiveness of dietary and farm management practices as a mitigation strategy. Animals, 10, 2083. doi: 10.3390/ani10112083.
169. Inoue, T. (2019) Carbon sequestration in mangroves. In Kuwae, T. and Hori, M. (eds) Blue Carbon in Shallow Coastal Ecosystems. Springer.
170. Intergovernmental Panel on Climate Change (2019) Global warming of 1.5°C. Special Report on Global Warming of 1.5°C. Geneva: Intergovernmental Panel on Climate Change.
171. Intergovernmental Panel on Climate Change (IPCC) (2022) Mitigation pathways compatible with 1.5°C in the context of sustainable development. In Global Warming of 1.5°C: IPCC Special Report on Impacts of Global Warming of 1.5°C above Pre-Industrial Levels in Context of Strengthening Response to Climate Change, Sustainable Development, and Efforts to Eradicate Poverty. Cambridge University Press, 93-174.
172. IPCC (2006) 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Prepared by the National Greenhouse Gas Inventories Programme. IGES.
173. IPCC (2007) Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Geneva, Switzerland: IPCC.
174. IPCC (2014a) Climate Change 2014 Synthesis Report: A Report of the Intergovernmental Panel on Climate Change. Geneva, Switzerland: IPCC.
175. IPCC (2014b) Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Geneva, Switzerland: IPCC.
176. IPCC (2019) Special Report on Climate Change and Land. IPCC.
177. Jackson, R.B. et al. (2020) Increasing anthropogenic methane emissions arise equally from agricultural and fossil fuel sources. Environmental Research Letters, 15, 071002. doi: 10.1088/1748-9326.
178. Jana, S.P. and Oksana, Y.B. (2021) Grassland biodiversity. Current Biology, 31, R1141-R1224.
179. Jansson, C., Faiola, C., Wingler, A., Zhu, X-G., Kravchenko, A., de Graaff, M-A., Ogden, A.J., Handakumbura, P.P., Werner, C. and Beckles, D.M. (2021) Crops for carbon farming. Frontiers in Plant Science, 12, 636709. doi: 10.3389/fpls.2021.636709.
180. Janzen, H.H. (2004) Carbon cycling in earth systems—a soil science perspective. Agriculture, Ecosystems & Environment, 104, 399-417.
181. Jia, G., Shevliakova, E., Artaxo, P., De Noblet-Ducoudré, N., Houghton, R. et al. (2019) Land–climate interactions. In Climate Change and Land: an IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems. doi: 10.1017/9781009157988.004.
182. Junkins, E.N., McWhirter, J.B., McCall, L.I. and Stevenson, B.S. (2022) Environmental structure

impacts microbial composition and secondary metabolism. ISME Communications, 2(1), 15. doi: 10.1038/s43705-022-00097-5.

183. Kallenbach, C.M., Frey, S.D. and Grandy, A.S. (2016) Direct evidence for microbial-derived soil organic matter formation and its ecophysiological controls. Nature Communications, 7, 13630.
184. Khresat, S., Rawajfih, Z. and Mohammad, M. (1998) Land degradation in northwestern Jordan: causes and processes. Journal of Arid Environments, 39, 623-629.
185. Kirby, K.R. and Potvin, C. (2007) Variation in carbon storage among tree species: implications for the management of a small-scale carbon sink project. Forest Ecology and Management, 246, 208.
186. Klumpp, K., Fontaine, S., Attard, E., Le Roux, X. et al. (2009) Grazing triggers soil carbon loss by altering plant roots and their control on soil microbial community. Journal of Ecology, 97, 876-885. doi: 10.1111/j.1365-2745.2009.01549. x.
187. Knapp, A.K. et al. (2002) Rainfall variability, carbon cycling, and plant species diversity in a mesic grassland. Science, 298, 2202-2205.
188. Kodera, S.M., Das, P., Gilbert, J.A. and Lutz, H.L. (2022) Conceptual strategies for characterizing interactions in microbial communities. iScience, 25(2), 103775. doi: 10.1016/j.isci.2022.103775.
189. Kothandaraman, S., Dar, J.A., Sundarapandian, S., Dayanandan, S. and Khan, M.L. (2020) Ecosystem-level carbon storage and its links to diversity, structural and environmental drivers in tropical forests of Western Ghats, India. Scientific Reports, 10, 1-15.
190. Krausmann, F. et al. (2008) Global patterns of socioeconomic biomass flows in the year 2000: a comprehensive assessment of supply, consumption and constraints. Ecological Economics.
191. Kremer, R.J. (2017) Biotechnology impacts on soil and environmental services. In Soil Health and Intensification of Agroecosystems, 353-375. doi: 10.1016/B978-0-12-805317-1.00016-6.
192. Külling, D.R., Menzi, H., Kröber, T.F., Neftel, A., Sutter, F., Lischer, P. and Kreuzer, M. (2001) Emissions of ammonia, nitrous oxide and methane from different types of dairy manure during storage as affected by dietary protein content. Journal of Agricultural Science, 137, 235-250. doi: 10.1017/S0021859601001186.
193. Kumar, P., Adelodun, A.A., Khan, M.F., Krisnawati, H. and Garcia-Menendez, F. (2020) Towards an improved understanding of greenhouse gas emissions and fluxes in tropical peatlands of Southeast Asia. Sustainable Cities and Society, 53, 101881. doi: 10.1016/j.scs.2019.101881.
194. Kumar, S.S., Wani, O.A., Krishna, J.R. and Hussain, N. (2022) 'Impact of climate change on soil health', International Journal of Environmental Science, 7, pp. 70-90.
195. Lal, R. (2004) Soil carbon sequestration impacts on global climate change and food security. Science, 304, 1623-1627.
196. Lal, R. (2010) Managing soils and ecosystems for mitigating anthropogenic carbon emissions and advancing global food security. Bioscience, 60, 708-721.
197. Lambin, E.F. and Meyfroidt, P. (2011) Global land use change, economic globalization, and the looming land scarcity. Proceedings of the National Academy of Sciences, 108, 3465-3472.
198. Lan, W. and Yang, C. (2018) Ruminal methane production: associated microorganisms and the potential of applying hydrogen-utilizing bacteria for mitigation. Science of the Total Environment, 654. doi: 10.1016/j.scitotenv.2018.11.180.
199. Lange, M., Eisenhauer, N., Sierra, C.A., Bessler, H., Engels, C., Griffiths, R.I. et al. (2015) Plant diversity increases soil microbial activity and soil carbon storage. Nature Communications, 6, 6707. doi: 10.1038/ncomms7707.
200. Le Quéré, C., Andres, R.J., Boden, T., Conway, T. et al. (2013) The global carbon budget 1959-2011. Earth System Science Data, 5, 165-185. doi: 10.5194/essd-5-165-2013.
201. Le Quéré, C., Raupach, M., Canadell, J. et al. (2009) Trends in the sources and sinks of carbon dioxide. Nature Geoscience, 2, 831-836. doi: 10.1038/ngeo689.
202. Lee, S.A., Kim, J.M., Kim, Y. et al. (2020) Different types of agricultural land use drive distinct soil bacterial communities. Scientific Reports, 10, 17418. doi: 10.1038/s41598-020-74193-8.
203. Lemaire, G. and Franzluebbers, A. (2013) Integrated crop-livestock systems: strategies to achieve synergy between agricultural production and environmental quality. Agriculture, Ecosystems & Environment, 190, 4-8. doi: 10.1016/j.agee.2013.08.009.
204. Li, Y., Brando, P.M., Morton, D.C. et al. (2022) Deforestation-induced climate change reduces carbon storage in remaining tropical forests. Nature Communications, 13, 1964. doi: 10.1038/s41467-022-

