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Regenerative Agriculture in Practice

A Review

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Abstract

Regenerative agriculture, a farming approach that focuses on soil health and ecosystems, has recently received considerable attention, particularly as an essential element of sustainable agriculture in the context of climate change. This paper reviews quantitative evidence of regenerative agriculture's impact on productivity, resilience, and climate change mitigation—through carbon sequestration in soil. The effectiveness of regenerative agriculture depends on local climate conditions and existing practices. In addition, large-scale adoption of regenerative agriculture faces multiple challenges, such as the trade-off between short-term loss and long-term gains, smallholder farmer profitability, and other common market failures in agriculture. These challenges are especially salient in African agriculture. However, payments for ecosystem services, though yet to be carefully designed, can potentially incentivize farmers to adopt regenerative agriculture and create an additional source of income. Finally, further empirical evidence on the causal impacts of regenerative agriculture is needed to support policy design and recommendations. The paper concludes with open questions on regenerative agriculture for future study.

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Regenerative Agriculture in Practice: A Review

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1. Introduction

Climate change imposes substantial negative impacts on agricultural productivity through extreme heat, drought, floods, and loss of biodiversity. Since 1961, anthropogenic climate change has resulted in a 21 percent decline in global agricultural TFP. The impact is even more pronounced in warmer regions, with reductions ranging from 26 to 34 percent, particularly affecting Africa (Ortiz-Bobea, et al. 2021). Losses in agricultural revenue exacerbate poverty in developing countries.

Consequently, the focus on carbon sequestration in soil has attracted much attention as a possible solution to mitigate global carbon emissions. Global soils contain a significant reservoir of organic carbon, storing approximately 1,500 gigatons of carbon within the first meter of depth; this is three times greater than the amount of carbon found in atmospheric CO_2. In addition, 900 gigatons of carbon are stored in the second meter of soil (Powlson, et al. 2014).

Regenerative agriculture, a farming approach that focuses on restoring and improving the health of soil and ecosystems, has attracted increasing interest from policy makers worldwide. Common regenerative agricultural practices include reduced-tillage or zero-tillage, vegetation cover, intercropping, applying compost and organic waste instead of chemical fertilizers, and livestock integration. These practices can potentially restore soil health, which can increase crop yields and resilience. Also, practices such as zero-tillage can reduce soil disturbance and sequester more carbon in soils.

Despite the growing attention on regenerative agriculture to achieve potential ‘triple wins’ --- increasing productivity, increasing resilience, and reducing carbon emissions --- empirical evidence on how effective regenerative agriculture is in achieving these three objectives is scarce. This paper aims to review existing empirical evidence, especially causal quantitative evidence, through an extensive examination of economic and scientific literature.

Building on lessons drawn from empirical evaluation of regenerative agriculture in practice and the broader literature on technology adoption in agriculture, we further discuss barriers to large-scale adoption of regenerative agriculture. These barriers, including the trade-off between short-term loss and long-term gains, smallholder farmer profitability, and other common market failures for technology adoption in agriculture, are especially salient in African agriculture. Moreover, payments for ecosystem services, though yet to be carefully designed, could potentially incentivize farmers to adopt regenerative agriculture, thereby creating an additional source of income. We discuss the potential and challenges of setting up payments for ecosystem services.

A limited number of papers have summarized evidence of impact related to regenerative agriculture. For instance, Piñeiro et al. (2020) conduct a scoping review that examines the adoption of sustainable practices and their impact on productivity as well as economic and environmental outcomes. They find that short-term economic benefit is the leading deciding factor for the adoption of sustainable practices. However, only qualitative outcomes of sustainable practices are included, as quantitative evidence is limited. Despite the high-level discussion on the trade-offs in the outcomes of sustainable practices, it does not further explore how adoption interacts with underlying factor market failures. Several meta-analysis papers (Pittelkow, et al. 2015, Bai, et al. 2019, Ogle, et al. 2019) gather evidence from scientific literature to examine the effectiveness of regenerative agricultural practices. These studies dig deeper to explain why the effectiveness of productivity and carbon sequestration depends on local climate conditions. However, the studies lack a more comprehensive evaluation of the impact of regenerative agriculture. Furthermore, Suri and Udry (2022) review the economics literature that tries to understand the stagnation of technological progress in general in Africa's agriculture. In this paper, we focus particularly on regenerative agriculture in the context of climate change. We argue that heterogeneity in returns can be substantial for regenerative agricultural practices as their effectiveness relies on not only local market conditions, but also local climate conditions.

The rest of the paper is organized as follows: Section 2 discusses the evolution of regenerative agriculture, its distinctions from other concepts related to sustainable agriculture, and its practical adoption across the world. Section 3 summarizes empirical evidence, especially quantitative evidence, of regenerative agriculture's impact on crop productivity, resilience under climate shocks, and carbon mitigation. Section 4 explores barriers to large-scale adoption of regenerative agriculture. Section 5 further examines the challenges and opportunities of regenerative agriculture in Africa under climate change. Section 6 concludes with open questions and further research that are needed to inform policy recommendations.

