# Aligning regenerative agricultural practices with outcomes to deliver for people, nature and climate

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The Food and Land Use Coalition

Food, Agriculture, Biodiversity, Land-Use, and Energy Consortium

Alliance Bioversity & CIAT

# Contents

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**The Food and Land Use Coalition (FOLU) is a global community of country platforms, partner organizations and Ambassadors working to advance sustainability, equity and resilience in food and land use systems. Created in 2017, FOLU supports diversity, embraces disruptive thinking and forges consensus through an evidence-based approach. The coalition empowers farmers, policymakers, businesses, investors and civil society to unlock collective action at scale.**

**Disclaimer:** The individuals and institutions acknowledged as reviewers have provided input and feedback into previous drafts, however they have not formally endorsed the final report.

Although the paper focuses on the evidence and outcomes of regenerative agricultural practices, the Food and Land Use Coalition strongly advocates for no land conversion or deforestation as part of any transition. The paper seeks to explore how implementing a specific set of regenerative agricultural practices has the potential to fit within a comprehensive reform agenda that was set out in FOLU's Growing Better report in the form of 10 Critical Transitions. The paper is based on the assumption that half of all ecosystem areas should remain intact and ensure that all agricultural lands have functional integrity (capacity to regenerate).

# Executive summary

**A growing body of evidence shows that large changes to food production and consumption are needed to feed 10 billion people by 2050 while halting and reversing ecosystem and biodiversity loss, safeguarding freshwater and soils, and keeping global warming below 1.5°C.**[1,2,3] The Food and Land Use Coalition (FOLU) published its flagship report *Growing Better* in 2019 which demonstrated how this better future is possible.[4] Consumption shifts, like reducing food loss and waste and shifting to healthy and sustainable diets, can reduce agriculture's resource demands and environmental impacts. But significant changes to food production are also needed, including halting deforestation, scaling up current best practices, improving soil and water management, and developing and deploying new technologies to enhance food and nutrition security, economic development, and environmental goals without exceeding the Earth's planetary boundaries.[5]

**"Regenerative agriculture" is gaining increasing interest amongst agri-food industry leaders, civil society organizations and farming communities.** But despite its increasing popularity, there is no universally accepted definition of the term, including the practices it entails, the outcomes it can achieve, and how it fits into the agri-food system transformation agenda. There is a lack of evidence (especially from low- and middle-income countries) to assess what regenerative practices can achieve across farm, landscape and global levels. Farmer experiences are often missing from the discussion and the development of metrics for reporting. Without building on practitioner experiences and needs, contextually relevant solutions may be missed – resulting in unintended consequences. Furthermore, the lack of definition and misalignment around practices and what constitutes as "regenerative" can create a risk of greenwashing.

**Moving towards an outcome-based framework of measuring and assessing regenerative agricultural practices is needed to support global alignment while also guiding practitioners to identify and innovate around site-specific interventions.** There is currently no universally accepted framework and set of metrics to set, track and measure the outcomes from regenerative agricultural practices. Such metrics are needed at different scales, from farm level up to the global level, in order to assess what agricultural practices are most effective in different contexts and to enable evidence to support moving from farm-level outcomes to global impact.

**This report reviews the evidence linking a dozen specific farm-level regenerative agricultural practices to three farm-level outcomes: biodiversity, climate change mitigation and yield.** These are all critical components of a future outcome-based framework, but they are not the only important outcomes. Other key environmental, social and economic outcomes that should be included in the development of such a framework include water, pollution, health (soil, animal, human), livelihoods, fairness (e.g. gender equity, youth inclusion), employment opportunities, profitability, and nutrition.

Evidence shows that crop diversification (through agroforestry, intercropping, crop rotations, or cover crops), embedding natural infrastructures, and low or no tillage practices have a positive effect on biodiversity. Cultivar mixtures, reducing chemical inputs, integrating crops and livestock, and holistically managed livestock systems, have no apparent effect on biodiversity outcomes. For climate change mitigation, agroforestry, intercropping, crop rotations, reducing chemical inputs, and holistically managed grazing, all have a positive effect on soil organic carbon or carbon sequestration rates. Cultivar mixtures and no or low till systems have no apparent effect on carbon storage or sequestration. However, when assessing overall greenhouse gas (GHG) emissions, results were negative (in cover crop systems) or indifferent. For yield, crop diversification (through agroforestry, intercropping, crop rotations, cover crops or cultivar mixtures) and inoculation have a positive effect on crop yield. In contrast, organic agriculture reduces crop yields. Embedding natural infrastructures and low or no tillage, reducing chemical inputs, integrated crop-livestock systems have a variable or no apparent effect on agricultural productivity.

All the evidence points to contextual factors such as climate, topography, soil type, field size and crop, livestock and land management (e.g. crop arrangements, tillage, agrochemicals) as influential in determining the direction and magnitude of change across the outcomes. This emphasizes the need for practices to be targeted to their context in order to maximize positive outcomes. As such, an outcome-based framework for assessing regenerative agricultural practices is key to set clear ambitions while allowing for context specific practices and innovation.

**An outcome-based framework and more robust data collection can help to tackle some of the limitations identified in the review.** Studies tend to focus on certain geographies (North America and Europe) and on certain farming systems (cereals) which makes it difficult to generalize results for farmers operating in different locations and systems, especially the majority of small farms in developing countries. Future studies should focus on collecting more robust data from the Global South and across diverse systems, especially those that can contribute to nutrition outcomes and climate resilience. The studies in the literature review largely focused on on-farm outcomes, but mostly neglected landscape- and global-level outcomes. Assessing outcomes across multiple scales is crucial to better understand potential trade-offs and avoid any leakage issues when scaling regenerative agricultural practices. A lack of standardized methodology for data collection and reporting limits the capacity for farmers to report on outcomes. An aligned outcome-based framework can help facilitate the reporting and better understand how practices can achieve positive outcomes on multiple scales.

**This paper calls for a coalition of actors to develop an outcome-based framework for assessing regenerative agricultural practices that can be used universally.** All stakeholders will have a role to play, including farmers, policy makers, businesses, civil society, academia and donor organizations. Civil society can play an important role in bringing together these stakeholders to assess, develop and implement an outcome-based framework for assessing agricultural practices.

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# Introduction

**The world's food and land use systems face several large and interconnected challenges of feeding 10 billion people by 2050, ensuring food and nutrition security for all and keeping humanity within the planetary boundaries.** Increasing production of healthy and nutritious food plays a central role in achieving food and nutrition security. Studies estimate there will be an increase between 35-56% in global demand for food by 2050.[6,7] At the same time, agriculture and food systems are important engines of economic development, and will need to contribute to global goals to end poverty and reduce inequality.[8] However, an estimated 828 million people in the world face hunger, even as obesity rates also continue to rise.[9] The recent economic and political challenges as a result of COVID-19 and Russia's invasion of Ukraine have led to rises in the cost of basic items such as food and fuel. As of June 2022, the number of acute food-insecure people has almost tripled in two years.[10] Climate-related disruptions are also bound to intensify as extreme weather events threaten food production and global supply chains.[11] Such devastating impacts are increasingly visible, e.g. Pakistan facing a national food security crisis in 2022 as flooding from abnormally intense monsoons washed away crops and livestock.[12]

**The growing global demand for food has been a leading factor in the world's crossing of six of the nine planetary boundaries: climate change, land use system change, biosphere integrity, biogeochemical flows, freshwater change and novel entities** (Figure 1).[13,14] Crossing the planetary boundaries poses a substantial threat to the Earth systems, undermining efforts to reduce poverty and leading to a deterioration of human wellbeing in many parts of the world.[15] Food production has been essential in providing more affordable, safe and plentiful food to the world, yet it requires significant resources. Agriculture is thus the largest global source of ecosystem degradation and biodiversity loss, the largest water user and a key driver of climate change.[16,17,18] It is increasingly clear that food systems themselves are greatly threatened by the environmental impacts associated with crossing the planetary boundaries, notably climate change, which is predicted to reduce major crop yields by 3–7% for every 1°C degree increase in temperature.[19] Actors across the entire value chain have a responsibility to help ensure that agricultural systems provide affordable and healthy food at the same time as protecting the planet.

**Agricultural expansion and unsustainable agricultural practices combined with the environmental impacts of crossing the planetary boundaries are resulting in widespread soil degradation and threatening food security.** The FAO estimates that at least one-third of agricultural soils are degraded,[20] and the soil organic matter content of many agricultural soils is very low. Half of the planet's topsoil has been lost in the last 150 years, and ploughed lands are losing over a millimetre of soil a year – about a hundred times faster than the rate of soil formation.[21] An additional 27 Gigaton (Gt) of soil organic carbon is expected to be lost to land conversion and land management by 2050,[22] resulting in reduced infiltration and water-holding capacity, as well as loss of nutrients and negatively affecting agricultural yields. This will not only threaten future global food security and the livelihoods of farmers and their communities, but also make it more difficult to produce more food to meet future human demand without clearing more natural ecosystems (see Box 1).

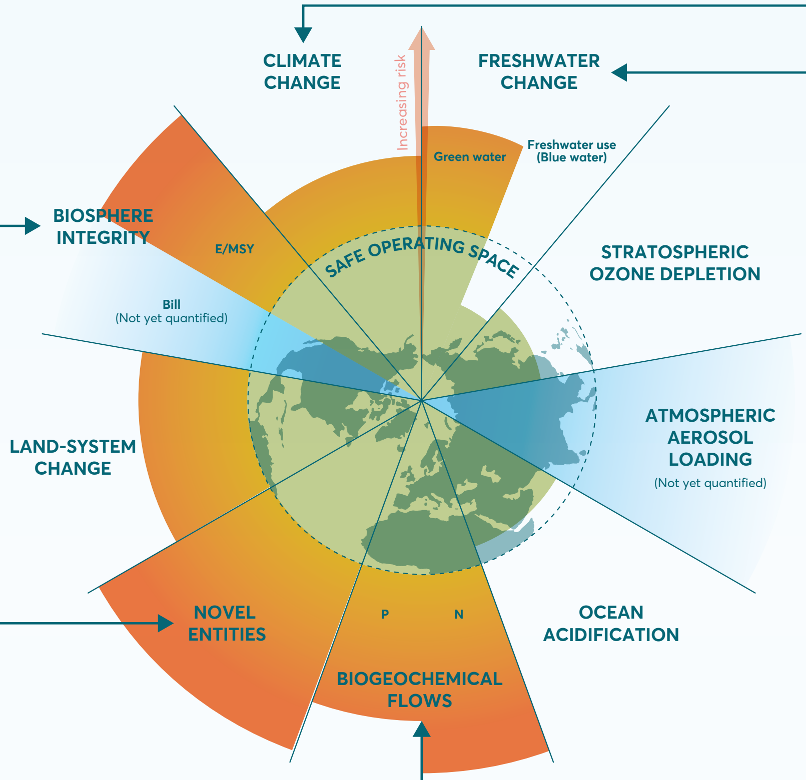
**A growing body of evidence shows that significant changes to food production and consumption could help feed 10 billion people by 2050 while halting and reversing ecosystem and biodiversity loss, safeguarding freshwater and soils, and keeping global warming below 1.5°C.**The Food and Land Use Coalition (FOLU) published its flagship report *Growing Better* in 2019 which demonstrated how this better future is possible. The Food, Agriculture, Biodiversity, Land-Use and Energy (FABLE) Consortium, a bottom-up modelling network at the science-policy interface has mapped out ambitious but realistic national pathways for achieving these multiple global objectives in tandem,[23] showing which policy actions are most important for driving positive change.[24] These and many other publications and research organizations, such as the World Resources Report, EAT Lancet Commission, and Chatham House, consistently show that consumption shifts, especially towards healthy and sustainable diets and reducing food loss and waste, are critical for meeting human nutritional needs in the future, while reducing agriculture's resource demands and environmental impacts.