29601-0.
205. Liang, C., Amelung, W., Lehmann, J. and Kastner, M. (2019) Quantitative assessment of microbial necromass contribution to soil organic matter. Global Change Biology, 25, 3578-3590. doi: 10.1111/gcb.14781.
206. Liang, C., Cheng, G., Wixon, D.L. and Balser, T.C. (2011) An absorbing Markov chain approach to understanding the microbial role in soil carbon stabilization. Biogeochemistry, 106, 303-309. doi: 10.1007/s10533-010-9525-3.
207. Liang, C., Kao-Kniffin, J., Sanford, G.R., Wickings, K., Balser, T.C. and Jackson, R.D. (2016) Microorganisms and their residues under restored perennial grassland communities of varying diversity. Soil Biology and Biochemistry, 103, 192-200. doi: 10.1016/j.soilbio.2016.08.002.
208. Liang, C., Schimel, J. and Jastrow, J. (2017) The importance of anabolism in microbial control over soil carbon storage. Nature Microbiology, 2(8), 17105. doi: 10.1038/nmicrobiol.2017.105.
209. Liebig, M.A., Faust, D.R., Archer, D.W., Kronberg, S.L. et al. (2020) Integrated crop–livestock effects on soil carbon and nitrogen in a semiarid region. Agrosystems, Geosciences & Environment, 3(1), e20098.
210. Liebig, M.A., Gross, J.R., Kronberg, S.L., Phillips, R.L. and Hanson, J.D. (2010) Grazing management contributions to net global warming potential: a long-term evaluation in the northern great plains. Journal of Environmental Quality, 39, 799-809. doi: 10.2134/jeq2009.0272.
211. Liu, H. et al. (2020) Annual dynamics of global land cover and its long-term changes from 1982 to 2015. Earth System Science Data, 12, 1217-1243.
212. Liu, X., Cai, Z. and Yuan, Z. (2021) Environmental burdens of small-scale intensive pig production in China. Science of the Total Environment, 770, 144720.
213. Liu, X., Zhou, F., Hu, G., Shao, S., He, H., Zhang, W. et al. (2019) Dynamic contribution of microbial residues to soil organic matter accumulation influenced by maize straw mulching. Geoderma, 333, 35-42. doi: 10.1016/j.geoderma.2018.07.017.
214. Llonch, P., Haskell, M.J., Dewhurst, R.J. and Turner, S.P. (2017) Review: current available strategies to mitigate greenhouse gas emissions in livestock systems: an animal welfare perspective. Animal, 11, 274-284. doi: 10.1017/S1751731116001440.
215. Loreau, M., Naeem, S., Inchausti, P., Bengtsson, J., Grime, J.P., Hector, A. et al. (2001) Biodiversity and ecosystem functioning: current knowledge and future challenges. Science, 294, 804-808.
216. Lorenz, K. and Lal, R. (2014) Soil organic carbon sequestration in agroforestry systems. A review. Agronomy for Sustainable Development, 34(2), 443-454.
217. Lorenz, K. and Lal, R. (2018) Soil Carbon Stock. In Carbon Sequestration in Agricultural Ecosystems. Springer, Cham. doi: 10.1007/978-3-319-92318-5_2.
218. Loulergue, L., Schilt, A., Spahni, R., Masson-Delmotte, V. et al. (2008) Orbital and millennial-scale features of atmospheric CH4 over the past 800,000 years. Nature, 453, 383-386. doi: 10.1038/nature06950.
219. Lu, X., Zhang, L. and Shen, L. (2021) Tropospheric ozone interacts with weather and climate. In Air Pollution and Climate Health, 15-46. doi: 10.1016/B978-0-12-820123-7.00006-1.
220. Lugato, E., Leip, A. and Jones, A. (2018) Mitigation potential of soil carbon management overestimated by neglecting N2O emissions. Nature Climate Change, 8, 219-223. doi: 10.1038/s41558-018-0087-z.
221. Ma, Z., Chen, H.Y., Bork, E.W., Carlyle, C.N. and Chang, S.X. (2020) Carbon accumulation in agroforestry systems is affected by tree species diversity, age and regional climate: a global meta-analysis. Global Ecology and Biogeography, 29, 1817-1828.
222. Ma, Z., Shrestha, B.M., Bork, E.W., Chang, S.X., Carlyle, C.N., Döbert, T.F., Sobrinho, L.S. and Boyce, M.S. (2021) Soil greenhouse gas emissions and grazing management in northern temperate grasslands. Science of the Total Environment, 796, 148975. doi: 10.1016/j.scitotenv.2021.148975.
223. Mach, V., Blaser, M.B., Claus, P., Chaudhary, P.P. and Rulik, M. (2015) 'Methane production potentials, pathways, and communities of methanogens in vertical sediment profiles of river Sitka', Frontiers in Microbiology, 6, p. 506. doi: 10.3389/fmicb.2015.00506.
224. Machmuller, M.B., Kramer, M.G., Cyle, T.K., Hill, N., Hancock, D. and Thompson, A. (2015) 'Emerging land use practices rapidly increase soil organic matter', Nature Communications, 6, p. 6995. doi: 10.1038/ncomms7995.