2. What Is Regenerative Agriculture?

2.1 Origin and Evolution of Regenerative Agriculture

Regenerative agriculture is a farming approach that focuses on restoring and improving the health of soil and ecosystems (Schreefel, et al. 2020). While its practices share similarities with other agricultural approaches, such as climate-smart agriculture and conservation agriculture, the underlying philosophy and objectives differ significantly, which we will discuss in more detail later. Unlike conventional farming practices, which often focus more on maximizing yields, regenerative agriculture aims to maximize yields with a priority on soil health, through reducing soil erosion and preserving biodiversity. These practices may ultimately lead to carbon drawdown, improved water retention, increased farm resilience to climate change, and strengthened health and vitality of the soil.

Though some of the regenerative agricultural practices are rooted in indigenous and longstanding farming practices, the term regenerative agriculture emerged in the 1980s (Rodale 1983). It gained attention in response to the growing concerns about the negative impacts of traditional agricultural practices, such as soil degradation, loss of biodiversity, and over-reliance on synthetic inputs. Regenerative agriculture was promoted as a farming method that restores the complex soil ecosystem and improves its ability to produce food. Regenerative agriculture aims to rebuild soil structure and thus vastly improves the ability of farmland to absorb and retain water, making crops less vulnerable to droughts and floods.

As climate change challenges farmers' productivity and food security, regenerative agriculture becomes a critical approach to study for its potential to create resilient and sustainable food systems (Lymbery 2021). A growing body of scientific research has studied the effectiveness of regenerative agriculture not only in improving soil health, but also in enhancing biodiversity and mitigating carbon emissions. This has increased interest in regenerative practices by governments, policy makers, and NGOs worldwide.

2.2 Distinctions from Climate-Smart Agriculture and Conservation Agriculture

Regenerative agriculture is a term that has often been used interchangeably with climate-smart agriculture (CSA); the latter being a concept that became popular over the last decade. Understanding the commonalities and distinctions among these closely related concepts can help clarify future research and policy design.

Climate-smart agriculture can be traced to the mid-2000s when the need for agricultural practices to both adapt to and mitigate climate change gained prominence. The concept gained formal recognition in a 2010 report by the Food and Agriculture Organization (FAO).[1] Climate-smart agriculture was defined as an approach that seeks to address three main objectives simultaneously: increasing agricultural productivity; adapting and building resilience to climate change; and reducing and/or removing greenhouse gas emissions. These three objectives are referred to as *triple wins* in practice. The concept of climate-smart agriculture has been embraced globally as a strategy to ensure food security in the face of climate change and to contribute to broader climate change mitigation efforts.

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[1] Climate-Smart Agriculture: Policies, Practices, and Financing for Food Security, Adaptation, and Mitigation, FAO, 2010.

Regenerative agriculture can be a potential approach to achieving climate-smart agriculture, but there are still distinctions. Despite the popularity of climate-smart agriculture among policy makers, there is a lack of clear definitions and core principles. Broadly speaking, any farming practice that can achieve triple wins belongs to climate-smart agriculture. The critical distinction between regenerative agriculture and climate-smart agriculture lies in the primary objectives of each approach. The main aim of regenerative agriculture is to improve the health of soil and ecosystems (Schreefel, et al. 2020). While achieving triple wins is possible in regenerative agriculture, such outcomes are not guaranteed. For climate-smart agriculture, triple wins are the main objectives.

Another closely related term often used interchangeably with regenerative agriculture is conservation agriculture. The overarching goal of conservation agriculture is to *maintain* soil from erosion and degradation, which aligns with regenerative agriculture's objectives. Although both regenerative agriculture and conservation agriculture focus on soil health, regenerative agriculture aims to *restore and build* soil quality and increase biodiversity as well as benefit ecosystems, which goes beyond conservation (Musto, Swanepoel and Strauss 2023).

Regenerative Agriculture	Climate-Smart Agriculture	Conservation Agriculture
A farming approach that focuses on restoring and improving the health of soil, biodiversity, and ecosystems	An approach that seeks to address three main objectives simultaneously: increasing agricultural productivity; adapting and building resilience to climate change; and reducing and/or removing greenhouse gas emissions	An approach to maintain soil from erosion and degradation
Minimum tillage, no-till, mulching with crop residue, crop rotation, legume-based cover crops, livestock rotations, use of compost and organic waste	Drought-resistant seeds, solar-powered pump systems	Minimum tillage, no-till, mulching with crop residue, crop rotation, legume-based cover crops

2.3 Regenerative Agriculture in Practice

Some regenerative agricultural practices are longstanding and have been used by farmers for generations. Some other practices are relatively new and require technological support and investment in machinery. This section summarizes regenerative agriculture's most common practices and the rationale behind each approach.

Reduce soil disturbance. Cultivation methods such as reduced-tillage or zero-tillage can reduce the disturbance of soil structure. This helps enhance nutrient cycling by allowing fungal hyphae to proliferate, reduce erosion, and preserve soil organic matter (Schreefel, et al. 2020). In addition, intact soil structure resulting from reduced disturbance allows for better water retention. This is particularly important in mitigating the impact of drought conditions, as the soil can hold and store more water for plant use.