Significant changes to food production are also needed, including sustainably intensifying production, replacing synthetic with natural pest controls, improving soil and water management, and developing and deploying new technologies to, for example, increase labour efficiency, connect producers and consumers, and facilitate peer-to-peer service exchange.[25] The 2021 UN Food Systems Summit highlighted that tomorrow's food and land use systems must be multi-objective with measurable impacts on not only food security, but also nutritional security, health security, environmental security, climate security, and livelihood security.[26]

## FIGURE 1: HOW THE FOOD SYSTEM IS RELATED TO THE PLANETARY BOUNDARIES

### Stockholm Resilience Centre

Below boundary (safe) | In zone of uncertainty (increasing risk) | Beyond zone of uncertainty (high risk)




**Novel entities used in agriculture have a destructive but still unquantified environmental effect**

- **Novel entities** such as **synthetic fertilisers, plastics,** and **chemical pesticides** cause **irreversible effects** on living organisms and the physical environment
- **Many examples** of additives and synergic effects of compounds (e.g. decreased bird population, losing fertility amongst animals, etc.)
- At present, **unable to quantify a pollution boundary** as science difficult to understand

**Agriculture is primary cause of land use change globally**

- **50%** of the world's habitable **land is used for agriculture**, of which 77% for livestock
- 90% of **tropical deforestation** is linked to **agricultural expansion**
- **Deforestation** causes $CO_2$ emissions and the degradation of carbon sinks, **accelerating climate change**
- **1/3 of the Earth's soils are acutely degraded** from intensive farming
- The **CBD** calls for **halting the conversion and restoring 20% of ecosystems and wilderness areas** which relies on **halting the expansion of agriculture**

**Biodiversity loss & lack of genetic diversity - driven largely by agriculture - risks undermining future food production**

- **62%** of IUCN globally **threatened species** are adversely affected by agriculture - primarily due to **land use change** and use of **chemical pesticides**
- Globally, **35%** of our **crops rely on pollinators**, yet over **40%** of all insects are declining, and a third are endangered
- **20%** of agricultural lands have **insufficient ecological integrity** to provide ecosystem services in support to food production
- **90% of crop varieties** and **50% of domestic animal breeds** have been lost - reduces agricultural resilience
- Freshwater withdrawals mean major rivers have **insufficient environmental flows to maintain aquatic biodiversity**, threatening ecosystem integrity and **undermining blue food production**

**Chemical agri fertilizers are the main cause of crossing nitrogen and phosphate boundaries by 200-250%**

- Global **nitrogen boundary crossed** by **250%**, **phosphate** by **200%**
- **20% of N and P fertilizer lost** through **runoff**, leading to overflow in land/ocean/waters and eutrophication
- Nearly **600 deltas and coastal areas** globally suffer from **season anoxia** driven by N and P contamination, approximately **80%** of which originates from food production
- ~80% of large marine eco-system subject to **eutrophication**, leading to **algal blooms** and deoxygenised **dead zones**
- **Fertilisers** are the main cause of $N_2O$ emissions; **300x more potent** than $CO_2$ and remains active for 100+ years in the atmosphere. Emission have increased **30% in past 30 yrs**

**The agri sector is also highly linked to social and health issues, largely driven by wider food system inequalities**

- **500+ million** farmers & fishers live **in poverty**
- **800 million** people are **hungry** every day, while **2 bn** people are **overweight** or obese
- **Lack of dietary diversity** is a primary cause of **diet-related disease**

**Agriculture is the primary global consumer of freshwater**

- **70%** of the world's **freshwater is withdrawn for agriculture**
- Planetary boundary hasn't been crossed, but the problem is a regional one: **90%** of available freshwater is used for agriculture in **low-income countries**; **40%** in **high income countries** (DE & NL less than 1%)

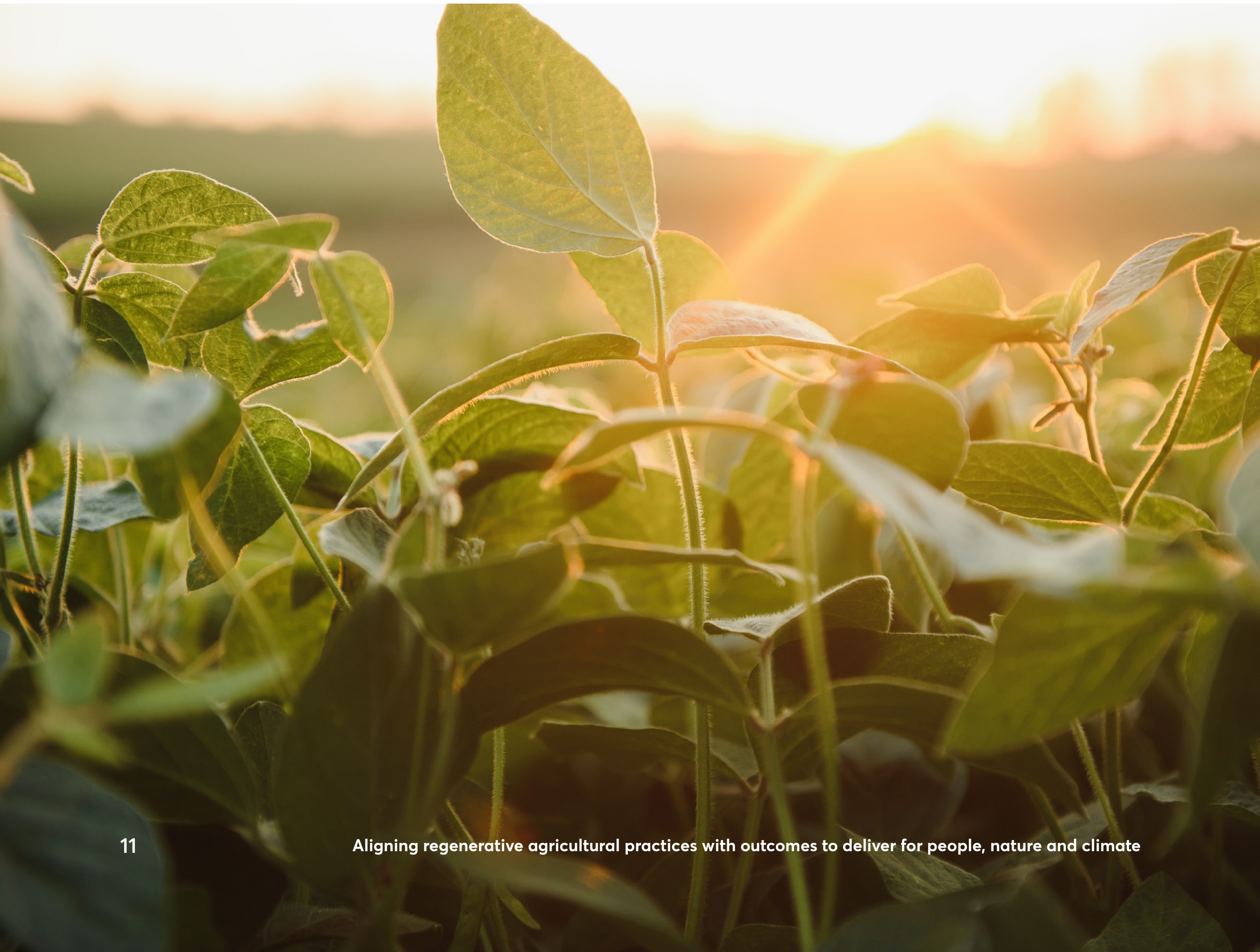
**Current agri practices contribute to 1/2 of annual GHGs which is accelerating climate change and in turn will reduce crop yields**

- **Crop and livestock production on farms, land use change, deforestation** and **food loss and waste** all contribute to emissions
- **Methane, $N_2O$** and **$CO_2$** emissions accumulate in atmosphere and create **a heat-reflective layer**
- Climate change is expected **to decrease crop yield e.g. maize** yields in **EU** by **22%**; **wheat** yields in **Southern EU by 49%**
- Keeping to **1.5C pathway** requires **halting land use change and restoring hundreds of millions of hectares** of ecosystems by **2050**

Sources in Appendix 2.

**Against this backdrop, there is increasing use of the term "regenerative agriculture" to describe the needed changes in the food and land use system transformation agenda.** FOLU identified "Scaling Productive and Regenerative Agriculture" as one of the 10 critical transitions needed.[27] Regenerative agriculture is gaining currency amongst agri-food industry leaders, civil society organizations and farming communities. Advocates for regenerative agriculture put forward the hypotheses that it can reduce the negative environmental impacts of agriculture, or even have a net positive effect.[28] Sometimes the term "regenerative agriculture" is associated with the carbon farming movement, where increasing carbon capture sits as one of its objectives. This movement asserts that changes in farm management practices on working lands can sequester substantial amounts of carbon and thereby fight climate change, and the goal is to find ways to pay farmers to implement these practices through public funds or private sources via supply chains or carbon markets.

But what exactly is "regenerative agriculture"? Can it credibly be defined as net positive? And how does it fit in to the agenda of transformative changes that are needed in the food and land use system to achieve our global goals and keep us within planetary boundaries? This paper explores these questions by providing **a review of 24 meta-analyses and systematic reviews to see how specific regenerative agricultural practices link to three farm-level outcomes (biodiversity, climate change mitigation and yield) and beyond (e.g. landscape- and global-level outcomes)**. This review thereby seeks to establish a shared understanding of the effects of these specific practices for stakeholders across the food and land use system and identify where additional research is needed. The authors conclude with recommendations for the development of an outcome-based framework to inform the evaluation, improvement and scale-up of the most effective regenerative agricultural practices.



## BOX 1: SOIL DEGRADATION – A GLOBAL PROBLEM

**Definition:** Soil degradation is a persistent and pervasive problem affecting agricultural lands across the planet. Soil degradation can be defined as "a change in the soil health status resulting in a diminished capacity of the ecosystem to provide goods and services for its beneficiaries".[29] There are many types of soil degradation – physical, chemical and biological – including soil erosion, depletion of organic matter, loss of soil biodiversity, nutrient depletion, contamination, compaction, salinization, alkalinization, and waterlogging. Soil degradation typically is a gradual process with cumulative effects and has been variously associated with the decline of many earlier civilizations.[i,30]

**Challenge:** The FAO estimates that human-induced soil degradation affects approximately one-third of all agricultural lands today.[31] This potentially has far-reaching implications for food security as 95% of human food is produced on soils.[32] Soil degradation also has wider implications for the landscape and the economy,[33,34,35] with some arguing for its inclusion within the planetary boundaries framework.[36] Yet despite its prevalence and decades of soil degradation research, the magnitude of the problem remains poorly quantified given measurement challenges across time and space, as well as variable data collection in different localities.[37]

Soil degradation on agricultural land is mainly the result of prevailing agricultural practices and associated environmental implications. These practices and implications are inherently context specific – often with gradients of imbalances (e.g. too little to too much nutrient application) and interactions. For instance, soil tillage can degrade soil structure, disrupt fungal networks and leave the soil exposed to the erosive effects of wind and water.[38,39] Use of heavy farm machinery can lead to soil compaction.[36] Monocultures can lead to imbalances and deplete the soil of certain nutrients, alter microbial communities as well as increase the risk of pest and disease outbreaks.[42,43,44] Excessive applications of chemical fertilizers can lead to soil acidification,[45] altering of microbial communities,[46] nutrient leaching, run-off and emissions. Pesticides can have negative impacts on soil biota.[47] Farming steep slopes and leaving the soil bare can exacerbate soil erosion.

Soil degradation undermines the productivity of agricultural lands. This agricultural productivity loss is pervasive – yet can still be difficult to observe given its cumulative nature, weather oscillations and potentially being masked by increased input use. For instance, the loss of soil organic matter can gradually undermine soil fertility, structure and productivity.[48,49] Further soil degradation potentially undermines global food productivity, potentially increasing food prices and/or increasing land expansion to meet food demand. Climate change is set to exacerbate agricultural stresses and undermine its productivity, including weather shocks and potentially increasing land degradation.[50]

**Solution:** Making agricultural practices more sustainable and climate smart thereby is key to halt soil degradation, restore soil health and help farmers better manage climate change. Healthy soils potentially allow more water to infiltrate and to retain more moisture, enabling it to absorb extreme rainfall as well as support crops during droughts more effectively.[51] More productive and regenerative agricultural practices thus potentially play a critical role in curbing soil degradation and maintaining and restoring soil health – albeit much depends upon the specific context. For instance, adoption of no till or minimum tillage – especially when combined with cover crops and diverse crop rotations – can significantly decrease erosion and improve soil health,[52,53,54] although implications for carbon sequestration remain more disputed.[55] Diverse crop rotations and cover crops can contribute to greater microbial richness and diversity.[56,57] Intercropping can increase nitrogen availability in the soil and decrease nitrogen leaching.[58] Mulching often reduces soil erosion, while potentially decreasing evaporation, increasing soil moisture retention, regulating temperature and over time improving nutrient availability.[59]

i See Montgomery (2008) for a thorough discussion of historical cases as well as the threat this issue poses to our present civilization. For instance, soil degradation has been associated with the decline and fall of the Sumerian civilization in ancient Mesopotamia and soil salinization from irrigated agriculture. The introduction of the plow and the spread of farming to hilly terrain led to widespread erosion in ancient Greece, a problem that was discussed by Greek philosophers like Plato and Aristotle. Agricultural practices in the ancient Mayan civilization accelerated soil erosion, and eventually reached a point where its agriculture could no longer sustain its population. The lesson is clear: civilizations that destroy their soil can't last.