225. Mahtta, R., Fragkias, M., Güneralp, B., Mahendra, A. et al. (2022) 'Urban land expansion: the role of population and economic growth for 300+ cities', npj Urban Sustainability, 2, p. 5. doi: 10.1038/s42949-022-00048-y.
226. Malik, P.K., Bhatta, R., Takahashi, J., Kohn, R.A. and Prasad, C.S. (2015) Livestock production and climate change. CABI Climate Change Series 6. CABI.
227. Marques, A., Martins, I.S., Kastner, T. et al. (2019) 'Increasing impacts of land use on biodiversity and carbon sequestration driven by population and economic growth', Nature Ecology & Evolution, 3, pp. 628-637. doi: 10.1038/s41559-019-0824-3.
228. Marsden, C., Martin-Chave, A., Cortet, J. et al. (2020) 'How agroforestry systems influence soil fauna and their functions - a review', Plant and Soil, 453, pp. 29-44. doi: 10.1007/s11104-019-04322-4.
229. Matos, P.S., Cherubin, M.R., Damian, J.M., Rocha, F.I., Pereira, M.G. and Zonta, E. (2022) 'Short-term effects of agroforestry systems on soil health in Southeastern Brazil', Agroforestry Systems, 96, pp. 897-908.
230. Mazzoncini, M., Sapkota, T.B., Barberi, P., Antichi, D. and Risaliti, R. (2011) 'Long-term effect of tillage, nitrogen fertilization and cover crops on soil organic carbon and total nitrogen content', Soil and Tillage Research, 114, pp. 165-174.
231. McAlpine, C., Etter, A., Fearnside, P., Seabrook, L. and Laurance, W. (2009) 'Increasing world consumption of beef as a driver of regional and global change: A call for policy action based on evidence from Queensland (Australia), Colombia and Brazil', Global Environmental Change, 19(1), pp. 21-33. doi: 10.1016/j.gloenvcha.2008.10.008.
232. McElwee, P., Calvin, K., Campbell, D., Cherubini, F. et al. (2020) 'The impact of interventions in the global land and agri-food sectors on nature’s contributions to people and the UN Sustainable Development Goals', Global Change Biology, 26, pp. 4691-4721.
233. McSherry, M.E. and Ritchie, M.E. (2013) 'Effects of grazing on grassland soil carbon: a global review', Global Change Biology, 19(5), pp. 1347-1357. doi: 10.1111/gcb.12144.
234. Mehmood, I. et al. (2020) 'Carbon Cycle in Response to Global Warming', in Fahad, S. et al. (eds) Environment, Climate, Plant and Vegetation Growth. Springer, Cham. doi: 10.1007/978-3-030-49732-3_1.
235. Meier, E.A., Thorburn, P.J., Bell, L.W., Harrison, M.T. and Biggs, J.S. (2020) 'Greenhouse Gas Emissions from Cropping and Grazed Pastures Are Similar: A Simulation Analysis in Australia', Frontiers in Sustainable Food Systems, 3, p. 121. doi: 10.3389/fsufs.2019.00121.
236. Melkamu, B.Y. (2019) 'Livestock and livestock product trends by 2050: Review', International Journal of Animal Research, 4, p. 30.
237. Mertens, B., Poccard-Chapuis, R., Piketty, M.G. and Venturieri, A. (2002) 'Crossing spatial analyses and livestock economics to understand deforestation processes in the Brazilian Amazon: the case of São Félix do Xingú in South Pará', Agricultural Economics, 27(3), pp. 269-294. doi: 10.1016/S0169-5150(02)00076-2.
238. Milchunas, D.G. and Lauenroth, W.K. (1993) 'Quantitative effects of grazing on vegetation and soils over a global range of environments', Ecological Monographs, 63, pp. 327-366. doi: 10.2307/2937150.
239. Ministry for the Environment (2023) How methane from livestock contributes to climate change. Publication number: INFO834.
240. Montagnini, F. and Nair, P.K.R. (2004) 'Carbon sequestration: An underexploited environmental benefit of agroforestry systems', Agroforestry Systems, 61-62, pp. 281-295.
241. Montes, F., Meinen, R., Dell, C., Rotz, A., Hristov, A.N., Oh, J. et al. (2013) 'SPECIAL TOPICS—Mitigation of methane and nitrous oxide emissions from animal operations: II. A review of manure management mitigation options', Journal of Animal Science, 91, pp. 5070-5094. doi: 10.2527/jas.2013-6588.
242. Morriën, E., Hannula, S.E., Snoek, L.B., Helmsing, N.R., Zweers, H., de Hollander, M. et al. (2017) 'Soil networks become more connected and take up more carbon as nature restoration progresses', Nature Communications, 8, p. 14349. doi: 10.1038/ncomms14349.
243. Morton, D.C., DeFries, R.S. and Shimabukuro, Y.E. (2009) 'Cropland expansion in cerrado and transition forest ecosystems: Quantifying habitat loss from satellite-based vegetation phenology', in Klink, C.A. (ed.) Cerrado Land Use and Conservation. Conservation International.
244. Mosier, S., Apfelbaum, S., Byck, P., Calderon, F., Teague, R., Thompson, R. and Cotrufo, M.F. (2021)

'Adaptive multi-paddock grazing enhances soil carbon and nitrogen stocks and stabilization through mineral association in southeastern U.S. grazing lands', Journal of Environmental Management, 288, p. 112409. doi: 10.1016/j.jenvman.2021.112409.

245. Mugwe, J. and Otieno, E.O. (2021) 'Integrated soil fertility management approaches for climate change adaptation, mitigation, and enhanced crop productivity', in Leal Filho, W. et al. (eds) Handbook of Climate Change Management. doi: 10.1007/978-3-030-22759-3_325-1.
246. Murgueitio, E., Van der Hoek, R., La¨derach, P., Hyman, G., Tapasco, J., Strassburg, B. et al. (2011) 'Challenges and opportunities for improving eco-efficiency of tropical forage-based systems to mitigate greenhouse gas emissions', Tropical Grasslands, 1, pp. 137-148.
247. Muthuri, C., Kuyah, S., Njenga, M., Kuria, A. et al. (2023) 'Agroforestry's contribution to livelihoods and carbon sequestration in East Africa: A systematic review', Trees, Forests and People, 14, p. 100432.
248. Myhre, G. et al. (2013) 'Chapter 8: Anthropogenic and natural radiative forcing', in Stocker, T.F. et al. (eds) Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.
249. Naeem, S., Knops, J.M.H., Tilman, D., Howe, K.M., Kennedy, T. and Gale, S. (2000) 'Plant diversity increases resistance to invasion in the absence of covarying extrinsic factors', Oikos, 91, pp. 97-108.
250. Nair, P.K.R. (2012) 'Carbon sequestration studies in agroforestry systems: a reality-check', Agroforestry Systems, 86, pp. 243-253. doi: 10.1007/s10457-012-9509-z.
251. Nair, P.K.R., Kumar, B.M. and Nair, V.D. (2021) An Introduction to Agroforestry: Four Decades of Scientific Developments. 2nd edn. Springer.
252. Nayak, N., Mehrotra, R. and Mehrotra, S. (2022) 'Carbon biosequestration strategies: a review', Carbon Capture Science and Technology, 4, p. 100065. doi: 10.1016/j.ccst.2022.100065.
253. OECD/FAO (2019) Agricultural Outlook 2019-2028. Available at: (link unavailable)
254. Oelbermann, M., Paul Voroney, R. and Gordon, A.M. (2004) 'Carbon sequestration in tropical and temperate agroforestry systems: a review with examples from Costa Rica and southern Canada', Agriculture, Ecosystems & Environment, 104, pp. 359-377.
255. Oktan, E., Kezik, U., Hacisalihoglu, S. and Yucesan, Z. (2022) Effects of Deforestation on Soil Erosion and Carbon Sequestration in the Soil. Fresenius Environmental Bulletin, 31, 2239-2249.
256. Oldfeld, E.E. et al. (2022) 'Crediting agricultural soil carbon sequestration', Science, 375, pp. 1222-1225.
257. O'Mara, F.P. (2012) 'The role of grasslands in food security and climate change', Annals of Botany, 110(6), pp. 1263-1270. doi: 10.1093/aob/mcs209.
258. Onen, O.I., Aboh, A.A., Mfam, A.N., Ako, M.O., Nweke, C.N. and Osuagwu, A.N. (2020) 'Microbial diversity: values and roles in ecosystems', Asian Journal of Biology, 9(1), pp. 10-22.
259. Ortiz, J., Neira, P., Panichini, M., Curaqueo, G. et al. (2023) 'Silvopastoral systems on degraded lands for soil carbon sequestration and climate change mitigation', in Dagar, J.C., Gupta, S.R. and Sileshi, G.W. (eds) Agroforestry for Sustainable Intensification of Agriculture in Asia and Africa. Springer. doi: 10.1007/978-981-19-4602-8_7.
260. Pablo, L.P., Banegas, N., Gasparri, I., Carranza, C.H. et al. (2018) 'Carbon Sequestration in Temperate Silvopastoral Systems, Argentina', in Montagnini, F. (ed.) Integrating Landscapes: Agroforestry for Biodiversity Conservation and Food Sovereignty. Advances in Agroforestry 12. doi: 10.1007/978-3-319-69371-2_19.
261. Pacala, S.W., Hurtt, G.C., Baker, D., Peylin, P., Houghton, R.A., Birdsey, R.A. et al. (2001) 'Consistent land- and atmosphere-based U.S. carbon sink estimates', Science, 292, pp. 2316-2320.
262. Palm, C., Tomich, T., van Noordwijk, M., Vosti, S., Gockowski, J., Alegre, J. and Verchot, L. (2004) 'Mitigating GHG emissions in the humid tropics: Case studies from the alternatives to slash-and-burn program (ASB)', Environment, Development and Sustainability, 6, pp. 145-162.
263. Palmer, L. (2021) 'How trees and forests reduce risks from climate change', Nature Climate Change, 11, pp. 374-377. doi: 10.1038/s41558-021-01041-6.
264. Pan, H., Feng, H., Liu, Y., Lai, C-Y. et al. (2021) 'Grazing weakens competitive interactions between active methanotrophs and nitrifiers modulating greenhouse-gas emissions in grassland soils', ISME Communications, 1, p. 74. doi: 10.1038/s43705-021-00068-2.
265. Pan, Y., Birdsey, R.A., Fang, J. et al. (2011) 'A large and persistent carbon sink in the world’s forests',