Maintain vegetation cover on the soil. When the main crop is not growing, planting cover crops, such as legumes or grasses, can protect the soil from erosion and improve water retention by reducing the evaporation rate. Cover crops can also insulate and buffer soil to keep the temperature in an ideal range for microbial life (Khangura, et al. 2023).

Increase soil organic matter and microbial diversity. Encouraging biodiversity through diverse crop and livestock rotations, intercropping, and preserving natural habitats on the farm promotes ecological resilience (Khangura, et al. 2023). Alternating the types of crops grown in a particular field can disrupt pest and disease cycles, enhance nutrient cycling, and minimize the risk of soil degradation associated with monoculture. Furthermore, incorporating livestock into cropping systems can replicate natural processes and improve soil fertility. In a nutshell, plant diversity contributes to healthy soils that are less dependent on chemical inputs and have natural pest and pathogen-suppressive qualities.

Maximize nutrient and water use efficiency by plants. Reducing the use of chemical fertilizers and pesticides, instead using compost and organic waste can improve soil health and preserve water quality. Techniques such as contour plowing, and cover cropping tend to reduce water runoff and soil erosion. Also, grass cover along waterways helps prevent soil erosion by stabilizing the soil with its root system. This reduces the risk of sedimentation in water bodies, preserving water quality (Elevitch, Mazaroli and Ragone 2018).

Livestock integration and holistic management/ rotational grazing. Another popular regenerative agricultural practice is rotational grazing. This restricts animals during the grazing duration and rotates them through a series of paddocks. Overgrazing is prevented, manure is recycled, and ecosystem and carbon benefits accrue through holistic livestock management. Even though livestock farming is widely blamed for contributing to methane emissions, rotational grazing increases Soil Organic Carbon and enhances soil health (Khangura, et al. 2023).

2.4 Adoption of Regenerative Agriculture

Numerous regenerative agricultural practices, including crop rotations, cover cropping, and integrating livestock, are commonly acknowledged as 'Good Agricultural Practices' and have already been implemented in various instances (Giller, et al. 2015). Some other practices, such as zero tillage, require more advanced techniques and more costly inputs (Giller, et al. 2021); they are therefore less common. To cope with threats such as soil erosion and degradation, some initial efforts from both public and private sectors have been made to promote regenerative agriculture. Despite anecdotal evidence of benefits from various programs, more supporting evidence is needed due to the nascent nature of these studies. In addition, achieving large-scale roll-out of regenerative agriculture still faces numerous practical challenges.

In terms of efforts made by large corporations, by September 2023, 50 of 79 global food and retail giants that are worth more than a combined 3 trillion dollars have mentioned regenerative agriculture initiatives in their disclosures, although only 16% of the companies have well-defined metrics to measure progress.[2] Evidence on the effectiveness of regenerative agriculture initiatives is even more limited.

The US Inflation Reduction Act (IRA) creates incentives for promoting regenerative farming practices. The Inflation Reduction Act delivers $40 billion for advancing regenerative farming practices, such as planting cover crops, reducing tillage, pasturing livestock, and agroforestry.[3] The induced adoption of regenerative agricultural practices as a result of the IRA and their impacts are yet to be evaluated.

Argentina is one of the few countries that managed to roll out regenerative agriculture at a large scale. Under the threat of substantial soil erosion, the adoption of no-till was promoted to transform the agriculture sector. The initial trials in Argentina commenced in the early 1970s; however, it was not until the 1990s that the adoption process surged. Starting from a few hundred thousand hectares in 1990, the adoption rapidly increased to over 23 million hectares, constituting approximately 79% of the Argentinean grain-cropped area in 2011. A pivotal factor influencing the adoption process was the proactive stance of farmer associations. This enthusiasm was primarily fueled by the potential to boost productivity and profits while effectively mitigating erosion. The advancement of specialized machinery, specifically planters and drills tailored for no-till practices, and the capability of efficiently working with substantial surface organic

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[2] The Four Labours of Regenerative Agriculture, FAIRR, 2023.

[3] US's Inflation Reduction Act of 2022.

materials played a crucial role. Additionally, the evolution of modern soil and plant management strategies, supported by improved herbicides, significantly propelled the adoption process forward (Peiretti and Dumanski 2014).

In India, voluntary carbon offset markets are under consideration to incentivize smallholder Indian farmers to adopt regenerative agriculture through the monetization of carbon mitigation.[4] A novel initiative by the International Maize and Wheat Improvement Center (CIMMYT) and the Indian Council of Agricultural Research Institute (ICAR) is working on establishing carbon markets among smallholder farmers in India. The primary objective is to curb greenhouse gas (GHG) emissions and promote climate-smart farming practices by providing financial incentives. One component of the initiative incorporates regenerative interventions, including direct dry seeding of rice, minimal tillage, crop diversification, use of biofertilizers, and perennial cropping. CIMMYT's initiative encourages participants in voluntary carbon markets to enhance their financial viability through the adoption of sustainable practices and the receipt of payments from carbon markets.