# 2

# Towards an outcome-based framework for assessing regenerative agricultural practices

**Despite its increasing popularity, there is no universally accepted definition of "regenerative agriculture".[ii] The lack of alignment leads to confusion among stakeholders about what regenerative agriculture can achieve.** This also limits the ability to test and measure what effects implementation has at global and local scales. Understanding regenerative agriculture as a specific set of practices without carefully examining their connection to outcomes in different contexts can lead to risks of greenwashing and misrepresentation of what it can and cannot achieve. Corporates are increasingly setting practice-based targets, such as PepsiCo's 2030 goal to scale regenerative farming practices over seven million acres. Such targets lack measurable outcomes at the farm, landscape and global level which limits the understanding of what regenerative agriculture can achieve. In contrast, the CGIAR has set making "agriculture and forest systems a net carbon sink by 2050" as a core target which has an outcome-based measure that can be monitored and tracked.[60] The net carbon sink requires regeneration of carbon pools, whether above or below ground, both on working agricultural lands and on forest lands, without predetermining a single practice to meet this goal – in other words, seeking the most effective practices depending on their context.

This paper does not put forward a definition, but instead seeks to explore and evaluate the potential for specific practices that are often associated with regenerative agriculture – both traditional and modern – to achieve positive social and environmental outcomes. **The paper advocates for moving away from practice-based definitions of regenerative agriculture and towards alignment around results to accurately measure and report on the potential to contribute to positive social and environmental co-benefits.**

### BOX 2: THE HISTORY BEHIND THE TERM "REGENERATIVE" AND HOW IT IS BEING DEFINED IN MULTIPLE WAYS

The first records of the word *regenerative* come from the 1300s and its etymology is the Latin verb *regenerāre*, meaning "to bring forth again". *Regenerative* means able to or tending to regrow or be renewed or restored, especially after being damaged or lost. The term is commonly used in the context of biology to describe the properties of organisms or environments that are capable of regrowth.[61]

In agriculture, the term is often used to describe a conservation and rehabilitation farming approach that focuses on rebuilding soil organic matter and restoring degraded soil biodiversity, which may ultimately lead to carbon drawdown, improved water cycle, increased farm resilience to climate change, and strengthened health and vitality of soil. It is a notion opposed to monoculture and input-intensive agriculture, carrying the hope of transforming degraded land, replacing vital nutrients and increasing local biodiversity.

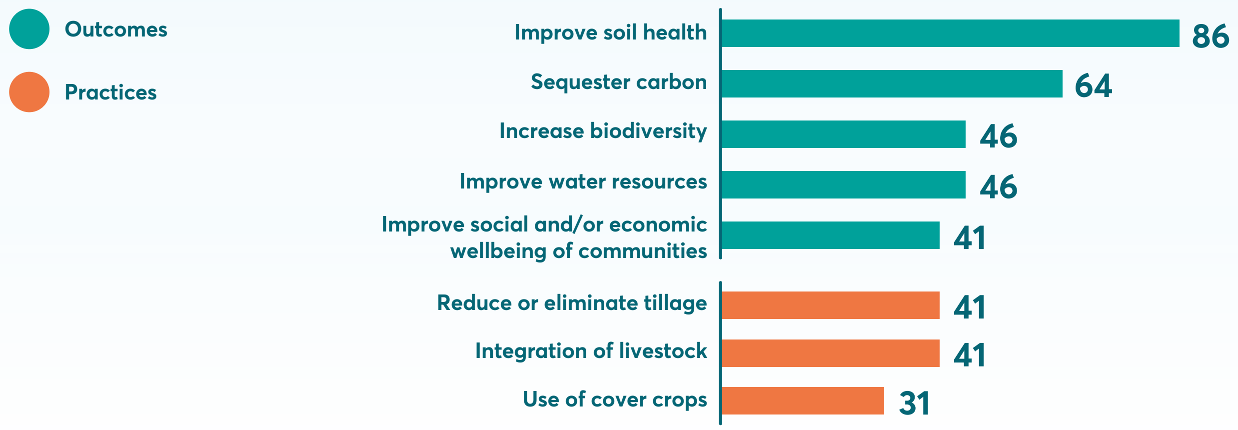
To date, there is no universally accepted definition of regenerative agriculture in the literature – some define typologies of practices, some define strict adherence to sets of practices, and others to outcomes.[62,63]

A review of 20 peer-reviewed papers published between 1983–2021, along with a review of publicly available documents from 44 food companies, businesses, and civil society organizations reveals a mix of practice-based and outcome-based definitions used by different stakeholders (Figure 2). Of the definitions reviewed, roughly half include outcomes, with most commonly stated outcomes being to improve soil health, sequester carbon, increase on-farm biodiversity, improve water resources, and improve the social and/or economic wellbeing of communities. Nearly all definitions include a mix of practices, with the most commonly mentioned practices including reducing or eliminating tillage, the reduction of agrochemical inputs, diverse crop rotations, the integration of livestock, and the use of cover crops.

It is important to note that in the review of 44 definitions of regenerative agriculture used by organizations across business, civil society, and philanthropy, 61% of organizations used a framework of outcomes or objectives to define the term.

ii See Box 2 and Appendix 1 for more information.

**FIGURE 2: COMMON OUTCOMES AND PRACTICES USED IN DEFINITIONS OF REGENERATIVE AGRICULTURE**




**Moving towards an outcome-based framework to measure regenerative agricultural practices can promote global alignment while also guiding practitioners in identifying site-specific interventions.** There is currently no universally accepted framework and set of metrics to set, track and measure outcomes from regenerative agricultural practices. An outcome-based framework helps to create alignment around metrics and enables us to look at how agriculture fits into the broader food and land use system transition. Although this paper focuses on specific practices in its review (see Figure 4), an outcome-based framework enables inclusion of all other sustainable agriculture movements and schools of thought, such as agroecology, conservation agriculture, climate smart agriculture and organic agriculture, recognizing they have many positive overlaps and complementarities. This paper seeks to move away from terminology siloes and unite evaluation of all agricultural practices around an outcome-based framework. In addition to an outcome-based framework, to ensure changes to agricultural practices help advance progress on systemic issues, such as lack of equity, a fair and just transition, and inclusivity, overarching principles should also be considered. There are a number of already existing principles, for example the 13 principles of agroecology,[64] which have been adopted by many countries and organizations. These principles can help to guide stakeholders and ensure the implementation of practices is holistic and does not prioritize one outcome over another, reducing risk of unintended consequences.

**Measuring outcomes requires working with farmers to develop standardized farm level metrics which can help to ensure that policy interventions and industry KPIs are delivering on desirable outcomes.** Currently there is a lack of alignment around farm-level metrics which are needed to measure outcomes. Regardless, governments are developing policies to promote regenerative agricultural practices; for example, the UK Environmental Land Management Scheme provides sustainable farming incentives that will pay farmers to manage their lands in an environmentally sustainable way. Agri-food industries are also making commitments to responsible, sustainable, and regenerative supply-chains and reporting on key performance indicators (KPIs). In some countries, farmers are being asked to report against many of these different frameworks and metrics. This is often a costly and labour intensive task that farmers cannot take on without greater support from upstream buyers and government. In fact, current frameworks tend to be targeted towards corporate stakeholders, without the participation and learning from farmers – many of whom are already using regenerative agricultural practices. The development of metrics will require a multi-stakeholder approach. However, it is particularly important to build on evidence from the farm to better understand context specific interventions and to identify the technical and capacity requirements to measure and adopt practices, before integrating the needs of business and policy. Providing farmers with access to data also enables a positive feedback loop in which farmers can adjust their practices directly to achieve better economic, social and environmental outcomes on the farm.

**Landscape- and global-level metrics are also critical to see how farm-level practices can be scaled to tackle global challenges, such as food security, climate change and biodiversity loss.** Positive outcomes on the farm do not always lead to positive outcomes at the landscape and global level. For example, increased on-farm carbon capture without emissions reductions will fail to tackle climate change in the same way that increasing on-farm biodiversity without halting deforestation will fail to address biodiversity loss. Therefore, it is critical for an outcome-based framework to include metrics that measure all levels of the system to ensure that regenerative agricultural practices at scale are able to help meet global goals. Table 1 reviews some of the current metrics available to measure the three outcomes of focus in this paper at farm, landscape and global levels.[iii] Unfortunately, there is not yet a standardized way of measuring outcomes in agricultural systems, but several attempts are under way. For example, the Global Farm Metric (GFM)[65] is a platform that is seeking to develop a whole-farm framework for measuring sustainability on all farming systems and landscapes in the UK. Metrics from GFM can provide guidance on how to achieve positive outcomes across multiple levels of the system, such as:

- **Physical output: measures the total yield of agricultural outputs at farm level for food and non-food products.** This metric encompasses the diversity of outputs from the farm. It moves beyond crop-specific yields which is the most common metric for yield, and also incorporates risk management and income diversity.

- **Emissions by source: net emissions on the farm that relate to each source (e.g. fuel, livestock, inputs) for each type of land use (croplands, forest and grassland).** This metric goes beyond a sole focus on carbon sequestration, to look at total GHG emissions across a landscape. It is critical to understand the total net emissions to understand climate impacts.

**This paper reviews on-farm evidence from academic literature of three specific outcomes: a) biodiversity b) climate change mitigation and c) yield.[iv]** There are many important environmental and social outcomes that can be assessed when looking at regenerative agricultural practices such as soil health, climate resilience, environmental health, water usage, human health and nutrition and farm-level economics. However, the authors have chosen to focus on the environmental outcomes of biodiversity and climate change mitigation, as well as yield in the first instance, because:

- **Putting humanity on a path to living within planetary boundaries is urgent and must be accomplished in the next decade.** As already described in the introductory chapter, agriculture, as a result of providing for growing global food demand, is responsible for the earth crossing six of the nine planetary boundaries, with climate and biodiversity as two of the most significantly impacted. Regenerative agricultural practices should be tested in their capacity to bring agriculture back within these environmental limits.

- **There are ongoing debates as to whether agricultural practices that increase on-farm biodiversity and carbon sequestration may compromise agricultural production.[66]** It is fundamental that agriculture provides food security for a growing population. Therefore, it is important to explore what evidence is available to better understand and inform this debate. It is also important to explore how different variables impact yield, for example, metrics (e.g. crop per hectare vs total system yield), crop type and study length – all of which will result in differing outcomes. This paper recognizes additional outcomes, such as productivity and profitability, that are critical when exploring yield, however have not been included in our review given the complexity and challenges in measuring these outcomes.

iii This list is not exhaustive. These indicators should be included alongside many other indicators within an outcomes based framework. For example, metrics linked to farm economics, such as amount of inputs, are crucial to ensure that excessive use of inputs is not leading to positive outcomes for yield and carbon.

iv The review explores different ways yield has been measured e.g. yield per individual crop vs total system yield. Yield per individual crop is the most commonly used metric.

- **There are ongoing debates about the technical and practical climate mitigation potential of regenerative agricultural practices.** The carbon sequestration potential of soil on working agricultural lands, and the extent to which it can realistically be scaled up to tackle climate change, is a topic of intense debate amongst scientists. Adding above ground carbon (e.g. through agroforestry) increases this carbon sequestration potential. That said, it is important to focus on climate change mitigation more broadly, rather than carbon sequestration alone, given the role of other GHG emissions such as methane ($CH_4$) and nitrous oxide ($N_2O$) in agriculture. In order to understand how carbon sequestration leads to climate change mitigation, it is important to understand if the $CO_2$ captured exceeds the $CO_2e$ lost.

- **There is more evidence and published literature on these three outcomes (biodiversity, climate change mitigation, and yield) and their potential trade-offs that allows for a substantial literature review.** These outcomes are among the most commonly discussed and measured in the literature.[67] Current available metrics are inconsistent in definition and application making comparisons ineffective (see Table 1 for the diversity of metrics used). For example, some studies only measure soil carbon sequestration, whereas others will look at total system carbon sequestration, including above and below ground. For biodiversity, the choices of proxy variables and methodology have a large impact on results.[68] Biodiversity as an outcome variable, versus biodiversity as a means to other positive outcomes, are often confounded in studies, providing additional challenges (e.g. carbon sequestration is a biological process which is dependent on biodiversity).