Science, 333, pp. 988-993. doi: 10.1126/science.1201609.
266. Paustian, K., Lehmann, J., Ogle, S., Reay, D. et al. (2016) 'Climate-smart soils', Nature, 532, pp. 49-57. doi: 10.1038/nature17174.
267. Penn State (2018) 'Agroforestry systems may play vital role in mitigating climate change', ScienceDaily, 1 February. Available at: (link unavailable) (Accessed: 18 March 2024).
268. Peterson, C.A., Nunes, P.A.A., Martins, A.P. et al. (2019) 'Winter grazing does not affect soybean yield despite lower soil water content in a subtropical crop-livestock system', Agronomy for Sustainable Development, 39, p. 26. doi: 10.1007/s13593-019-0573-3.
269. Phelps, L.N. and Kaplan, J.O. (2017) 'Land use for animal production in global change studies: Defining and characterizing a framework', Global Change Biology, 23(11), pp. 4457-4471. doi: 10.1111/gcb.13732.
270. Philippot, L., Chenu, C., Kappler, A. et al. (2023) 'The interplay between microbial communities and soil properties', Nature Reviews Microbiology. doi: 10.1038/s41579-023-00980.
271. Pimentel, D., Berger, B., Filiberto, D., Newton, M. et al. (2004) 'Water Resources: Agricultural and Environmental Issues', BioScience, 54(10), pp. 909-918. doi: 10.1641/0006-3568(2004)054[0909: WRAAEI].
272. Poeplau, C., Don, A., Vesterdal, L., Leifeld, J., Van Wesemael, B., Schumacher, J. and Gensior, A. (2011) 'Temporal dynamics of soil organic carbon after land-use change in the temperate zone - carbon response functions as a model approach', Global Change Biology, 17, pp. 2415-2427. doi: 10.1111/j.1365-2486.2011.02408. x.
273. Poore, J. and Nemecek, T. (2018) 'Reducing food's environmental impacts through producers and consumers', Science, 360, pp. 987-992. doi: 10.1126/science. aaq0216.
274. Popp, A., Calvin, K., Fujimori, S., Havlik, P. et al. (2017) 'Land-use futures in the shared socioeconomic pathways', Global Environmental Change, 42, pp. 331-345. doi: 10.1016/j.gloenvcha.2016.10.002.
275. Popp, A., Humpenöder, F., Weindl, I., Bodirsky, B.L. et al. (2014) 'Land-use protection for climate change mitigation', Nature Climate Change, 4, pp. 1095-1098. doi: 10.1038/nclimate2444.
276. Popp, A., Lotze-Campen, H. and Bodirsky, B. (2010) 'Food consumption, diet shifts and associated non-CO2 greenhouse gases from agricultural production', Global Environmental Change, 20(3), pp. 451-462. doi: 10.1016/j.gloenvcha.2010.02.001.
277. Portmann, R., Beyerle, U., Davin, E., Fischer, E.M. et al. (2022) 'Global forestation and deforestation affect remote climate via adjusted atmosphere and ocean circulation', Nature Communications, 13, p. 5569. doi: 10.1038/s41467-022-33279-9.
278. Powers, R.P. and Jetz, W. (2019) 'Global habitat loss and extinction risk of terrestrial vertebrates under future land-use-change scenarios', Nature Climate Change, 9, pp. 323-329. doi: 10.1038/s41558-019-0458-9.
279. Que, F.G., Villanueva-López, G., Alcudia-Aguilar, A., Fan, S.M., Gloor, M., Malhlman, J., Pacala, S., Sarmiento, J. and Takahashi, T. et al. (1998) A large terrestrial carbon sink in North America implied by atmospheric and oceanic CO2 data and models. Science, 282, 442-446.
280. Rackley, S. (2023) 'The global carbon cycle', in Negative Emissions Technologies for Climate Change Mitigation. pp. 67-74. doi: 10.1016/B978-0-12-819663-2.00002-2.
281. Radchuk, V., Reed, T., Teplitsky, C., Van de Pol, M. et al. (2019) 'Adaptive responses of animals to climate change are most likely insufficient', Nature Communications, 10, p. 3109. doi: 10.1038/s41467-019-10924-4.
282. Ramankutty, N. and Foley, J.A. (1999) 'Estimating historical changes in global land cover: croplands from 1700 to 1992', Global Biogeochemical Cycles, 13, pp. 997-1027.
283. Regnier, P., Resplandy, L., Najjar, R.G. et al. (2022) 'The land-to-ocean loops of the global carbon cycle', Nature, 603, pp. 401-410. doi: 10.1038/s41586-021-04339-9.
284. Reichstein, M., Bahn, M., Ciais, P., Frank, D. et al. (2013) 'Climate extremes and the carbon cycle', Nature, 500, pp. 287-295. doi: 10.1038/nature12350.
285. Reisinger, A. and Clark, H. (2018) 'How much do direct livestock emissions actually contribute to global warming?', Global Change Biology, 24, pp. 1749-1761. doi: 10.1111/gcb.13975.
286. Reppin, S., Kuyah, S., de Neergaard, A., Oelofse, M. and Rosenstock, T.S. (2020) 'Contribution of agroforestry to climate change mitigation and livelihoods in Western Kenya', Agroforestry Systems,