China launched a national plan to phase out the use of chemical fertilizers to cope with soil degradation. The unprecedented growth in agricultural output in China often relies on the heavy use of fertilizers and pesticides, leading to soil degradation.[5] On average, around 446 kilograms of agricultural fertilizer was used per hectare in 2015, far exceeding the accepted upper limit of 225 kilograms/ha (Chen, Pu and Zhong 2022). In 2015, China formally launched a national fertilizer reduction initiative, China's Zero-Growth Action Plan, which aims to maintain the annual growth rate of chemical fertilizer and pesticide use to be less than 1% from 2015 to 2019 and achieve zero growth by 2020. More specifically, organic fertilizers from livestock manure and crop residues are promoted as replacements for chemical fertilizers and pesticides.

In Sub-Saharan Africa, various initiatives and pilots of regenerative agricultural practices have been implemented through private companies and non-profit organizations, reaching over 100,000 farmers.[6] Farmers are trained in and encouraged to field-test practices including intercropping, crop rotations, ideal plant spacing, ecological pest management, and integrating livestock. For example, in Ethiopia, demos are shown to farmers to encourage adoption. In Ghana, financial incentives, such as conditional premium payments for cocoa, are offered to farmers under the condition of sustainable land use. In Uganda, Tanzania,

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[4] Bringing voluntary carbon offset markets to smallholder Indian farmers, International Maize and Wheat Improvement Center, CIMMYT, 2022.

[5] Lessons from China's farmers in green growth transformation, FAO.

[6] Regenerative agriculture, Africa Regenerative Agriculture Study Group, 2021.

and Zambia, trials have been conducted to test how practices such as optimal plant spacing and minimal tillage affect yields and resilience of cereals (barley and sorghum) and local tubers (cassava).

These initiatives and pilots of regenerative agriculture in Sub-Saharan Africa are still at a small scale. Engaging millions of smallholder farmers in Africa and scaling up regenerative agriculture remains hard. Challenges for large-scale adoption include setting up local technical support to customize regenerative agricultural practices that incorporate farmers' demands, involving farmers to gain confidence and trust in the success of regenerative agriculture, coping with potential loss in yields during the transition to regenerative agriculture, and overcoming costs of adoption.[7]

3. Evidence of Impact on Global Agriculture

This section provides a review of scientific literature on the empirical impacts of regenerative agriculture and other related practices. We focus on impacts on three aspects — agricultural productivity, resilience to climate shocks, and carbon mitigation.[8] In summary, there is insufficient empirical, especially causal, evidence demonstrating that regenerative agriculture can simultaneously achieve productivity gains, resilience, and carbon mitigation. Additionally, the impacts of regenerative agriculture vary depending on underlying climate and economic conditions. Further research is needed to assess the cost-effectiveness of regenerative agriculture under various situations.

Practice	Productivity	Resilience	Mitigation
No-till practices through meta-analysis of 74 published studies in the U.S. and southern Canada (Ogle, et al. 2012)	Crop productivity can decrease in cooler and/or wetter climatic conditions, while increasing in some other regions, such as cotton in southeastern U.S.		The overall carbon impact depends both on soil organic carbon (SOC) stocks and carbon input.

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[7] Farmer Led Regenerative Agriculture for Africa, 2020, Institute for Global Prosperity.

[8] Only papers published in peer-reviewed journals are included in this section.

No-till practices through a new assessment model applied to the global area under cereal crops (Powlson, et al. 2014)	Abundant evidence of benefits on increasing soil quality in many, yet not all, situations	Beneficial for climate adaptation	Equivocal evidence on carbon sequestration
No-till practices from a global meta-analysis using 5,463 paired yield observations from 610 studies across 48 crops and 63 countries in Asia, Africa, North and South America, Europe, and Australia (Pittelkow, et al. 2015)	No-till reduced yield by 5.7% overall, although the impact could be positive under certain local conditions; but no-till in combination with the residue retention and crop rotation significantly increased rainfed crop productivity in dry climates by 7.3%		An increase in SOC stocks by 20% and an increase in nitrogen by 24% when regenerative practices were deployed
Legume-based cover crops, no-till, and grazing the crop field with livestock on 76 cornfields in the US (LaCanne and Lundgren 2018)	Regenerative corn fields produced 29% less corn grain but 78% higher profits than conventional operations, driven by lower fertilizer costs and higher revenue from meat production.		
Conservation tillage, cover crops, and biochar applications from a meta-analysis of 3,049 paired measurements from 417 global peer-reviewed articles			Biochar applications represented the most effective approach for increasing SOC content (39%), followed by cover crops (6%) and

published from 1990 to 2017 (Bai, et al. 2019)			conservation tillage (5%).
Crop residue utilization, crop rotation, and minimum tillage in Malawi and Zimbabwe (Makate, et al. 2019)	Increased cereal productivity by 12%-18%		
Minimum tillage, mulching with crop residue, and crop rotation in Zimbabwe for a multi-cropping system that includes maize, sorghum, millet, groundnut, and cowpea (Michler, et al. 2019)	No yield gains compared to conventional practices under normal rainfall	Effective in mitigating the negative impacts of low and high rainfall shocks; the returns turn positive after a more than one standard deviation in rainfall	
No-till management by combining a global dataset of 178 experimental sites (Ogle, Alsaker, et al. 2019)	Reduced soil erosion	Helped adapt to climate change and ensure food security	Mixed evidence on soil organic C (SOC) storage: Higher SOC stocks in the surface topsoil at depths less than 20 cm and lower SOC at depths greater than 20 cm; worked better in warmer and wetter climates than drier and cooler climates
Rainwater harvesting techniques in 180	Increased the value of agricultural production by 0.12 to 0.15 standard	An average of 0.3 hectares of previously	