**TABLE 1: DIVERSITY OF METRICS[v] USED TO MEASURE BIODIVERSITY, CLIMATE CHANGE AND YIELD OUTCOMES AT FARM, LANDSCAPE AND GLOBAL LEVELS**

<table>
<tr><th rowspan="2">Outcome</th><th colspan="3">Level of metrics[vi]</th></tr>
<tr><th>Farm-level metrics</th><th>Landscape metrics</th><th>Global metrics</th></tr>
<tr><td>Biodiversity</td><td>• Species abundance, richness and evenness, with a preference for native/indigenous/endemic species (can be calculated using Shannon diversity index)<br>o Diversity of crops, seeds and livestock on the farm<br>o Diversity of other plants and animals e.g. pollinators on the farm<br>• Landscape complexity<br>• Soil biodiversity</td><td>• Regional agricultural diversity of farms across the landscape<br>• Regional natural diversity: richness, evenness and abundance of species, with a preference for native/indigenous/endemic species<br>• Habitat and spatial diversity in spatial structure: species and genetic diversity</td><td>• Total estimated change in species abundance, richness and evenness (e.g. balancing biodiversity gains on-farm with off-farm losses if yields decline)</td></tr>
<tr><td>Climate change mitigation</td><td>• Soil carbon content or concentration, measured at different depths<br>• Soil carbon sequestration<br>• Tree and other vegetative carbon (above and below ground)<br>To calculate net gains of sequestration, include:<br>• $N_2O$ and $CH_4$ emissions reduction<br>• Emissions by source: net emissions on-farm that relate to each other<br>• $CO_2$ from on-farm energy use</td><td>• Soil organic carbon sequestration - $CO_2e$ ha−1 year−1<br>• Net emissions for all land uses to calculate net gains of carbon sequestration</td><td>• Total estimated change in net GHG emissions, (e.g. balancing on-farm C sequestration with off-farm C losses if soil amend-ments are imported or yields decline)</td></tr>
<tr><td>Yield</td><td>• Crop yield:<br>o Individual crop per ha, crop varieties in the field and across the farm<br>o Total system yield (all crops grown together over the area of the farm and nearby farms), includes crop varieties and crops suitable for local diets/culture<br>o Crops relevant to local diets and culture (rather than crops for export)<br>• Grass production<br>• Nutrient density of food production<br>• Energy production<br>• Yield stability<br>• Long term yield<br>• Crop yield ratio<br>• Livestock yield (output of meat or milk per hectare; animal weight)</td><td>• Land equivalent ratio<br>• Mix of land use in the landscape e.g. forests, croplands and grazing lands</td><td>• Changes in global yields, total, (cropland and pasture land) and food security of populations based on nutritional outcomes</td></tr>
</table>

v The specific unit of measurement used which allows practitioners to evaluate how changes in practices do or do not lead to specific outcomes. List not exhaustive.

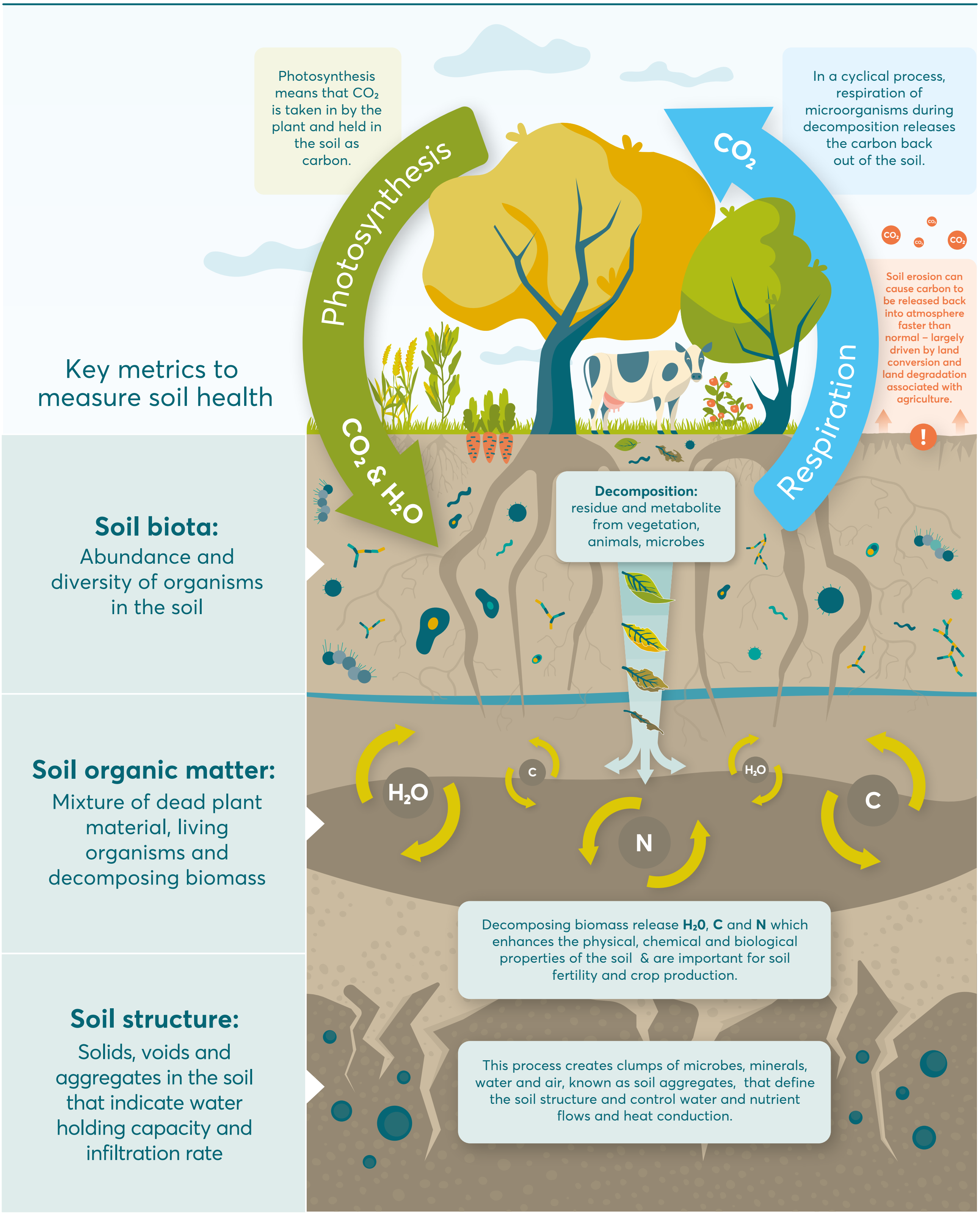
vi Definitions. Farm: average farm size. Landscape: an area defined in terms of its natural features and environmental characteristics, often referred to as an eco-region, e.g. the Amazon biome. Global: outcomes that cannot be attributed to a specific area, e.g. GHG emissions from production of fertilizers or global GHG emissions.

**One key element of regenerative agricultural practices is the emphasis on soil health to store carbon and maintain yield. Soil health is significantly influenced by agricultural management practices and spatial factors such as topography, parent material, soil biology, and climatic conditions.** Soil heath is most notably linked to the presence of soil organic matter but also high soil biodiversity and good soil structure[vii] – all of which are interlinked (Figure 3)[69]. The loss of soil organic matter (SOM) is a widely understood indicator of decline in soil health and fertility. The loss of healthy soils reduces agricultural yields and could result in a food production shortfall of 25% by 2050.[70] (See box 1 that discusses the global problem of soil degradation and how it is linked to productivity). A key element of regenerative agricultural practices is to help maintain soil organic matter and restore degraded soil biodiversity, which strengthens soil functions essential for storing carbon, improving water infiltration and storage, and improving nutrient cycles for good crop growth. The relationship between SOM and yield is contested, and this is largely due to the contextual factors such as management, climate and soil type that can confound the SOM–yield relationship.[71] Therefore, some scientists claim that the amount of SOM is unnecessary for crop yields as long as fertilizers are used (with hydroponics being the extreme example of soilless agriculture),[72] whereas others highlight the need to build SOM to increase crop yields while minimizing environmental harm. Nevertheless, there is experimental evidence showing that building SOM positively affects yield.[73,74,75] For example, research in Argentina, India, and the West African Sahel has found that crop yields can be increased by 20–70 kg/ha for wheat, 10–50 kg/ha for rice, and 30–300 kg/ha for maize with every 1000 kg/ha increase in soil organic carbon (SOC – a component of soil organic matter) around plant roots.[76] Studies point to thresholds of where yield increases level off with higher SOC concentrations. One global meta-analysis on maize and wheat show that yields were greater with higher concentrations of SOC. However, yield increases level off at ~2–5% SOC.[77] Nevertheless, approximately two-thirds of the world's cultivated maize and wheat lands currently have SOC contents of less than 2%.

The physical, chemical and biological soil properties are significantly influenced by spatial factors such as farm-level topography, climatic conditions, parent material, presence of organisms and also time. Therefore, a given set of regenerative agricultural practices applied to farms in one location will not necessarily lead to the same outcomes at others (Box 3), so it can be difficult to replicate locally proven good regenerative agricultural practices elsewhere or scale them up towards sizable impacts globally. Developing aligned farm level metrics is critical to allow farmers, scientists and other stakeholders to identify the best agricultural practices suited to particular spatial and temporal contexts.

vii Soils with high permeability for air, water and roots.

## FIGURE 3: HOW SOIL ORGANIC MATTER, SOIL BIODIVERSITY AND SOIL STRUCTURE CONTRIBUTE TO HEALTHY SOILS




Source: Infographic developed for the purpose of this report using soil health metrics from the Global Farm Metric.

### BOX 3: THE IMPORTANCE OF CONTEXT WHEN ASSESSING REGENERATIVE AGRICULTURAL PRACTICES

It is tempting to sort agricultural practices into "good" or "bad," and from there recommend shifts from "bad" to "good" agricultural practices in order to improve environmental and social outcomes, and to measure success as the rate or extent of adoption of the "good" agricultural practices. However, the wide variation of agricultural contexts across the world shows that a more nuanced approach, focused on evaluating progress against outcomes, is needed.

Take agroforestry as an example. Integrating trees or shrubs (many of which fix nitrogen) into croplands and pasturelands has rightly garnered increased attention in recent years. In some places and for some production types, well-managed agroforestry has the potential to boost yields and profits, improve soil health and local biodiversity, improve freshwater availability and quality, store carbon in vegetation and soils, reduce reliance on chemical fertilizers, and provide additional goods such as timber or tree crops, among other benefits. Intensive silvopastoral systems in Latin America are a prime example. They can boost milk production by several times per hectare while improving resilience to drought.[78,79] As another example, integrating nitrogen-fixing trees has boosted dryland crop yields across several African countries, while providing tree-related goods and improving drought resilience.[80,81,82]

With these multiple-win outcomes, it can be tempting to recommend scaling up agroforestry in food production systems everywhere, but the mere fact that a form of agroforestry works well in one location does not mean that it or other forms will work the same way elsewhere. For example, the success of intensive silvopastoral systems in tropical Latin America by itself does not say anything about either the yield responses or the practicality of adding trees to a maize field in the United States. In silvopastoral systems in Latin America, light is not limiting, shrubs fix nitrogen, and rows of trees provide shade for cattle and help maintain moisture – and the benefits are more than enough to compensate for any reduction in productive area under the trees. Elsewhere, however, trees can compete with the primary crops (or even grasses) for area and water. If the total system yield goes down under agroforestry adoption (even when accounting for uses of the new tree-related goods), then the same tradeoff with off-farm carbon and biodiversity elsewhere noted in this paper can occur. Other constraints, such as increased needs for labor and management skills or land tenure issues (e.g., farming on rented instead of owned land), also limit the practical extent to which trees can be integrated into agricultural landscapes worldwide.

The importance of clear definitions – noted as an issue for the general term "regenerative agriculture" in Section 2 of this paper – also holds for each regenerative agricultural practice assessed. Continuing with the example of agroforestry, the term typically describes not only integration of trees into cropland and pasturelands, but also tree crop plantations (e.g., rubber, cocoa, oil palm, coffee), some energy crops, and timber plantations.[83,84] The expansion of these tree crop plantations has generally been tied to loss of natural forests. In general, for agroforestry to provide net environmental benefits, it must replace or enhance production of annual crops or fodder and it must do so well on existing agricultural lands instead of creating incentives to clear new lands.

Ultimately, assessing the effectiveness of adopting a form of each practice in each location and for each farming system—as argued in this paper—is critical to determining where it should be promoted.

3

# What evidence links on-farm practices to specific outcomes?

## 3.1 Synthesis of evidence

Chapter 2 highlights the need for an outcome-based framework to assess which agricultural practices are most effective in different contexts at delivering positive outcomes for people, nature and climate. This chapter summarizes the evidence on how practices like diversification, input and tillage reduction, and more holistic management of agricultural systems can contribute to three outcomes: biodiversity, climate change mitigation and yields. The practices that we included in our review, alongside their descriptions, are provided in the evidence heatmap (Figure 4). The evidence heatmap was developed by synthesizing quantitative evidence from 127 meta-analytic reviews (representing 55,485 original experiments) integrating and building on syntheses from two recent, comprehensive studies: Beillouin et al. (2021)[85] and Tamburini et al. (2020)[86]. The included meta-analyses were global (91) or regional (36) in scope, and variously cover major crop and livestock systems (Figure 5).

All reviews retained in our evidence synthesis compared quantitative outcome indicators related to biodiversity, climate change mitigation and/or yield. Most studies compared practices and outcomes at the plot and field level, while a minority focused on the farm or landscape-level. For climate change mitigation, most retained studies reported soil carbon storage or carbon sequestration, and only two reviews reported results for greenhouse gas emissions. In section 3.1.2 on climate change mitigation, we discuss the issues and trade-offs associated with only focussing on carbon storage and sequestration as a climate change mitigation tool.