94, pp. 203-220. doi: 10.1007/s10457-019-00383-7.
287. Retallack, G.J. (2013) 'Global cooling by grassland soils of the geological past and near future', Annual Review of Earth and Planetary Sciences, 41, pp. 69-86. doi: 10.1146/annurev-earth-050212-124001.
288. Reynolds, C., Crompton, L. and Mills, J. (2010) 'Livestock and climate change impacts in the developing world', Outlook on Agriculture, 39, pp. 245-248.
289. Rocher-Ros, G., Stanley, E.H., Loken, L.C., Casson, N.J. et al. (2023) 'Global methane emissions from rivers and streams', Nature, 621, pp. 530-535. doi: 10.1038/s41586-023-06344-6.
290. Rojas-Downing, M.M., Nejadhashemi, A.P., Harrigan, T. and Woznicki, S.A. (2017) 'Climate change and livestock: Impacts, adaptation, and mitigation', Climate Risk Management, 16, pp. 145-163.
291. Roman-Cuesta, R.M. et al. (2016) 'Hotspots of gross emissions from the land use sector: patterns, uncertainties, and leading emission sources for the period 2000-2005 in the tropics', Biogeosciences, 13, pp. 4253-4269.
292. Rosegrant, M.W., Fernandez, M. and Sinha, A. (2009) 'Looking into the future for agriculture and AKST', in McIntyre, B.D., Herren, H.R., Wakhungu, J. and Watson, R.T. (eds) International Assessment of Agricultural Knowledge, Science and Technology for Development (IAASTD). Agriculture at a Crossroads. Island Press, pp. 307-376.
293. Rosenzweig, C., Mbow, C., Barioni, L.G., Benton, T.G. et al. (2020) 'Climate change responses benefit from a global food system approach', Nature Food, 1, pp. 94-97. doi: 10.1038/s43016-020-0031-z.
294. Roshetko, J.M., Delaney, M., Hairiah, K. and Purnomosidhi, P. (2002) 'Carbon stocks in Indonesian homegarden systems: Can smallholder systems be targeted for increased carbon storage?', American Journal of Alternative Agriculture, 17, pp. 138-148.
295. Rouquette, F.M., Sollenberger, L.E., Vendramini, J.M.B. (2023) Grazing management and stocking strategy decisions for pasture-based beef systems: experimental confirmation vs. testimonials and perceptions. Translational Animal Science, 7(1), txad069. doi: 10.1093/tas/txad069.
296. Rowntree, J.E., Ryals, R., DeLonge, M.S., Teague, W.R., Chiavegato, M.B. and Byck, P. et al. (2016) 'Potential mitigation of midwest grass-finished beef production emissions with soil carbon sequestration in the United States of America', Future of Food: Journal of Food, Agriculture and Society, 4, pp. 31-38.
297. Roy, P.S., Ramachandran, R.M., Paul, O., Thakur, P.K. et al. (2022) 'Anthropogenic Land Use and Land Cover Changes—A Review on Its Environmental Consequences and Climate Change', Journal of the Indian Society of Remote Sensing, 50, pp. 1615-1640. doi: 10.1007/s12524-022-01569-w.
298. Royal Society (2018) Greenhouse Gas Removal. London: Royal Society. Available at: (link unavailable).
299. Ruehr, S., Keenan, T.F., Williams, C. et al. (2023) 'Evidence and attribution of the enhanced land carbon sink', Nature Reviews Earth & Environment, 4, pp. 518-534. doi: 10.1038/s43017-023-00456-3.
300. Russell, S. (2014) 'Everything you need to know about agricultural emissions', World Resources Institute.
301. Russelle, M.P., Entz, M.H. and Franzluebbers, A.J. (2007) 'Reconsidering integrated crop–livestock systems in North America', Agronomy Journal, 99, p. 325. doi: 10.2134/agronj2006.0139.
302. Sanderson, M.A., Archer, D., Hendrickson, J., Kronberg, S., Liebig, M., Nichols, K. et al. (2013) 'Diversification and ecosystem services for conservation agriculture: outcomes from pastures and integrated crop-livestock systems', Renewable Agriculture and Food Systems, 28(2), pp. 129-144.
303. Sarkar, R., Corriher-Olson, V., Long, C. and Somenahally, A. (2020) 'Challenges and potentials for soil organic carbon sequestration in forage and grazing systems', Rangeland Ecology & Management, 73(6), pp. 786-795. doi: 10.1016/j.rama.2020.04.002.
304. Saunois, M., Stavert, A., Poulter, R., Bousquet, B. et al. (2020) 'The Global Methane Budget 2000–2017', Earth System Science Data, 12(3), pp. 1561-1623. doi: 10.5194/essd-12-1561-2020.
305. Savian, J.V., Neto, A.B., de David, D.B., Bremm, C. et al. (2014) 'Grazing intensity and stocking methods on animal production and methane emission by grazing sheep: implications for integrated crop-livestock system', Agriculture, Ecosystems & Environment, 190, pp. 112-119. doi: 10.1016/j.agee.2014.02.008.
306. Schimel, J. and Schaeffer, S.M. (2012) 'Microbial control over carbon cycling in soil', Frontiers in Microbiology, 3, p. 348. doi: 10.3389/fmicb.2012.00348.
307. Schlesinger, W.H. (1999) Carbon sequestration in soils. Science, 284, 25 June.