villages in the Sahel (Aker and Jack 2023)	deviations compared to the control group	uncultivable land had been restored.	
No-till and winter cover crops for winter wheat, maize, and soybean, in Piacenza, Po Valley, Northern Italy (Lorenzetti and Fiorini 2024)	The gross profit margin outperformed conventional tillage by 6% to 200% over 2011 to 2020.		SOC, measured at 0–30 cm depth, increased by 2.75% annually from 2011 to 2020 and didn't vary by the type of cover crop.

3.1 On Productivity

Research has shown that certain regenerative agricultural practices or their combination can enhance crop productivity, particularly in dry climates. A global meta-analysis involving 610 studies found that employing no-till alongside residue retention and crop rotation significantly boosts rainfed crop productivity in dry climates (Pittelkow, et al. 2015). Additionally, rainwater harvesting techniques have demonstrated a notable increase in the value of agricultural production, ranging from 0.12 to 0.15 standard deviations compared to the control group in the Sahel (Aker and Jack 2023). In Malawi and Zimbabwe, the adoption of practices such as crop residue utilization, crop rotation, and minimum tillage has been associated with a substantial 12%-18% increase in cereal productivity (Makate, et al. 2019). In addition, some evidence suggests that a combination of regenerative agricultural practices can create a larger impact on productivity gains than being adopted in isolation (Tambo and Mockshell 2018).

However, most of the literature only focuses on the benefits of adopting regenerative agricultural practices, such as an increase in yield and household income, without carefully evaluating the costs and trade-offs associated with adopting each regenerative agricultural practice. For example, adopting regenerative agricultural practices may lower input costs because of a reduction in fertilizer use in some developed countries (LaCanne and Lundgren 2018), but may also increase costs of adopting machines and other equipment. Evaluating the costs and benefits associated with each practice based on local conditions is critical to determine whether certain practices should be recommended to farmers. Also, it takes time for the soil to restore its nutrients and health through regenerative agriculture and productivity may drop during the restoration process in the short term. Thus, farmers may face the trade-off between short-term productivity loss and long-term sustainable production. How farmers weigh the trade-off needs to be carefully studied to design incentives for promoting sustainable agriculture.

Lastly, the impact of regenerative agricultural practices on productivity can vary across locations, depending on local economic, climate, and soil conditions (Khonje, et al. 2018). Despite evidence of positive productivity impact, there have been instances of reduced crop yields under no-till practices in moist climates after heavy rainfalls. In addition, in situations where there is already extensive use of inputs and technology, the introduction of regenerative agricultural techniques may not result in positive productivity gains. Thus, the promotion of regenerative agriculture should be carefully customized to specific local conditions. Also, institutions that aid local scientific research are needed to unlock the full potential of regenerative agriculture effectively.

3.2 On Resilience

Climate change imposes substantial negative impact on agricultural productivity through extreme heat, drought, floods, and loss of biodiversity. Given the current crop-growing regions in the United States, the area-weighted average yields are predicted to decrease by 30%–46% before the end of the century under the slowest warming scenario (Schlenker and Roberts 2009). Thus, increasing agricultural resilience is critical to global food security.

Existing literature shows little evidence of long-run climate change adaptation in agriculture in developed countries. The productivity of corn and soy in the United States responded to extreme heat between 1980 and 2000 the same way as it did to annual shocks of extreme heat. This suggests that farmers were not able to mitigate the negative shocks from climate change in the long run (Burke and Emerick 2016).

As regenerative agricultural practices show the potential to enhance crop productivity, they can be a candidate to serve as a strategy to offset losses caused by climate shocks, thereby increasing resilience to climate change. Immediate benefits, such as improved water retention and reduced erosion, has the potential to aid in mitigating the negative impact of extreme heat and drought. Over the long term, changes in soil structure and microbial activity, while taking a few years to become prominent, may result in heightened nutrient availability and improved soil health. This, in turn, has the potential to enhance overall crop growth and productivity.

Despite these potential positive aspects in theory, there is still limited empirical evidence on how regenerative agriculture leads to short-run adaptation to climate shocks and long-term adaptation to climate change. In the short run, alternative adaptation strategies, such as increasing the use of irrigation under drought conditions or increasing the use of chemical fertilizers can boost productivity, probably to a larger extent compared to regenerative agriculture. However, these strategies may not be sustainable in the long run when groundwater depletion and soil degradation become an issue. As a result, farmers may face a trade-off between more effective short-run adaptation to climate shocks and more sustainable long-run adaptation to climate change. What adaptation strategies are more optimal in the short-run versus in the long-run and how to weigh these trade-offs remains an open question.