The practices with the largest number of studies include agroforestry, cover crops, crop rotations, intercropping, no or low tillage and organic amendments (i.e. applying organic fertilizers and biochar). Practices with the smallest number of studies include cultivar mixtures, embedded natural infrastructure, inoculation, integrated crop-livestock systems, and holistically managed livestock. No quantitative studies were identified that considered the effects of inoculation or integrated crop-livestock systems on biodiversity or climate change mitigation outcomes. These gaps represent important areas for further research.

The evidence synthesis shows that **crop diversification and low or no tillage practices have a significant positive effect on biodiversity outcomes** (ranging from a 7% increase in local (on-farm) biodiversity under intercropping based on 8676 original comparisons to a 93% increase when incorporating embedding natural structures into fields based on 149 comparisons[87,88]). Some practices like cultivar mixtures, reducing chemical inputs, integrating crops and livestock, and holistically managed livestock systems have no apparent effect on biodiversity outcomes (i.e. similar levels of biodiversity were reported in these systems and their respective control systems). **Agroforestry, intercropping, crop rotations, reducing chemical inputs, and holistically managed grazing all have a significant positive effect on climate change mitigation in terms of soil organic carbon (SOC) and/or carbon sequestration rates** (e.g. an increase of 19.2% in SOC and 0.97 Mg ha/yr in carbon sequestration under organic farming based on 53 comparisons[89]). Cover crops have mixed effects on climate change mitigation, leading to an increase in SOC and an increase in GHG (direct $N_2O$). Cultivar mixtures, no or low tillage, and systems with embedded natural infrastructures had no apparent effect on climate change mitigation. For yield, **crop diversification and inoculation have a significant positive effect on crop yield.** For example, inoculation with arbuscular mycorrhiza fungi or rhizobacteria resulted in increases ranging from 19% to 57% in crop yields.[90,91,92,93,94] In contrast, **organic agriculture reduced crop yields**, particularly for barley, potato and wheat systems, with average reductions of 19% based on 1071 comparisons.[95] However, yield reductions are much smaller when organic systems are diversified.[96] Embedding natural infrastructures had mixed effects on yield, while low or no tillage, reducing chemical inputs, integrated crop-livestock systems had no apparent effect on crop yields, while holistically managed grazing had no apparent effect on livestock productivity.

**FIGURE 4 (1/2): EVIDENCE HEATMAP OF THE EFFECTS OF SELECTED REGENERATIVE AGRICULTURAL PRACTICES ON BIODIVERSITY, CLIMATE CHANGE MITIGATION (MEASURED PRIMARILY AS SOC OR CARBON SEQUESTRATION), AND YIELD**

positive — no significant difference — variable — negative — unknown

| Outcome | Description of practice | Biodiversity | Carbon* | Yield | Source | # reviews | # effect size | # original comp | Experimental scale** | Response variables |
|---|---|---|---|---|---|---|---|---|---|---|
| **Agroforestry** | Woody plants (trees, shrubs) planted sequentially or simultaneously with productive crops (e.g. alley cropping, multistrata systems, parklands, hedgerows, silvopastures), compared to cropland without woody plants. | + | + | + | 85 | 13 | 49 | 4905 | Plot, field | Biodiversity: richness and abundance of multiple species of animals and plants<br>Carbon: soil organic carbon<br>Yield: grain yield |
| **Cover crops** | Non-woody plants sown simultaneously or sequentially with a productive crop for agronomic or environmental purposes, either within the field to increase soil cover, or at field borders as grass (or buffer) strips. | + | +/- | + | 85 | 25 | 112 | 12135 | Plot, field | Biodiversity: soil microbial community abundance and structure; animal and plant diversity<br>Carbon: soil organic carbon<br>Yield: grain yield |
| **Crop rotation** | Productive crops grown in succession on the same agricultural land, compared to land repeatedly planted with a single crop. | + | + | + | 85 | 12 | 51 | 2441 | Plot, field | Biodiversity: soil microbial community abundance, richness, diversity<br>Carbon: soil organic carbon<br>Yield: grain yield |
| **Intercropping** | At least two crop species planted simultaneously on the same agricultural land, usually in alternate rows or strips, compared to land used to cultivate a single crop species. | + | + | + | 85 | 18 | 82 | 8676 | Plot, field | Biodiversity: soil microbial community abundance, richness, diversity; animal (including pollinator, natural enemy and pests) species richness and abundance<br>Carbon: soil organic carbon<br>Yield: grain yield, land equivalent ratio, grass production |
| **Cultivar mixture** | At least two cultivars of the same crop species planted simultaneously on the same agricultural land, compared to land used to cultivate a single crop variety. | o | o | + | 85 | 5 | 20 | 7804 | Plot, field | Biodiversity: soil microbial community diversity<br>Carbon: soil organic carbon<br>Yield: grain yield |
| **No / minimal tillage** | No or reduced soil tillage, compared to conventional tillage. | + | o | o | 86 | 14 | 21 | 8803 | Plot, field, farm, greenhouse | Biodiversity: earth worm diversity, AMF richness<br>Carbon: soil organic carbon<br>Yield: grain yield |
| **Embedded natural infrastructure** | Plots with diverse field margins (e.g. flower strips, hedgerows) compared to simple or no field margins; small field sizes compared to large; fallow compared to no fallow; high landscape complexity compared to low. | + | o | +/- | 88, 104, 105 | 3 | 6 | 1503 | Plot, field, farm, landscape | Biodiversity: crop diversity, non-domesticated species richness, abundance and evenness for multiple taxon (birds, insects, bacteria, fungi, mammals)<br>Carbon: GHG emissions<br>Yield: kg/ha, $/ha, land equivalent ratio, biomass |
| **Inoculation** | Arbuscular mycorrhiza fungi inoculation or plant growth promoting rhizobacteria inoculation, compared to no inoculation. | ? | ? | + | 90-94 | 5 | 5 | 1290 | Plot, field, farm, greenhouse | Yield: crop yield, crop biomass |

## FIGURE 4 (2/2): EVIDENCE HEATMAP OF THE EFFECTS OF SELECTED REGENERATIVE AGRICULTURAL PRACTICES ON BIODIVERSITY, CLIMATE CHANGE MITIGATION (MEASURED PRIMARILY AS SOC OR CARBON SEQUESTRATION), AND YIELD

| Outcome | Description of practice | Biodi-versity | Carbon* | Yield | Source | # reviews | # effect size | # original comp | Experi-mental scale** | Response variables |
|---|---|---|---|---|---|---|---|---|---|---|
| **Organic agriculture** | Agricultural land with organic certification (tpically meaning no use of synthetic pesticides or fertilizers) compared to land where synthetic pesticides and fertilizers are applied. | +/- | + | - | 89, 95, 102, 111, 110, 132 | 6 | 6 | 1898 | Plot, field | Biodiversity: species richness for arthropods, birds, microbes, plants; abundance and richness of pollinators<br>Carbon: SOC concentration, SOC stock, C sequestration<br>Yield: crop yield |
| **Organic ameniments** | Organic fertilizers (manure, mulch, biogas residue) compared to mineral fertilizers, biochar amendment compared to no biochar, residue retention compared to residue removal. | 0 | + | 0 | 86 | 21 | 34 | 4978 | Plot, field | Biodiversity: nematode diversity<br>Carbon: soil organic carbon<br>Yield: crop yield, root biomass |
| **Holistically managed grazing** | Rangeland management that comprises rotational grazing compared to continual grazing; light grazing intensity compared to high or moderate intensity. | 0 | + | 0 | 112, 113, 121, 122 | 4 | 6 | 806 | Plot, field | Biodiversity: bird abundance and species richness, plant richness, plant diversity<br>Carbon: soil organic carbon<br>Yield: animal weight gain, animal production |
| **Integrated crop-livestock systems** | Integration of crops with livestock (spatially co-located), compared to unintegrated, single-purpose systems | ? | ? | 0 | 150 | 1 | 1 | 246 | Plot, field | Yield: crop yield |

* We include carbon instead of climate change mitigation in the column because the majority of studies only measure soil organic carbon and carbon sequestration which can be problematic when measuring climate change mitigation due to permanence and leakage. Only two reviews look at GHG emissions: cover crops and embedded natural structures

** Farm level positive outcomes do not always lead to positive outcomes at the landscape or global level. Yield declines or yield that is unable to meet growing global demand could have potential risk for off-farm biodiversity, carbon sequestration and climate mitigation as more land will need to be converted elsewhere to make up for food demand. See Evidence to Action chapter

Note: Evidence is synthesized from existing meta-analytic reviews published since 2018 (see Source column for details). The description of each practice reflects the treatments and controls as described in the underlying reviews. For each practice, we provide the number of meta-analyses synthesized (# reviews), number of average effect sizes extracted from these meta-analyses (# effect sizes), and the number of underlying original comparisons used to calculate these average effect sizes across the meta-analyses (# original comparisons), and the scale (e.g., plot, field, farm, landscape). The response variables describe the metrics used to measure biodiversity, climate change mitigation and yield outcomes.

The overall significance of results from multiple reviews were not tested for inoculation effects on yield, organic farming effects on SOC and C sequestration, embedded natural effects on biodiversity and holistically managed livestock effects on SOC. Where all reviews report a significant result with the same directionality (e.g. all positive), this is described as 'significant positive' (or negative) in the text and implies consistently significant positive (or negative) results. Where all reviews report non-significant results, this is described as 'no significant change'. Otherwise results for these practices are described as 'variable' (significance or directionality varies) or 'unknown' (if no relevant reviews were identified). For all other practices, the overall significance of results from multiple reviews were tested in second-order meta-analyses (see Beillouin et al. (2021) and Tamburini et al (2020) for details).

**FIGURE 5: SELECTED CHARACTERISTICS OF THE HEATMAP SOURCES**

| Practice | Source | Type of paper | Geographic coverage | Crop / livestock coverage | Experimental scale |
|---|---|---|---|---|---|
| **Agroforestry** | 85 | Meta-analysis (of meta-analyses) | Global (8 reviews), Europe (1), sub-Saharan Africa (2), tropical regions (1) | Multiple, e.g. coffee, cocoa, maize, rice, pasture | Plot, field |
| **Cover crops** | 85 | Meta-analysis (of meta-analyses) | Global (20 reviews), China (1), Europe (2), Nordic countries (1), USA (1) | Multiple, e.g. maize, wheat, soybean, cotton, fruit ochards | Plot, field |
| **Crop rotation** | 85 | Meta-analysis (of meta-analyses) | Global (8 reviews), Canada (3), China (1), Europe/China (1) | Multiple, including rotations of cereals, cereals and legumes, creal and non-legumes, cereals and vege-tables, fruit and vegetables | Plot, field |
| **Intercropping** | 85 | Meta-analysis (of meta-analyses) | Global (13 reviews), Africa (1), Europe (2), sub-Saharan Africa (1), USA (1) | Multiple, e.g. intercropped cereals and legumes, bananas and beans | Plot, field |
| **Cultivar mixture** | 85 | Meta-analysis (of meta-analyses) | Global, but predominantly Europe and North America | Multiple, but mainly mixtures of cereals or legumes | Plot, field |
| **No / minimal tillage** | 86 | Meta-analysis (of meta-analyses) | Global (8 reviews), China (5), Australia (1) | Multiple | Plot, field, farm, greenhouse |
| **Embedded natural infrastructure** | 88, 104, 105 | Meta-analyses, systematic review (with significance testing) | Global | Multiple, including cereals, oilseeds, fruits, vegetables, fibres, and pastures | Plot, field, farm, landscape |
| **Inoculation** | 90-94 | Meta-analyses | Global | Multiple, e.g. maize, wheat, sunflower, lettuce, cotton, tobacco, cucumber, tomato | Plot, field, farm, greenhouse |
| **Organic agriculture** | 89, 95, 102, 111, 110, 132 | Meta-analyses | Global (4 reviews), Europe (1), Mediterranean (1) | Multiple, including cereals, fruits, nuts, oilseed crops, roots and tubers, vegetables, forage legumes, pasture | Plot, field |
| **Organic amendments** | 86 | Meta-analysis (of meta-analyses) | Global (11 reviews), Australia (1), China (6), Europe (1), Mediterranean (1), North America (1) | Multiple | Plot, field |
| **Holistically managed grazing** | 112, 113, 121, 122 | Meta-analysis | Global | Domesticated livestock (e.g. cattle, sheep, goats, deer) | Plot, field |
| **Integrated crop-livestock systems** | 150 | Meta-analysis | Global | 12 crops (e.g. com, cotton, wheat, soybean, canola, rye) and 4 livestock types (beef cattle, dairy cattle, sheep, goats) | Plot, field |

The following sections discuss the mechanisms explaining the evidence synthesis results and strengths and limitations of the evidence base for each outcome. Table 2 provides recommendations for further research.