308. Schlesinger, W.H. and Bernhardt, E.S. (2013) Biogeochemistry: An Analysis of Global Change. Academic Press.
309. Searchinger, T., Hanson, C., Ranganathan, J., Lipinski, B. et al. (2014) Creating a Sustainable Food Future. A Menu of Solutions to Sustainably Feed More Than 9 Billion People by 2050. World Resources Institute.
310. Searchinger, T., Heimlich, R., Houghton, R.A., Dong, F., Elobeid, A., Fabiosa, J., Tokgoz, S., Hayes, D. and Yu, T.H. (2008) 'Use of U.S. croplands for biofuels increases greenhouse gases through emissions from land-use change', Science, 319, pp. 1238-1240.
311. Searchinger, T.D., Wirsenius, S., Beringer, T. and Dumas, P. (2018) 'Assessing the efficiency of changes in land use for mitigating climate change', Nature, 564, pp. 249-253. doi: 10.1038/s41586-018-0757-z.
312. Seguin, B. (2008) 'The consequences of global warming for agriculture and food production', in Rowlinson, P., Steele, M. and Nefzaoui, A. (eds) Livestock and Global Climate Change. Cambridge University Press, pp. 9-11.
313. Sejian, V., Bhatta, R., Malik, P.K., Madiajagan, B. et al. (2016) 'Livestock as Sources of Greenhouse Gases and Its Significance to Climate Change'. InTech. doi: 10.5772/62135.
314. Sejian, V., Gaughan, J., Baumgard, L. and Prasad, C.S. (2015) Climate Change Impact on Livestock: Adaptation and Mitigation. Springer-Verlag GMbH Publisher.
315. Sekaran, U., Lai, L., Ussiri, D.A.N., Kumar, S. and Clay, S. (2021) 'Role of integrated crop-livestock systems in improving agriculture production and addressing food security – a review', Journal of Agriculture and Food Research, 5, p. 100190. doi: 10.1016/j.jafr.2021.100190.
316. Sha, Z., Bai, Y., Li, R., Lan, H. et al. (2022) 'The global carbon sink potential of terrestrial vegetation can be increased substantially by optimal land management', Communications Earth & Environment, 3, p. 8. doi: 10.1038/s43247-021-00333-1.
317. Shi, L., Feng, W., Xu, J. and Kuzyakov, Y. (2018) 'Agroforestry systems: Meta-analysis of soil carbon stocks, sequestration processes, and future potentials', Land Degradation & Development, 29, pp. 3886-3897. doi: 10.1002/ldr.3136.
318. Shi, R., Irfan, M., Liu, G., Yang, X. and Su, X. (2022) 'Analysis of the Impact of Livestock Structure on Carbon Emissions of Animal Husbandry: A Sustainable Way to Improving Public Health and Green Environment', Frontiers in Public Health, 10, p. 835210. doi: 10.3389/fpubh.2022.835210.
319. Shibu, J. and Sougata, B. (2012) 'Agroforestry for biomass production and carbon sequestration: an overview', Agroforestry Systems, 86, pp. 105-111.
320. Shrestha, J., Subedi, S., Timsina, K.P., Chaudhary, A., Kandel, M. and Tripathi, S. (2020) 'Conservation agriculture as an approach towards sustainable crop production: a review', Farm Management, 5(1), pp. 7-15.
321. Siegl, S., Hagenbucher, S., Niggli, U. and Riedel, J. (2023) 'Addressing dairy industry’s scope 3 greenhouse gas emissions by efficiently managing farm carbon footprints', Environmental Challenges, 11, p. 100719. doi: 10.1016/j.envc.2023.100719.
322. Smith, J., Winograd, M., Gallopin, G. and Pachico, D. (1989) 'Dynamics of the agricultural frontier in the Amazon and savannas of Brazil: analysing the impact of policy and technology', Environmental Modeling & Assessment, 3, pp. 31-46.
323. Smith, J.M.B. (2024) 'Grassland', Encyclopedia Britannica. Available at: (link unavailable) (Accessed: 25 March 2024).
324. Smith, P. et al. (2008) 'Greenhouse gas mitigation in agriculture', Philosophical Transactions of the Royal Society B: Biological Sciences, 363, pp. 789-813.
325. Smith, P., Calvin, K., Nkem, J., Campbell, D. et al. (2020) 'Which practices co-deliver food security, climate change mitigation and adaptation, and combat land degradation and desertification?', Global Change Biology, 26, pp. 1532-1575. doi: 10.1111/gcb.14878.
326. Snyder, H. (2019) 'Literature review as a research methodology: An overview and guidelines', Journal of Business Research, 104, pp. 333-339. doi: 10.1016/j.jbusres.2019.07.039.
327. Sollins, P., Swanston, C., Kleber, M., Filley, T., Kramer, M., Crow, S. et al. (2006) 'Organic C and N stabilization in a forest soil: Evidence from sequential density fractionation', Soil Biology and Biochemistry, 38(11), pp. 3313-3324.
328. Soussana, J.F. and Lemaire, G. (2014) 'Coupling carbon and nitrogen cycles for environmentally

sustainable intensification of grasslands and crop-livestock systems', Agriculture, Ecosystems & Environment, 190, pp. 9-17. doi: 10.1016/j.agee.2013.10.012.

329. Soussana, J.F., Loiseau, P., Vuichard, N., Ceschia, E., Balesdent, J., Chevallier, T. and Arrouays, D. (2004) 'Carbon cycling and sequestration opportunities in temperate grasslands', Soil Use and Management, 20, pp. 219-230. doi: 10.1111/j.1475-2743.2004.tb00362.x.
330. Soussana, J.F., Tallec, T. and Blanfort, V. (2010) 'Mitigation the greenhouse gas balance of ruminant production systems through carbon sequestration in grasslands', Animal, 4, pp. 334-350. doi: 10.1017/S1751731109990784.
331. Stanley, P.L., Rowntree, J.E., Beede, D.K., DeLonge, M.S. and Hamm, M.W. (2018) 'Impacts of soil carbon sequestration on life cycle greenhouse gas emissions in Midwestern USA beef finishing systems', Agricultural Systems, 162, pp. 249-258. doi: 10.1016/j.agsy.2018.02.003.
332. Steinfeld, H. and Wassenaar, T. (2007) 'The Role of Livestock Production in Carbon and Nitrogen Cycles', Annual Review of Environment and Resources, 32, pp. 271-294. doi: 10.1146/annurev.energy.32.041806.143508.
333. Steinfeld, H., Gerber, P., Wassenaar, T., Castel, V., Rosales, M. and Haan, C. (2006) Livestock's Long Shadow: Environmental Issues and Options. FAO, Rome.
334. St-Pierre, N.R., Cobanov, B. and Schnitkey, G. (2003) 'Economic losses from heat stress by U.S. livestock industries', Journal of Dairy Science, 86, pp. E52-E77.
335. Tamburini, E., Gaglio, M., Castaldelli, G. and Fano, E.A. (2020) 'Is Bioenergy Truly Sustainable When Land-Use-Change (LUC) Emissions Are Accounted for? The Case-Study of Biogas from Agricultural Biomass in Emilia-Romagna Region, Italy', Sustainability, 12, p. 3260. doi: 10.3390/su12083260.
336. Tanentzap, A.J., Lee, W.G. and Coomes, D.A. (2012) 'Soil nutrient supply and Chionochloa grasses', Bulletin of the Ecological Society of America, 93(3), pp. 229-232. doi: 10.1890/0012-9623-93.3.229.
337. Tarawali, S., Herrero, M., Descheemaeker, K., Grings, E.E. et al. (2011) 'Pathways for sustainable development of mixed crop livestock systems: Taking a livestock and pro-poor approach', Livestock Science, 139(1-2), pp. 11-21. doi: 10.1016/j.livsci.2011.03.003.
338. Teague, R. and Kreuter, U. (2020) 'Managing grazing to restore soil health, ecosystem function, and ecosystem services', Frontiers in Sustainable Food Systems, 4, p. 534187. doi: 10.3389/fsufs.2020.534187.
339. Teague, W.R., Dowhower, S.L., Baker, S.A., Haile, N., DeLaune, P.B. and Conover, D.M. (2011) 'Grazing management impacts on vegetation, soil biota and soil chemical, physical and hydrological properties in tall grass prairie', Agriculture, Ecosystems & Environment, 141, pp. 310-322. doi: 10.1016/j.agee.2011.03.009.
340. Terefe, H., Argaw, M., Tamene, L. et al. (2020) 'Sustainable land management interventions lead to carbon sequestration in plant biomass and soil in a mixed crop-livestock system: the case of Geda watershed, central highlands of Ethiopia', Ecological Processes, 9, p. 34. doi: 10.1186/s13717-020-00233-w.
341. Tesfaye, B. and Li, F. (2020) 'Review on contribution of integrated soil fertility management for climate change mitigation and agricultural sustainability', Cogent Environmental Science, 6(1). doi: 10.1080/23311843.2020.1823631.
342. Thakur, M.P. et al. (2015) 'Plant diversity drives soil microbial biomass carbon in grasslands irrespective of global environmental change factors', Global Change Biology, 21, pp. 4076-4085.
343. Thapa, B. and Dura, R. (2024) 'A review on tillage system and no-till agriculture and its impact on soil health', Archives of Agriculture and Environmental Science, 9, pp. 612-617. doi: 10.26832/24566632.2024.0903028.
344. Thorlakson, T. and Neufeldt, H. (2012) 'Reducing subsistence farmers' vulnerability to climate change: evaluating the potential contributions of agroforestry in western Kenya', Agriculture & Food Security, 1, p. 15. doi: 10.1186/2048-7010-1-15.
345. Thornton, P.K. and Gerber, P.J. (2010) 'Climate change and the growth of the livestock sector in developing countries', Mitigation and Adaptation Strategies for Global Change, 15, pp. 169-184.
346. Tilman, D. and Clark, M. (2014) 'Global diets link environmental sustainability and human health', Nature, 515, pp. 518-522.
347. Torres, C.M.M.E., Jacovine, L.A.G., Nolasco de Olivera Neto, S. et al. (2017) 'Greenhouse gas emissions and carbon sequestration by agroforestry systems in southeastern Brazil', Scientific Reports,