3.3 On Mitigation

The global soils contain a significant reservoir of organic carbon, storing approximately 1,500 gigatons of carbon (equivalent to 5,500 gigatons of CO_2) within the first meter of depth. There is an additional 900 gigatons of carbon stored in the subsequent meter. The organic carbon present in the top meter alone is three times greater than the amount of carbon found in atmospheric CO_2 (Powlson, et al. 2014). Consequently, the focus on carbon sequestration in soil has attracted much attention as a possible solution to address and mitigate global carbon emissions.

A meta-analysis of 417 peer-reviewed articles has shown some positive evidence on soil organic carbon (SOC) sequestration using regenerative agricultural practices (Bai, et al. 2019). Their findings indicate that, on average, the most effective method for increasing SOC content was the application of biochar, showing a 39% increase. This was followed using cover crops (6%) and conservation tillage (5%). Additional analysis suggests that these practices were more prominent in regions with warmer climates or lower nitrogen fertilizer inputs.

Nonetheless, it is still premature to claim that regenerative agriculture can increase carbon sequestration and mitigate carbon emissions in global agriculture. The impact of regenerative agriculture on SOC sequestration is highly context-specific and encounters numerous challenges and trade-offs.

First, regenerative agricultural practices may decrease, rather than increase SOC stocks under certain climate conditions. For instance, the adoption of no-till on existing cropland can increase the SOC stocks in the surface topsoil at depths less than 20 centimeters while decreasing SOC at depths exceeding 20 centimeters. The reduced levels of SOC in deeper soil layers may offset the increased SOC near the soil surface under no-till management, which leads to an overall reduction in SOC stocks. The SOC stocks in the topsoil should be sufficiently high to generate a net increase in SOC stocks. Certain soil conditions, such as sandy soils of tropical moist climates, are more likely to generate a net increase in SOC stocks (Ogle, et al. 2019). As a result, identifying the right practices at the local level is necessary to evaluate the carbon mitigation benefits of regenerative agriculture.

In addition, carbon sequestration in agricultural soil is not necessarily permanent and can be reversible. The additional carbon accumulated under no-till is primarily in labile form,[9] susceptible to decomposition if no-till practices are discontinued, and a return to conventional tillage occurs (Powlson, et al. 2014). Thus, monitoring and evaluation systems should be established to accurately count the amount of carbon sequestration to prevent an overestimation and rollback.

Also, the capacity of soil to sequester carbon is finite with a decreasing rate of accumulation over time. It can take 25 to more than 100 years, depending on climate and soil conditions, for soils to reach their carbon sequestering capacity (Powlson, et al. 2014). Some short-term studies that measure SOC stocks from regenerative agricultural practices may overestimate the long-term impact on carbon emissions.

Furthermore, more research is required to quantify the causal effect and understand the general equilibrium effect of regenerative agriculture on mitigating carbon emissions. Most existing literature estimates the carbon mitigation impact purely from a soil perspective. However, regenerative agricultural practices can alter the usage of equipment and energy, which results in changes in carbon emissions as well (Gao, et al. 2018). Thus, the impact of regenerative agriculture on carbon emissions should take into consideration all margins that can alter carbon emissions.

Lastly, despite abundant anecdotal evidence, there is very limited causal evidence on how regenerative agricultural practices impact productivity and carbon mitigation simultaneously. Theoretically, the optimal practices for carbon mitigation may not be aligned with the optimal ones for boosting productivity under various local climatic conditions. There can be a trade-off between productivity and carbon mitigation when choosing which regenerative agricultural practice(s) to adopt. As a result, further evidence is needed to investigate when there is a trade-off and measure the extent of the trade-off. These studies will provide the empirical foundation on whether to include carbon mitigation as one of the objectives and how to design mechanisms to promote practices for carbon mitigation if desired.

4. Barriers to Large-Scale Adoption

4.1 Trade-Offs

The adoption or promotion of regenerative agriculture on a large scale faces many trade-offs and depends on the objectives of farmers and governments. Understanding the extent of these trade-offs is important to

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[9] Soil organic matter comprises various forms characterized by differing turnover times or rates of decomposition. The labile form, which undergoes relatively rapid turnover (less than 5 years), primarily consists of freshly added residues like plant roots and living organisms. In contrast, resistant residues, shielded either physically or chemically, exhibit slower turnover rates (20-40 years).

form policy recommendations and design necessary incentive schemes to assist the adoption when large-scale adoption is desired. Future rigorous empirical studies are needed to carefully gauge the extent of these trade-offs in practice for regenerative agriculture to be recommended as a solution to challenges under climate change.

Short-term productivity loss and long-term productivity gain. Regenerative agricultural practices aim to enhance soil health by preserving soil organic matter and allowing fungal hyphae to proliferate. It takes time for the soil to replenish and some practices such as no-tilling require costly machines and equipment. As a result, farmers may experience a short-term loss in productivity and profits when transitioning to regenerative agriculture. For farmers who are credit-constrained and highly value short-term gains, regenerative agriculture may not be attractive despite the potential long-run gain in productivity. Complementary policies that can ease credit constraints or short-term incentives that compensate for the temporary loss from regenerative agriculture can facilitate the adoption.