## 3.1.1 Biodiversity

**Key message: Crop diversification and low/no tillage practices have a significant positive effect on biodiversity outcomes (evidence: strong, confidence: high).** Diversification practices here include agroforestry, intercropping, crop rotations, intercropping, embedding natural infrastructures at field and landscape levels. Cultivar mixtures are an exception which, along with reducing chemical inputs, integrating crops and livestock, and holistically managed livestock systems, do not alter biodiversity outcomes. No practices reportedly had negative effects on biodiversity at the farm and landscape level, meaning that diversification, reducing inputs, reducing tillage, and more holistic management can be safe bets for biodiversity on the farm. Extrapolation and modelling is required to identify how these impacts can be scaled at a global level (not included in this review). It is important to acknowledge that mixed and variable yield effects can have adverse impacts on biodiversity at the landscape and global level. Lower yields could result in land conversion and biodiversity loss to meet growing food demand.

**Review of evidence:** It is widely agreed that higher crop diversification has positive outcomes for on-farm biodiversity, both domesticated and non-domesticated.[97,98] Evidence highlights agroforestry, crop rotation, cover crops and intercropping as crop diversification strategies that have positive impacts on biodiversity, with agroforestry showing the largest benefits.[99,100,101,102] In addition, embedding natural infrastructures has positive impacts on biodiversity at field level when adding hedgerows, flower strips, grass borders or fallow periods of over 6 months[103,104], and at landscape level when increasing complexity[105].

Practices associated with mixed biodiversity results include organic agriculture, adding organic amendments, cultivar mixtures and holistically managed grazing.[106,107,108,109,110,111,112,113] The reason for mixed results in organic farming may be due to the diversity of metrics and taxa measured across the studies. For example, although organic agriculture increases species abundance and richness at both farm and landscape levels, it also results in the presence of more rare taxa,[viii] which decreases species evenness.[ix] Rare and common taxa can be important for maintenance of multiple ecosystem services at farm and regional scales.[114] A review of organic farming in Europe showed that richness and abundance increased in croplands, but with no apparent difference in grasslands.[115] No quantitative study was found on biodiversity and inoculation or integrating crop/livestock systems. However, a qualitative review points to positive trends on above and below ground biodiversity when integrating crop/livestock systems on perennial pastures.[116]

Many studies highlighted the importance of targeting farm management to local conditions.[117,118] For example, Lichtenberg et al. (2017) showed that Mediterranean biomes might see greater arthropod richness gains by increasing in-field plant diversity than organic agriculture, and certain crops may be more likely to boost arthropod abundance with organic farming.[x] When looking at the biodiversity outcomes from farm to landscape levels, Lichtenberg et al. (2017) also found that regional diversity positively correlated with on-farm diversity under organic and plant diversification farm management schemes. For example, the addition of hedgerows to crop fields has been shown to increase community heterogeneity and species turnover (measures of local diversity), which are important components of landscape diversity.[119] Studies also highlight the importance of looking at the mobility of organisms to identify impact at a landscape scale. For example, practices that increase plant, earthworm and spider richness in the field may not at the landscape level, whereas practices that increase richness of mobile pollinators, such as bees, also increased at the regional scales.

viii Rare taxa is small world populations that, though not at present endangered or vulnerable, are at risk. These taxa are localized within restricted geographical areas or habitats or thinly scattered over a more extensive range.

ix Species evenness refers to how close in numbers each species in an environment is. Mathematically it is defined as a diversity index, a measure of biodiversity which quantifies how equal the community is numerically.

x In some instances you can combine to have organic intercrops.

## 3.1.2 Climate change mitigation

**Key message: Agroforestry, intercropping, crop rotations, reducing chemical inputs, and holistically managed grazing, all have a significant positive effect on climate change mitigation, measured in terms of soil organic carbon or carbon sequestration rates (evidence: strong, confidence: high).** Cover crops have mixed effects on climate change mitigation, leading to an increase in SOC and an increase in GHG (direct N20). Cultivar mixtures, no or low tillage, and systems with embedded natural infrastructures had no apparent effect on climate change mitigation. Few studies looked at overall changes in both carbon storage, sequestration and GHG emissions in tandem, and this represents an important gap that needs closing in future studies. However, the existing evidence shows that no practices had significantly negative effects on soil organic carbon or carbon sequestration, meaning that diversification, reducing inputs, reducing tillage, and more holistic livestock management are good options for increasing the carbon sink potential of farmlands.

**Review of evidence:** Positive results on on-farm SOC included agroforestry, cover crops, crop rotation, intercropping, organic agriculture, organic amendments and holistically managed grazing. Results with this highest SOC include organic farming (+19.2%) and rotational grazing (+25%).[120,121,122] However, livestock need to be carefully managed as results can be confounded by the effects of high stocking rate and grazing intensity.[123,124] The majority of studies only look at soil carbon content, with the exception of studies looking at agroforestry which showed positive carbon capture above ground. One meta-analysis focussing on cocoa showed an increase of 250% in tree carbon under agroforestry.[125,126] However, a field study in West Africa looking at cocoa agroforestry questions whether it contributes to soil carbon sequestration.[127] This disagreement likely reflects the context specificity of the results.

Organic agriculture and amendments tended to show a positive effect.[128,129,130,131,132] However, one review explained that chemical fertilizer does also increase soil carbon compared to no fertilizer use because the application of nutrients stimulates the growth of biomass which is a key input to carbon sequestration in soils.[133] Furthermore, adding soil amendments does not necessarily lead to an additional drawdown of carbon from the atmosphere, but rather re-allocates a limited resource (e.g. manure or compost) onto one site over another.[134]

The literature review shows no apparent change for cultivar mixtures, no/minimal tillage, and embedded natural infrastructures. Although minimizing tillage can concentrate SOC in the top 15-20 cm of soils, several studies have found these gains compensated by losses of SOC at deeper depths (e.g., 30 cm or more), making the overall carbon gain much smaller or negligible.[135] Soil properties were also seen to impact results; fine-textured soils show larger carbon sequestration rates than medium and coarse soils when using cover crops and SOC under minimizing tillage, but these results were often crop and climate dependent.[136,137]

It is important to note that greater carbon sequestration alone will not lead to climate change mitigation. Some studies highlight that crop diversification could actually increase GHG emissions due to an increase in $N_2O$ emissions, even when soil carbon increases.[138,139] For example, meta-analyses on cover crops showed an increase in GHG emissions because of higher mineralizable carbon that increases $N_2O$ emissions compared to non-cover crop management. The application of organic amendments can also increase GHG emissions because the organic material triggers the degradation of older soil organic matter leading to the release of $CO_2$ and $N_2O$, which can offset some of the soil carbon gains.[140] One study even predicted that the positive climatic effects of increased carbon storage in organically fertilized agricultural soils could be offset by $N_2O$ by 2060.[141] Interestingly, carbon sequestration is referenced many more times than GHG emissions or climate change mitigation in literature seeking to define regenerative agriculture.[142] This shows that the literature is not always acknowledging the system wide impacts of carbon gains and losses and potential trade-offs that could arise. More evidence is required to better understand which practices lead to net benefits for climate change mitigation, through studies that collect data on carbon storage and sequestration while factoring in potential trade-offs of $N_2O$ and $CH_4$ emissions under different practices. There are also spatial and temporal limitations of assuming carbon sequestration can lead to climate change mitigation because of issues around permanence and leakage. For example, lower yields noted in some studies could lead to leakage via agricultural expansion and carbon losses off-farm.

No quantitative outcome data was found on integrating crop-livestock systems and climate change mitigation and there is ongoing debate on the topic. A qualitative review reports that organic livestock systems increase soil sequestration via adding amendments, and multi-paddock grazing results in similar or increased soil organic matter.[143] However, it is important to note that importing organic biomass from one place to another will increase soil carbon locally at the expense of removing carbon elsewhere. Manure amendments from grass fed livestock in the same pasture area are more circular and thereby reduce such carbon displacements. A study also explains that dual purpose crops used in integrated livestock systems improve soil health and switching between grazing and cropping on the same area improves nutrient cycling and increases soil fertility, although the study does not specifically mention carbon sequestration. However, the uneven distribution of grazers can negatively impact soil fertility because of uneven manuring.[144] Finally, if integrating livestock into an area displaces crops, then the carbon consequences of replacing the foregone crops elsewhere should also be counted for completeness. These studies also do not include potential implications of increased enteric methane when integrating livestock.

### 3.1.3 Yield

**Key message: Crop diversification and inoculation have a significant positive effect on crop yield (evidence: strong, confidence: high). However, organic agriculture reduces crop yields**, although reductions are smaller when organic systems are diversified.[145] Other practices considered here have mixed or no apparent effects on yield. Practices that lead to yield gains while also impacting positively on biodiversity and/or climate change mitigation, such as agroforestry, crop rotations and intercropping, are promising options to reach agronomic and environmental outcomes synergistically. Practices that lead to trade-offs, notably for yield under organic farming, or where there are uncertain yield outcomes, such as when embedding natural infrastructures, need to be used with care and may need to either be used in tandem with other practices that offset or eliminate losses, or incorporated into food system shifts that reduce overall food demand (e.g. dietary shifts)[146]. Avoiding yield losses is optimal in a world with a projected 35–56% growth in food demand to 2050, and where land clearing for agriculture needs to halt as soon as possible to stay within planetary boundaries. Yield declines increase the likelihood of agricultural land expansion, raising potential risks for off-farm biodiversity and carbon sequestration. These trade-offs are discussed in the Evidence to Action chapter.

**Review of evidence:** Beillouin et al. (2021) found that the combination of crop diversification strategies assessed tended to increase yields by 14%. Practices that involve two diversification strategies relying on the simultaneous cultivation of different plant species within one field (i.e. agroforestry and intercropping) improve agricultural crop production most significantly.[147,148,149] Our evidence synthesis shows that reduced or no tillage, embedded natural structures, organic amendments, holistically managed livestock and integrated crop/livestock systems all led to no apparent changes in yield.[150]

Organic agriculture was the only practice showing a negative result.[151] In agreement, many studies find that organic agriculture will decrease yields. For example, Seufert and Ramankutty (2017) found that numerous meta-analyses showed that overall, organic yields were 19–25% lower than conventional.[152] A model by Smith et al (2018) even suggests a 60% yield decline under organic farming. However, Ponisio et al. (2015) also found that increasing crop diversity could reduce the yield gap, to approximately 9% through the use of multi-cropping and to approximately 8% through the use of crop rotations.[153] A 30-year study by the Rodale Institute, an organization that conducts long-term research on organic farming, have also found equivalent yields between organic and conventional production, with organic outperforming conventional in drought years.[154]

The effect of a change in agricultural practice on yield responses vary with several factors, including the combination of practices used, soil management, agrochemical inputs, yield metric (main crop or whole system yields), cropping system and climatic conditions. For example, Himmelstein et al.'s (2017) study on intercropping showed that yield increase was highest when intercropping was combined with integrated pest management, while there was minimal change when intercropping was combined with no till, high levels of pesticides or fertilizers. Another example is from Reiss and Drinkwater (2018) who found that cultivar mixtures had a stronger positive impact on yield when there were environmental stresses like disease pressure, low SOC and variable weather. For agroforestry systems, tree density is an important variable. Yield is negatively impacted by tree canopy coverage above 30% in agroforestry systems in West Africa.[155] These studies highlight the importance of considering contextual factors when interpreting results and designing agricultural practices to enhance yields.

Most soil scientists and agronomists agree that many regenerative agricultural practices can restore soil health and increase soil organic matter, which are important for maintaining and increasing crop yields over time. However, most studies tend to be short term and there are a limited number of studies demonstrating long-term positive effects or measuring total system yield rather than individual crop yield. In addition, studies do not account for climate change impacting yields under business as usual. Already over the last 60 years, global farming productivity is 21% lower than it could have been without climate change.[156] In addition, it is important to note that measuring the output of diverse crop systems versus monocultures raises methodological challenges because yields from different crops are not comparable. Suitable metrics, such as the land equivalent ratio, need to be used in intercropping and agroforestry systems. These capture whole system yields and can be used to make meaningful comparisons.