7, p. 16738. doi: 10.1038/s41598-017-16821-4.

348. Trivedi, P., Singh, B.P. and Singh, B.K. (2018) 'Soil Carbon: Introduction, Importance, Status, Threat, and Mitigation', in Soil Carbon Storage: Modulators, Mechanisms and Modelling, pp. 1-28. doi: 10.1016/B978-0-12-812766-7.00001-9.
349. Trumbore, S.E. (1997) 'Potential responses of soil organic carbon to global environmental change', Proceedings of the National Academy of Sciences, 94(16), pp. 8284-8291.
350. Tubiello, F.N., Salvatore, M., Ferrara, A.F., House, J. et al. (2015) 'The Contribution of Agriculture, Forestry and other Land Use activities to Global Warming, 1990-2012', Global Change Biology, 21(7), pp. 2655-2660. doi: 10.1111/gcb.12865.
351. Tubiello, F.N., Salvatore, M., Rossi, S., Ferrara, A. et al. (2013) 'The FAOSTAT database of greenhouse gas emissions from agriculture', Environmental Research Letters, 8, p. 015009. doi: 10.1088/1748-9326/8/1/015009.
352. Tubiello, F.N., Schmidhuber, J., Howden, M., Neofotis, P.G. et al. (2008) Climate change response strategies for agriculture: challenges and opportunities for the 21st century. Agriculture and Rural Development Discussion Paper No. 42. World Bank.
353. Turner, A.J., Frankenberg, C. and Kort, E.A. (2019) 'Interpreting contemporary trends in atmospheric methane', Proceedings of the National Academy of Sciences, 116, pp. 2805-2813. doi: 10.1073/pnas.1814297116.
354. Turner, B.L., Lambin, E.F. and Reenberg, A. (2007) 'The emergence of land change science for global environmental change and sustainability', Proceedings of the National Academy of Sciences, 104(52), pp. 20666-20671. doi: 10.1073/pnas.0704119104.
355. Udawatta, R.P., Walter, D. and Jose, S. (2022) 'Carbon sequestration by forests and agroforests: A reality check for the United States', Carbon Footprints, 1, p. 8.
356. Valin, H., Sands, R.D., van der Mensbrugghe, D., Nelson, G.C. et al. (2014) 'The future of food demand: understanding differences in global economic models', Agricultural Economics, 45, pp. 51-67.
357. Van der Heijden, M.G.A., Bardgett, R.D. and Van Straalen, N.M. (2008) 'The unseen majority: soil microbes as drivers of plant diversity and productivity in terrestrial ecosystems', Ecology Letters, 11, pp. 296-310. doi: 10.1111/j.1461-0248.2007.01139.x.
358. Van der Werf, G., Morton, D., DeFries, R., Olivier, J.G.J. et al. (2009) 'CO2 emissions from forest loss', Nature Geoscience, 2, pp. 737-738. doi: 10.1038/ngeo671.
359. Van Dijk, M., Morley, T., Rau, M.L., Saghai, Y. et al. (2021) 'A meta-analysis of projected global food demand and population at risk of hunger for the period 2010-2050', Nature Food, 2, pp. 494-501. doi: 10.1038/s43016-021-00322-9.
360. Van Noordwijk, M. (2014) 'Climate Change: Agricultural Mitigation', in Encyclopedia of Agriculture and Food Systems, Vol. 2, pp. 220-231.
361. Veneman, J.B., Muetzel, S., Hart, K.J., Faulkner, C.L., Moorby, J.M., Perdok, H.B. et al. (2015) 'Does Dietary Mitigation of Enteric Methane Production Affect Rumen Function and Animal Productivity in Dairy Cows?', PLOS ONE, 10(10), p. e0140282. doi: 10.1371/journal.pone.0140282.
362. Verchot, L., Van Noordwijk, M., Kandji, S., Tomich, T. et al. (2007) 'Climate change: Linking adaptation and mitigation through agroforestry', Mitigation and Adaptation Strategies for Global Change, 12, pp. 901-918. doi: 10.1007/s11027-007-9105-6.
363. Vermeulen, S., Zougmoré, R., Wollenberg, E., Thornton, P. et al. (2012) 'Climate change, agriculture and food security: a global partnership to link research and action for low-income agricultural producers and consumers', Current Opinion in Environmental Sustainability, 4, pp. 128-133. doi: 10.1016/j.cosust.2011.12.004.
364. Veysset, P., Lherm, M. and Bébin, D. (2010) 'Energy consumption, greenhouse gas emissions and economic performance assessments in French Charolais suckler cattle farms: Model-based analysis and forecasts', Agricultural Systems, 103(1), pp. 41-50. doi: 10.1016/j.agsy.2009.08.005.
365. Wang, J., Cardenas, L.M., Misselbrook, T.H., Cuttle, S., Thorman, R.E. and Li, C. (2012) 'Modelling nitrous oxide emissions from grazed grassland systems', Environmental Pollution.
366. Wang, T., Teague, W.R., Park, S.C. and Bevers, S. (2015) 'GHG mitigation potential of different grazing strategies in the United States Southern great plains', Sustainability, 7, pp. 13500-13521. doi: 10.3390/su71013500.
367. Wang, X. et al. (2016) 'Grazing improves C and N cycling in the Northern Great Plains: a meta-