Short-term adaptation to climate shocks and sustainable adaptation to climate change. When focusing on short-term adaptation to climate shocks, such as drought and extreme heat, farmers may prefer more effective yet unsustainable alternative adaptation strategies. For example, increasing the use of groundwater irrigation and the use of chemical fertilizers during climate shocks can boost productivity effectively in the short run, probably to a larger extent compared to regenerative agriculture. However, these strategies may not be sustainable in the long run when groundwater depletion, soil degradation, and pollution become an issue. As a result, farmers may face the trade-off between more effective short-run adaptation to climate shocks and more sustainable long-run adaptation to climate change. For countries with rich unexploited groundwater resources and low use of fertilizers, this trade-off may be trivial. Thus, alternative adaptation strategies that can boost productivity more effectively may be more cost-effective than regenerative agriculture.

Productivity and carbon mitigation. Adopting practices that can enhance crop productivity can also serve as a strategy to offset losses caused by climate shocks, thereby increasing resilience to climate change. Thus, increasing productivity and resilience to climate change are often achieved simultaneously. However, the set of optimal practices to achieve the most gain in productivity can be different from the ones to achieve the highest carbon mitigation. When deciding which practices are optimal to adopt, there can be a trade-off between enhancing productivity and carbon mitigation. Consequently, it is important to understand when this trade-off is more salient and what incentive schemes need to be designed if carbon mitigation is one of the objectives.

4.2 Costs and Benefits

Certain regenerative agricultural practices involve investments in equipment and labor, which can be costly for farmers. For instance, no-till planters and seed drills are needed to plant seeds without disturbing the soil. The costs of obtaining necessary equipment vary by location and size of the farms. In particular, the prevalence of small-scale agriculture, coupled with policies that discourage farm consolidation, can reduce the cost-effectiveness of investing in equipment. Moreover, low farm gate prices and limited market access can make the adoption of regenerative agriculture less appealing due to associated costs. Thus, despite the potential positive impact of regenerative agriculture on productivity and resilience, these practices may not necessarily be profitable for farmers to adopt.

Moreover, accessibility is another key factor influencing adoption. For instance, in Malawi and Zimbabwe, the adoption of regenerative agricultural practices is negatively associated with access to fertilizers (Makate, et al. 2019). Applying fertilizers is more profitable when they are accessible in this context.

The potential for carbon mitigation through regenerative agriculture, though supported by mixed evidence, presents a promising avenue to increase the benefits through soil carbon credits. Farmers engaged in carbon markets can receive financial incentives or credits for adopting and maintaining these sustainable practices. This introduces an additional source of income for farmers, which can make regenerative agriculture more attractive.

4.3 Lack of Local Knowledge Support and Information

The effectiveness of regenerative agriculture is intricately tied to specific local climate and soil conditions, which are subject to change over time. Hence, there is a crucial need for local knowledge support to assist farmers in adopting the most suitable practices based on their evolving conditions.

With the help of the growing accessibility of satellite data and advancements in machine learning techniques, the costs associated with local knowledge support can significantly diminish, enabling widespread availability. For instance, e-extension services can utilize predictive machine learning technology to offer insights based on highly detailed soil nutrient status.[10] Even when regenerative agriculture is suitable and profitable based on the local climate and soil conditions, it can still take time to raise awareness among farmers and train farmers to learn how to utilize the technologies. Demo plots may

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[10] For example, iSDAsoil provides soil and agronomy maps with a 30-meter resolution covering the entire African continent. In addition, Global Agro-Ecological Zones (GAEZ), supported by the Food and Agriculture Organization of the United Nations (FAO) and the International Institute for Applied Systems Analysis (IIASA), can identify suitable agricultural land utilization options at a 9 x 9 km grid cell level for the entire globe.

be needed to demonstrate the performance of these practices to farmers. Also, training programs can help farmers learn more about different regenerative practices and facilitate their adoption. For example, Otara, et al. (2023) reveal that 80.3% of the respondents would need to be trained on how to undertake regenerative agriculture in the drylands of Embu County in Kenya. However, empirical evidence is very limited on how training or other information provision programs help promote regenerative agriculture.

4.4 Lack of Insurance and Income-Smoothing Mechanisms

The lack of insurance or other income-smoothing mechanisms can deter farmers from taking any uncertain investments even when the investments are beneficial for them in the long run. In Ghana, experimental evidence has shown that rainfall index insurance can result in a significant increase among maize farmers in agricultural investment and the adoption of riskier production choices in agriculture (Karlan, et al. 2014).

However, the insurance products that aim to smooth farmers' income and consumption need to be carefully designed to avoid moral hazard. Policies such as minimum support prices and crop insurance may disincentivize farmers to engage in adaptation behavior to climate shocks, which can lead to less adoption of regenerative agriculture. For example, the United States government provides substantial subsidies for crop insurance programs, which enables farmers to be more sensitive to extreme heat. This limits farmers' adoption as they may prefer subsidized yield guarantees over more costly adaptation technologies (Annan and Schlenker 2015). Further research can investigate how to design insurance or other income-smoothing products to incentivize farmers to adopt unfamiliar practices and engage in climate change adaptation in the context of developing countries.