Only a few studies comment on long-term yield effects or yield stability, often due to the lack of comparable data over time. Some studies have looked at diversification strategies and sometimes found longer-term gains even with shorter term declines.[157,158]

## TABLE 2: TABLE OF RECOMMENDATIONS IDENTIFIED FROM THE LITERATURE REVIEW

| Biodiversity | Climate Change Mitigation | Yield |
|---|---|---|
| Studies should collect data beyond species richness and look at yield alongside biodiversity to better understand the implications of increased biodiversity on weeds, natural enemies and pests, which could also impact yield.<br><br>Research should also explore how using environmental DNA surveys can scale up knowledge and data of on-farm biodiversity. For example, organizations such as NatureMetrics provide biodiversity monitoring data with environmental DNA surveys. | Research to better understand the maximum capacity of sequestration above and below ground on farmland, including greater understanding of the impact of shifting crop type over time.<br><br>Understand how practices that might increase SOC could also increase $N_2O$ and $CH_4$, having a potential negative effect on total GHG emissions.<br><br>Research to better understand the carbon leakage potential off farm and through global trade of inputs and commodities.<br><br>Increase research into agroforestry as a climate solution given its ability to sequester carbon above and below ground. Measure this alongside total system yield to better understand links between productivity and carbon storage.<br><br>Research to better understand future scenarios under current trends where climate change becomes an increasing issue.<br><br>• Scientists need to help farmers and policymakers better understand the impact of extreme weather events on carbon levels. This can help inform policymakers to ensure farmers implementing regenerative agricultural practices do not lose out as a result of climate change.<br><br>• Scientists should factor in the impact of increased $CO_2$ levels in the atmosphere impacting soil carbon levels under future scenarios. | Test new technologies to increase productivity of regenerative agricultural practices, particularly in areas where yields are very low and future food security is at risk without productivity gains.<br><br>Use different metrics to measure yield.<br>For example:<br><br>• Yield stability: Measure long term impacts of practices under different climate impact scenarios to see whether climate resilience in the form of soil health can counteract the negative yield impacts that will occur due to climate change.<br><br>• Total system yield: to better understand the diversity of crops on a farm contributing to food security, also important when thinking about climate resilience. |

**Crosscutting recommendations for all outcomes**

**Build a more robust evidence base:**

- Increase the number of primary studies looking at farm performance outside of North America and Europe, as well as for a greater diversity of crop and livestock types. This will help build a more robust evidence base that will enable us to better understand how targeted farm practices can lead to desirable outcomes.
- Collect data on biodiversity and climate change mitigation alongside yield data to better understand system-wide effects and trade-offs. This will help to inform the land sharing vs land sparing debate (See Box 5 for detail on the debate).
- Increase studies that look at how a combination of practices can achieve positive outcomes, rather than one practice alone.
- Conduct longer-term studies. Most existing studies are 1-2 years in length yet biodiversity, carbon and yield effects can vary significantly over time.

**Develop an outcome-based framework:** Work with farmers to develop standardized metrics and an outcome-based framework to easily measure and report on how practices are linked to outcomes.

### 3.1.4 Other key outcomes

We have focused on three key outcomes in this paper but there are a number of other important outcomes that should be assessed when examining the impact of regenerative agricultural practices, as well as the linkages between outcomes. These include soil health, human health and nutrition, climate adaptation, agrochemical use, water and nutrient management, water storage and infiltration rates in the soil, pollution, as well as socioeconomic parameters such as farmer incomes, labour and energy usage, social cohesion, gender equity, youth inclusion, and livelihoods of rural communities. These outcomes again will have multi-tiered implications, both on the farm and wider landscape.

Taking the example of healthy diets, there is evidence starting to emerge of how some practices can contribute to increasing the availability of healthy and nutritious foods that are suited to local dietary requirements. For instance, one study from the US found that a combination of no-till, cover crops, and diverse rotations produced crops with higher soil organic matter levels, soil health scores, and nutrient density (vitamins, minerals and phytochemicals) than conventional crops.[159] The same study found that beef and pork raised on one of the same regenerative farms had higher levels of omega-3 fatty acids and healthier omega-6 to omega-3 ratios than conventionally produced meat. Studies have also shown that dairy production fed organic forage enhance the nutritional quality with higher concentrations of linoleic acid and omega-3.[160,161]

## 3.2 From evidence to action

When using evidence from meta-analyses, systematic reviews and local field experiments, moving from evidence to action requires several considerations. This includes a) targeting farm management to local conditions, b) assessing how local impacts could be scaled to landscape and global impacts and c) ensuring there are the right enabling conditions for farmers to adopt new practices.

### 3.2.1 Targeting farm management to local conditions

**The challenge:** Meta-analyses and systematic reviews are useful for gathering an accumulation of evidence and facilitating the generalization of results to a larger population. However, the effects of agricultural practices on biodiversity, yield and climate mitigation are highly context specific, varying with, for example, farm size, adjacent land cover, climate conditions, crop species and varieties, and management intensity. This means generalized conclusions are not always helpful in determining a practice (e.g. which crop varieties/species, which livestock breeds, which tree species, optimal crop and tree arrangements, optimal management) can lead to multiple important outcomes at a local level. In addition, much of the evidence stems from North America and Europe. There is a risk that these geographies dominate global narratives on food, which means that certain forms of evidence are elevated and important voices from other geographies across Latin America, Africa and Asia are missed. Additionally, the reductionist approach to field trials which dominate the research literature struggle to assess the more systemic multi-practice approach used by farmers who often adapt and combine practices to suit their needs. Greater co-design, collaboration and engagement with the farmer community can help to provide insights not just as to the biophysical potential of regenerative agricultural practices but also to the socio-economic conditions that favour (or hinder) their adoption. Without diverse evidence, including experiences of farmers and food producers, contextually relevant solutions may be missed, resulting in unintended consequences at farm, landscape and global levels.[162] Field studies and pilots, especially those that are able to show long-term trends (e.g. Rodale Institute), are also heavily focused on North America and Europe and therefore make it difficult to generalize the results to other countries.[163] Current research investments tend to be lower for "transformative" agriculture, such as agroecology, and for crops that are better adapted to future climates and contribute to healthy diets. Increasing research funds for on-farm biodiversity conservation, climate change adaptation and nutrition security is critical.[164,165]

#### Evolving solutions

**Standardized metrics and frameworks:** Assessing multiple outcomes together in a consistent framework is critical to identify what regenerative agricultural practices are suited to a particular environment, as discussed previously in this paper. Organizations are starting to develop standardized frameworks for farm-level metrics, such as the **Global Farm Metric** and the **Cool Farm Alliance** which allows better comparisons of evidence across regions. **OP2B** is a regenerative agriculture framework for corporates that aims to provide consistency across the industry, enable regenerative agricultural practices, inform corporate strategies and provide an essential process for measuring impact in a transparent way. **The Science Based Target Network** is also producing characterization factors to estimate the effects of practice changes on land and biodiversity indicators. However, lack of alignment across frameworks and metrics means that it is difficult for farmers to measure certain outcomes. It is critical that these metrics are designed in collaboration with farmers and producers to ensure applicability of the framework and to also build on learnings from the farm. **The Regen10 Initiative**, supported by FOLU, plans to build on already existing frameworks to create a farmer-driven, outcome-based framework to assess regenerative agricultural practices.

**Further research and evidence:** Research institutions are continuing to collect and publish data on the impact of practices leading to positive outcomes in different regions and equipping farmers with the tools and knowledge required. Examples include:

- International research collaborations like the **CGIAR Initiative on Agroecology and the CGIAR Initiative on Nature Positive Agriculture** that seek to transform food, land and water systems to equitably support food and livelihoods on the ground.

- **Ecdysis Foundation's 1000 Farmers Initiative** in the United States is gathering data to show the performance of regenerative agricultural practices, with the plan to scale the process elsewhere.

- **Soils Revealed** are seeking to address the scalability debate of carbon sequestration on climate change by tracking soil carbon storage across the world and predicting maximum carbon storage potential.

## 3.2.2 Going from local evidence to global impact

**The challenge:** There are many practices that can generate positive outcomes on farms; however, there are insufficient evidence and analytical tools available that can show how these practices can deliver on landscape or global-level goals when scaled beyond the farm (e.g. food security, climate change, halting deforestation and ecosystem conversion). Current narratives and evidence around regenerative agricultural practices tend to focus on farm-level outcomes and ignore the broader landscape and global-level impacts. Focusing solely on farm-level outcomes limits the ability to know if a given practice, implemented in a given place, is a net "win" for food security, the environment (e.g. mitigating the climate change and biodiversity loss), and other societal goals. Therefore, a wider systems lens that ascertains how farm-level outcomes interact with landscape and global challenges should be included when referring to the evidence of regenerative agricultural practices.[166] For example, positive outcomes in one place do not necessarily eliminate the driving force for land conversion. Such examples include:

- Improved yields and profitability can incentivize some farmers to expand production, sometimes into highly biodiverse ecosystems that are also storing carbon and mitigating climate change. For example, between 1980 and 2014, yield gains from major food crops such as soybean, maize, rice and wheat did not prevent the expansion of production area over time. This demonstrates that efficiency and productivity gains alone are not enough to halt land expansion.[167] Therefore government regulations on land conversion must be complementary to regenerative agricultural practices.

- Where yield could be compromised, it may result in farmers encroaching into areas of high carbon stocks or biodiverse environments to make up for the productivity lost on the farm. This could have negative effects that offset or negate the on-farm carbon or biodiversity gains. As such, assessing the productive functions of regenerative agricultural practices is critical.

- Transitioning to regenerative agricultural practices in one country might lead to unsustainable agricultural intensification or expansion in other countries to keep up with demand, especially where prices may increase due to a switch to regenerative agricultural practices.

Therefore, switching to regenerative agricultural practices has the potential to be contradictory to global climate and biodiversity goals if we do not carefully assess their potential and ensure that the right practices are used in the right contexts. These trade-offs emphasize the need for more research on how on-farm metrics, such as yield, climate change mitigation and biodiversity can lead to landscape and global outcomes. By measuring across landscape and global levels, it can help to ensure stakeholders take a systemic approach to forest and natural ecosystem protection, including through shifts in diets and markets (e.g. away from meat and dairy in countries overconsuming these products, and towards plant-based foods).[168,169] Governments and corporates must also eliminate agricultural support that incentivizes unsustainable agricultural expansion into natural ecosystems and tighten regulations in supply chains.

Considerations around the spatial and temporal limitations of evidence are also important. As mentioned previously, research has shown that soil properties are significantly influenced by spatial factors (such as topography and climate), making it inappropriate to scale up solutions found in one soil type for sizable impacts globally. The evidence also faces temporal limitations due to the changing nature of crops on agricultural land. For example, agroforestry shows strong potential for carbon sequestration but questions around its rotations means that the emissions reduction function over time is not guaranteed. Therefore, it is difficult to guarantee that these practices can address climate change unless steps are taken to ensure continuity in the medium to long term.

**Evolving solutions:**

- **The Food and Land Use Coalition**: FOLU's country platforms focus on specific initiatives around regenerative agricultural practices at the farm and landscape level that is complemented and connected to the wider global FOLU agenda to transform food and land use systems at a global scale.

- **Aligning metrics across farm, landscape and global levels**: Organizations develop metrics to align all stakeholders around the same outcomes and connect farm level outcomes to landscape and global outcomes. For example, the Science Based Target Network are developing characterization factors that enable corporates to identify how local impacts are linked to landscape and global impacts.

- **The FABLE Consortium**: Uses data and modelling infrastructure to promote ambitious, integrated strategies towards sustainable land use and food systems in multiple countries. Develops pathways and scenarios for policymakers to better understand how sustainable agricultural practices can achieve positive outcomes.

- **Investing in new technology**: Improving agricultural production technology that sustainably boosts yields, such as using IT to optimize inputs and increase soil quality, or CRISPR technology that unlocks traits in crop genes to increase yields. These technologies can complement many of the practices mentioned in this paper.

## 3.2.3 The enabling environment

**The challenge:** This paper highlights the importance of evidence, metrics and frameworks to better understand the impact of regenerative agricultural practices and identify context appropriate solutions in agriculture. However, agricultural producers will still face additional barriers to operationalizing an outcome-based framework and, where appropriate, adopting new approaches. These barriers include lack of capital, insufficient capacity and information and perverse policy incentives. A paper on operationalizing positive tipping points, explores the enabling conditions to address these barriers in greater detail.[170] For example, the measurement tools must be affordable and the practice needs to be economically attractive compared to conventional farming. In some regions, incentives in the form of government subsidies for inputs like fertilizers favour high-input monoculture farming over practices associated with regenerative farming. Farmers also need to have the right capabilities, such as knowledge, tools and capital, to practice and measure new approaches. It is especially important to think about this in context of disadvantaged and minority groups, such as women, youth and Indigenous peoples who often face additional barriers, such as access to land and resource rights, which hinder their opportunity to gain financial access, limiting their ability to experiment and innovate. Farmers are also members of communities and societies, and therefore are influenced by cultural and social factors, such as what their peers are doing.[171] This all needs to be taken into consideration when operationalizing an outcome-based framework to farmers globally.

**Evolving solutions:**

- **Repurposing agricultural subsidies in support of sustainable agriculture.** Policy discourses on repurposing agricultural subsidies as one of the financing mechanisms for nature investment are high on G7 and G20 governments' agenda.[172] Governments across Europe are starting to find ways to reform subsidies so that farmers that generate (or regenerate) ecosystem services are rewarded – for example, the UK Environmental Land Management schemes and the EU's new common agricultural policy from 2023 introduce a number of reforms including the redistributive income support mechanism.[173]

- **Organizations supporting peer-to-peer farmer networks with data, knowledge and capabilities.** Examples include:

  - The Kakataima Agroecology School in Colombia that is training a new generation of local farmers how to best work with their land using this alternative farming technique and connecting curious consumers to their organic food markets.[174]

  - ReNature provides mid- to long-term capacity building programmes to build deep expertise within local farmers' groups which includes courses, training and a knowledge hub for the region.