analysis', Scientific Reports, 6, p. 33190.
368. Wassenaar, T., Gerber, P., Verburg, P., Rosales, M., Ibrahim, M. and Steinfeld, H. (2007) 'Projecting land use changes in the Neotropics: The geography of pasture expansion into forest', Global Environmental Change, 17(1), pp. 86-104. doi: 10.1016/j.gloenvcha.2006.03.007.
369. Weindl, I., Popp, A., Bodirsky, B.L., Rolinski, S. et al. (2017) 'Livestock and human use of land: Productivity trends and dietary choices as drivers of future land and carbon dynamics', Global and Planetary Change, 159, pp. 1-10.
370. Whitehead, D. (2020) 'Management of grazed landscapes to increase soil carbon stocks in temperate, dryland grasslands', Frontiers in Sustainable Food Systems, 4, p. 585913. doi: 10.3389/fsufs.2020.585913.
371. Wiesmeier, M., Mayer, S., Paul, C., Helming, K. et al. (2020) 'CO2-Zertifikate für die Festlegung atmosphärischen Kohlenstoffs in Böden: Methoden, Maßnahmen und Grenzen', BonaRes Series, 24. doi: 10.20387/BONARES-F8T8-XZ4H.
372. Wiesmeier, M., Urbanski, L., Hobley, E. and Lang, B. (2019) 'Soil organic carbon storage as a key function of soils—A review of drivers and indicators at various scales', Geoderma, 333, pp. 149-162. doi: 10.1016/j.geoderma.2018.07.026.
373. Wigley, T.M.I. and Schimel, D.S. (2005) The Carbon Cycle. Cambridge University Press.
374. Willers, C.D., Maranduba, H.L., de Almeida Neto, J.A. et al. (2017) 'Environmental Impact assessment of a semi-intensive beef cattle production in Brazil's Northeast', International Journal of Life Cycle Assessment, 22, pp. 516-524. doi: 10.1007/s11367-016-1062-4.
375. Willett, W., Rockström, J., Loken, B., Springmann, M. et al. (2019) 'Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems', The Lancet, 393, pp. 447-492. doi: 10.1016/S0140-6736(18)31788-4.
376. Wilsey, B.J. (2018) The Biology of Grasslands. Oxford University Press, Oxford, United Kingdom.
377. Winkler, K., Fuchs, R., Rounsevell, M. and Herold, M. (2021) 'Global land use changes are four times greater than previously estimated', Nature Communications, 12, p. 2501. doi: 10.1038/s41467-021-22702-2.
378. Winkler, K., Gessner, U. and Hochschild, V. (2017) 'Identifying droughts affecting agriculture in Africa based on remote sensing time series between 2000–2016: rainfall anomalies and vegetation condition in the context of ENSO', Remote Sensing, 9, p. 831.
379. Winterstein, F., Tanalski, F., Jöckel, P., Dameris, M. and Ponater, M. (2019) 'Implication of strongly increased atmospheric methane concentrations for chemistry–climate connections', Atmospheric Chemistry and Physics, 19, pp. 7151-7163. doi: 10.5194/acp-19-7151-2019.
380. Wolf, J., Chen, M. and Asrar, G.R. (2021) 'Global Rangeland Primary Production and Its Consumption by Livestock in 2000–2010', Remote Sensing, 13, p. 3430. doi: 10.3390/rs13173430.
381. Wright, C.L. and Lehtovirta-Morley, L.E. (2023) 'Nitrification and beyond: metabolic versatility of ammonia oxidizing archaea', ISME Journal, 17, pp. 1358-1368. doi: 10.1038/s41396-023-01467-0.
382. Wright, I.A., Tarawali, S., Blummel, M., Gerard, B. et al. (2012) 'Integrating crops and livestock in subtropical agricultural systems', Journal of the Science of Food and Agriculture, 92, pp. 1010-1015.
383. Wu, H., Cui, H., Fu, C., Li, R., Qi, F. et al. (2023) 'Unveiling the crucial role of soil microorganisms in carbon cycling: A review', Science of The Total Environment, 909, p. 168627.
384. Xu, X., Sharma, P., Shu, S., Lin, T-S. et al. (2021) 'Global greenhouse gas emissions from animal-based foods are twice those of plant-based foods', Nature Food, 2, pp. 724-732. doi: 10.1038/s43016-021-00358-x.
385. Xu, X., Xu, Y., Li, J., Lu, Y. et al. (2023) 'Coupling of crop and livestock production can reduce the agricultural GHG emission from smallholder farms', iScience, 26, p. 106798. doi: 10.1016/j.isci.2023.106798.
386. Xu, Y., Tan, J., Wang, X., Li, W., He, X., Hu, X. and Fan, Y. (2021) 'Synergetic management of water-energy-food nexus system and GHG emissions under multiple uncertainties: an inexact fractional fuzzy chance constraint programming method', Agricultural Water Management, 262, p. 107323. doi: 10.1016/j.agwat.2021.107323.
387. Yang, Y., Shi, Y., Sun, W. et al. (2022) 'Terrestrial carbon sinks in China and around the world and their contribution to carbon neutrality', Science China Life Sciences, 65, pp. 861-895. doi: 10.1007/s11427-021-2045-5.

388. You, Y., Liu, Y., Xiao, T. and Hou, F. (2023) 'Effects of grazing and nitrogen application on greenhouse gas emissions in alpine meadow', Science of The Total Environment, 894. doi: 10.1016/j.scitotenv.2023.164894.
389. Zehetmeier, M., Hoffmann, H., Sauer, J., Hofmann, G., Dorfner, G. and O'Brien, D. (2014) 'A dominance analysis of greenhouse gas emissions, beef output and land use of German dairy farms', Agricultural Systems, 129, pp. 55-67. doi: 10.1016/j.agsy.2014.05.006.
390. Zhang, K. et al. (2008) 'Satellite-based model detection of recent climate-driven changes in northern high-latitude vegetation productivity', Journal of Geophysical Research: Biogeosciences, 113. doi: 10.1029/2007JG000621.
391. Zhang, M., Delgado-Baquerizo, M., Li, G., Isbell, F. et al. (2023) 'Experimental impacts of grazing on grassland biodiversity and function are explained by aridity', Nature Communications, 14, p. 5040. doi: 10.1038/s41467-023-40809-6.
392. Zhou, G., Zhou, X., He, Y., Shoa, J., Hu, Z. and Liu, R. et al. (2017) 'Grazing intensity significantly affects belowground carbon and nitrogen cycling in grassland ecosystems: a meta-analysis', Global Change Biology, 23, pp. 1167-1179. doi: 10.1111/gcb.13431.
393. Zhu, X., Jackson, R.D., DeLucia, E.H., Tiedje, J.M. and Liang, C. (2020) 'The soil microbial carbon pump: From conceptual insights to empirical assessments', Global Change Biology, pp. 1-8. doi: 10.1111/gcb.15319.
394. Zhu, Z. et al. (2016) 'Greening of the Earth and its drivers', Nature Climate Change, 6, pp. 791-795.
395. Zomer, R.J., Bossio, D.A., Sommer, R. and Verchot, L.V. (2017) 'Global sequestration potential of increased organic carbon in cropland soils', Scientific Reports, 7, pp. 15554-15554. doi: 10.1038/s41598-017-15794-8.
396. Zomer, R.J., Neufeldt, H., Xu, J., Ahrends, A., Bossio, D., Trabucco, A., van Noordwijk, M. and Wang, M. (2016) 'Global Tree Cover and Biomass Carbon on Agricultural Land: The contribution of agroforestry to global and national carbon budgets', Scientific Reports, 6, p. 29987. doi: 10.1038/srep29987.