4.5 Factor Market Failures and Distortions

Factor market failures and preexisting distortions can create barriers to adopting regenerative agriculture at a large scale. Ambiguous property rights and high transaction costs to acquire land can prevent productive farmers from benefiting from economies of scale due to mechanization (Foster and Rosenzweig 2022). Limited access to credits can discourage farmers from investing in necessary equipment for regenerative agriculture (Suri and Udry 2022). Low farm gate prices as a result of market power of intermediates and lack of market access can make regenerative agriculture less cost-effective for smallholder farmers (Chatterjee 2023). Further research can unpack which factors in what locations matter more for the adoption of regenerative agriculture.

5. Challenges and Opportunities for Africa’s Agriculture

5.1 Low Yields and Technology Adoption for Smallholder Farmers

Agricultural yields in Africa exhibit both lower levels and slower growth rates compared to global averages, despite heterogeneity across regions (Lowder, Skoet and Raney 2016). The adoption of widely used agricultural technologies, such as irrigation, mechanization, and high-yielding variety seeds, remains substantially low. Thus, many options are still available to further boost crop productivity in Africa that can be more suitable and cost-effective than regenerative agriculture. Also, approximately 80% of farmers in Africa operate on less than two hectares of land. Various existing frictions, including limited access to credit and insecure property rights, discourage land consolidation and contribute to the persistence of small-scale agriculture. Consequently, the cost-effectiveness of regenerative agriculture as the optimal technology for enhancing productivity in Africa at the current stage remains unclear.

5.2 Lack of Institutional Support

The effectiveness of regenerative agriculture relies on local support. Local knowledge and technical support are required to pin down optimal regenerative agricultural practices suitable to local climate and soil conditions. Also, training programs can be necessary for farmers to trust and learn how to practice regenerative agriculture. Weak local institutional support in guiding scientific farming in Africa poses a significant challenge to the widespread adoption of regenerative agriculture (Rocklifee et al, 2020).

5.3 The Potential of Climate Finance

Given the potential of carbon sequestration by adopting regenerative agriculture, financial incentives from payments for ecosystem services (PES) can promote regenerative agriculture and offer an additional source of income, transferred from countries seeking to offset carbon. This additional income may overcome some preexisting constraints, such as limited access to credit, enabling farmers to invest in technologies that boost crop productivity and adaptation to climate shocks. PES has shown some promising evidence of incentivizing farmers to adopt environmentally sustainable practices. For instance, experimental evidence shows that PES has curbed crop residue burning in India significantly (Jack, et al. 2022) and has reduced deforestation in Uganda (Jayachandran, et al. 2017) and Latin America (Grima, et al. 2016).

Over the last decade, PES schemes have been widely discussed and introduced in Africa as an implementation mechanism for dealing with increasing deforestation and land degradation.[11] Some regenerative agricultural practices are aligned with PES objectives and thus are included in the PES programs. For example, coffee and cocoa farmers can be subsidized to plant shade trees on their agricultural lands to mitigate the risk of lower production under water scarcity and extreme heat. Verified carbon sequestration from these planted trees can provide additional income from carbon credits offered by programs such as Reducing Emissions from Deforestation and Forest Degradation (REDD+). In addition, PES can fund investments in climate-smart agriculture aimed at supporting the resilience of local productive systems. However, PES needs to be carefully designed based on the context factors to be effective (Wunder, et al. 2020). Further empirical research can shed light on how regenerative agriculture can be combined with PES schemes to unlock the benefits of regenerative agriculture for farmers.

6. Open Questions and Future Research

First, despite the evidence on the positive impact of regenerative agriculture on crop productivity and resilience, there is scant evidence documenting the potential trade-offs between productivity gain versus carbon mitigation. These trade-offs include short-term productivity loss versus long-term productivity gain during the transition to regenerative agriculture, the availability of more cost-effective alternative practices for short-term adaptation to climate shocks versus sustainable adaptation to climate change. Further research is needed to understand under which conditions these trade-offs are present and salient and when it is cost-effective to adopt regenerative agriculture given these trade-offs.

Furthermore, existing literature focuses on evaluating the impact of a particular practice or a certain combination of practices of regenerative agriculture. However, comparing the cost-effectiveness of regenerative agriculture to other common practices, such as the use of drought-resistant seeds and fertilizers, is necessary to decide which practice is more beneficial to adopt in each context. This is because, especially in Africa, there are still low-hanging fruits to increase productivity using other more conventional farming practices.

Third, it is important to understand how to incentivize the establishment of local scientific and institutional support for agricultural practices. Regenerative agriculture, especially, requires local knowledge for it to be effective. With the help of increasingly available satellite data and machine learning techniques, research can explore whether generating local knowledge can promote local institutional support.

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[11] Payment For Environmental Services: A Promising Tool For Natural Resources Management In Africa, 2015, African Development Bank Group.

In addition, engaging farmers in sustainable farming without loss of income is necessary for the persistent adoption of regenerative agriculture. Climate finance through carbon credits that offer a potential income source for farmers can be a possible pathway. Lastly, it is an open question to test whether climate finance can be designed to mitigate some of the constraints that hinder economic development in Africa. For example, with additional income from climate finance, farmers may be more willing to invest in the adoption of productivity and resilience-enhancing technologies. Also, the payment system set up by a carbon credit market may be an opportunity to increase digital financial inclusion of farmers in the future.

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