  - Cooperation between Germany and India which is scaling Andhra Pradesh's Community Managed Natural Farming.[175]

  - Field to Market multi-stakeholder convening to advance shared learning and drive collective action.

- **Financial support to measure outcomes and transition to new approaches accordingly:** Financial support such as the Agri3 Fund that aims to de-risk traditional agricultural lending to help mobilize additional private capital to support the transition to sustainable agriculture.

### BOX 4: "LAND SPARING" VS "LAND SHARING" DEBATE

There is often a scientific debate between the benefits of "land sparing" and "land sharing" approaches. A key way to drive carbon storage and enhance biodiversity is to protect primary forests and grasslands while maintaining and improving high-yielding agricultural practices on a smaller area of land, a "land sparing" approach, often referred to as "sustainable intensification". The Global Biodiversity Framework has drafted new 2030 targets; "at least 30% of land and sea areas globally are conserved through effectively and equitably managed, ecologically representative and well-connected systems of protected areas and other effective area-based conservation measures, and integrated into the wider landscapes and seascapes." With this need in mind, it is important to think about how sufficient food can be produced on existing farmland to avoid expansion into protected areas. However, high yields are often achieved using intensive management (chemical fertilizers and pesticides, irrigation, tillage), lessening and often undermining the benefits for biodiversity and potentially undermining soil health and yields in the long term.

Regenerative agriculture is often associated with a "land sharing" approach, where agriculture and conservation can happen simultaneously by increasing biodiversity on the farm, as well as providing ecological restoration to degraded agricultural land. However, more research and innovation is needed to identify and target practices that regenerate environmental function while ensuring total yield is compatible with food production needs. This includes a better understanding of total system yield as an important outcome when looking at crop diversification on the farm.

Demand reduction strategies, such as mitigating food loss and waste and reducing consumption of animal products, are important in both scenarios to reduce the amount of land used for farming and livestock, whilst at the same time improving productivity, allowing more land to be spared. It is also possible to implement land sparing at field and farm scales with certain practices associated with regenerative agriculture, such as embedding natural structures like hedgerows, which can increase community heterogeneity and regional diversity. There is still no consensus around which scenario is most effective in reaching our global goals and it will most likely to be a combination of land sharing and land sparing. However, it will also depend on the potential for cultural shifts around what and how we eat, which is very difficult to predict in modelling efforts.

4

# Conclusion and recommendations

To conclude, this paper:

**Argues for an outcome-based framework to measure and report on regenerative agricultural practices across farm, landscape and global levels.** Developing a framework and corresponding metrics should be based on research, evidence, experience and insights of farmers, Indigenous peoples, local communities, civil society and academia. The framework will inform the evaluation and continuous improvement of regenerative agricultural practices across the world, and also inform strategies to scale up adoption of the most effective practices. An outcome-based framework will allow farmers and practitioners to adopt and measure regenerative agricultural practices that are having a positive effect on people and planet relative to business as usual at the farm, value chain, corporate and landscape level. This paper focuses on three important outcomes to be integrated into the framework – biodiversity, climate change mitigation and yield – but also recognizes that there are other important outcomes that should be included.

**Summarizes the evidence in academic literature that links a dozen specific regenerative agricultural practices to three farm-level outcomes around biodiversity, climate change mitigation, and yield.** Evidence showed positive impacts on on-farm biodiversity and on-farm carbon sequestration, although at different magnitudes depending on contextual variations. Effects on on-farm net GHG emissions tended to be neutral, inconclusive or negative largely due to the limited evidence and trade-offs associated with other emissions. Effects on yield tended to be highly variable with a range from -64% to +40% which presents a challenge in a world projecting strong growth in food demand and an urgent need to halt agricultural expansion and deforestation. Evidence suggests that maintaining soil health has a positive impact on productivity over time and improvements in soil health are valuable to curtail widespread soil degradation that negatively impacts yields.[176] All the evidence points to contextual variations such as climate, topography and soil type as key determinants for results across the outcomes, emphasizing the need for an outcome-based framework to ensure that the practices selected lead to the best outcomes in different geographies. The paper has also highlighted the importance of looking at outcomes beyond just the farm. Including landscape and global metrics in the framework can mitigate potential trade-offs and ensure that switching practices can achieve global goals.

**Makes specific recommendations for further research (see Table 3).** This includes exploring the use of new technologies that can assist farmers to self-report, document and leverage the innovation that is already being practiced by farmers around the world.

## TABLE 3: AREAS FOR FURTHER RESEARCH

| Areas of further research identified in this paper | |
|---|---|
| **Biodiversity** | • Expand the evidence base to include more countries, in particular the Global South and include a wider variety of farming systems<br>• Collect evidence that can clarify the links between biodiversity and yield over time, including more studies looking at soil biodiversity rather than just above ground biodiversity<br>• Evidence should cover results on-farm but also at landscape and global levels. This helps stakeholders to set policies and regulations that will avoid trade-offs at global level, where increasing biodiversity in one landscape might negatively impact biodiversity in another<br>• Data collection should be aligned to consistent metrics to allow for better comparison across studies and to make sure that all the important elements of biodiversity are considered (such as species evenness as well as richness) |
| **Climate mitigation** | • Evidence should look at the impacts of changing crop type over time on climate mitigation, adaptation and resilience<br>• Evidence should look beyond just carbon sequestration and include GHG emissions, notably $CH_4$ and $N_2O$ as well as looking at total GHG emissions across farming systems<br>• Evidence should better explore the links between GHG emission reduction and yield, and GHG emission reduction and nutrition<br>• Evidence should cover results on-farm but also at landscape and global levels. This includes looking at trade-offs where increasing soil carbon sequestration in one landscape might negatively impact carbon stocks in another<br>• More studies should examine the impacts of regenerative agricultural practices on climate adaptation and resilience in different contexts |
| **Yield** | • More long-term testing of the conditions under which regenerative agricultural practices can improve yields, in combination with reducing GHG emissions and improving biodiversity at farm, landscape and global level<br>• Research into technologies and approaches that can help to increase yield (including combinations of different technologies and approaches)<br>• Greater focus on total system yield of all crops and livestock grown on a particular area of land, rather than only on the yields of one crop<br>• Expand the evidence base to include more countries, especially where yields are very low and threaten future food security if not improved<br>• Examine nutrient density of food produced by practices achieving positive outcomes as a key metric of productivity (nutrients/ha rather than just yields/ha) |
| **Outcomes not reviewed but core to developing an outcome-based framework** | • More evidence needs to be collected across a broad range of outcomes. Including:<br>  • Socio-economic outcomes, such as farmer incomes, profits, health and wellbeing, and livelihoods of communities<br>  • Other planetary boundary outcomes such as soil health, agrochemical use, freshwater resources and biogeochemical flows (phosphorous and nitrates)<br>• Farmers' testimonials, articles and books should be considered as evidence in addition to academic literature for all the relevant outcomes |
| **Spatial and temporal trade-offs** | • Evidence should cover outcomes on-farm but also at landscape and global levels that will help to identify the broader policies that can mitigate leakage and trade-offs<br>• Evidence to show impacts of aligned biodiversity, land, and climate indicators from practice changes in specific locations and farming systems |

**Moving to an outcome-based framework to measure, improve and scale practices that achieve positive outcomes is critical to address some of the challenges in food production.** Soil degradation threatens humanity's future and urgently needs to be addressed. We have already crossed six of the nine planetary boundaries, largely driven by agriculture and associated land expansion. At the same time, recent global economic and political crises are increasing the number of people unable to afford food. The way we produce and consume food needs to change. Consumption shifts will play a key role in the transition to reduce resource demands and environmental impacts (e.g. reducing food loss and waste and shifting to healthy and sustainable diets). However, this paper has chosen to focus on the role of food production in the transition, and explores how regenerative agricultural practices can be part of the solution on the supply side. The mixed results on yield reiterate the need to focus on and only scale practices that are both productive and regenerative as originally envisaged as one of FOLU's critical transitions.[177] Given the ongoing debates around the potential yield, carbon and broader biodiversity impacts of regenerative agricultural practices, it is critical for stakeholders to align around an outcome-based framework and standardized metrics that will enable the measurement of how the practices can lead to positive outcomes at the farm, value chain, corporate, landscape, national, and global levels. The framework will allow the improvement and adoption of the practices that are best suited to local contexts and will allow the scaling up of these approaches to meet global goals.

**The challenges around food production are a result of complex social dynamics across the value chain, requiring farmers, policymakers, businesses, civil society and academia to work together to transform food and land use systems.** This requires a whole food systems approach. Implementing regenerative agricultural practices will not be a silver bullet, but instead can be part of a solution in the wider food system to achieve our goals and stay within planetary boundaries. This is why FOLU advocates for a comprehensive reform agenda in the form of 10 Critical Transitions to transform food and land use. Below we highlight key actions for stakeholders across the value chain to help develop an outcome-based framework and scale practices that achieve positive outcomes across the system:

### (a) Farmers

- With agronomists and environmental scientists, design and develop an outcome-based framework and set of tools.
- Experiment with agricultural practices that increase environmental outcomes, and means to ensure their economic viability across a diversity of contexts.
- Challenge neighbours and peers to improve the environmental performance of their farms.
- Lobby for greater accountability, performance and economic rewards based on environmental performance of farmers.

### (b) Policymakers

- Eliminate support measures that encourage unsustainable agricultural practices, agricultural expansion and land conversion.
- Set laws and regulations that halt land conversion globally.
- Repurpose agricultural subsidies to fund education and research on regenerative agricultural practices. This can help address gaps in evidence and incentivize farmers to adopt and scale up regenerative practices that are proven to be effective locally. Reinforce the use of outcome-based frameworks to measure performances of sustainable farming practices through legislation.

### (c) Business

- Utilize the outcome-based framework that has been developed using a multistakeholder approach, specifically including farmers, rather than trying to develop independent versions.
- Set outcome-based targets (rather than only practice-based targets) to drive the adoption of regenerative agricultural practices that are suitable to local contexts but also tackle wider system issues at landscape and global level.
- Make public any data and evidence on how regenerative agricultural practices have led to positive outcomes.

### (d) Civil society

- Align key stakeholders and develop an outcome-based framework to measure how regenerative agricultural practices can lead to outcomes, which can then inform targets made by policymakers and businesses.
- Multistakeholder coalitions are specifically needed to galvanize a movement. Civil society can play a leading role in bringing important actors into the coalition.

## (e) Agricultural research organizations and academia

- Provide clear environmental performance metrics and tools for measurement.
- Assess the needed contribution and global potential of regenerative agricultural practices.
- Address gaps in evidence to date, e.g. more evidence from the Global South, more diverse cropping systems and longer-term studies.
- Bridge the gap between farmers and scientists in evidence generation by working directly with farmers to learn from and to help document on-farm evidence on a regular basis.

## (f) Donors

- Provide funding for education and research on regenerative agricultural practices to help address gaps in evidence, the development of an outcome-based framework, and to encourage R&D.

# Appendix I

# Comparing definitions of regenerative agriculture

Building on recent similar analyses and reviews,[178] we a) compare different definitions of regenerative agriculture in the academic literature, b) map how the term is used by various stakeholders, and c) compare the term to others often used, such as sustainable agriculture or agroecology.

## a Definitions of regenerative agriculture

Interpretations and definitions of regenerative agriculture variously comprise principles/practices and outcomes. The literature review (Table 4) shows that some definitions are centred around "a system of principles and practices" and that these overarching principles and set of "good agricultural practices" remain integral to conventional farming.[179] These practices can be defined as the inclusion of an activity, such as cover crops or crop rotation, or by the exclusion of an activity, soil tillage or use of synthetic inputs.[180] The same literature also lists various outcome implications (Table 4).

On the other hand, some proponents of the term focus on the benefits of regenerative agriculture. Most importantly, advocates argue that regenerative principles and practices can move agriculture from being "non-degrading" to being "enhancing" relative to current agriculture, which quite literately sets the term apart from conservation agriculture and sustainable agriculture.

## TABLE 4: AN OVERVIEW OF THE TERM "REGENERATIVE AGRICULTURE" COVERED BY ACADEMIC LITERATURE

| Definitions | Burgess et al. (2019)[181] | Schreefel et al. (2020)[182] | Newton et al. (2020)[183] | Giller et al. (2021)[184] |
|---|---|---|---|---|
| **Principle and practice-oriented definitions** | 1. Abandoning tillage<br>2. Eliminating bare soil<br>3. Fostering plant diversity<br>4. Encouraging water percolation into the soil<br>5. Integrating livestock and cropping operations | 1. Minimizing external inputs<br>2. Mixed farming<br>3. Minimizing tillage<br>4. Crop rotation<br>5. Use of manure and compost<br>6. Other soil activities that are not captured above | Processes which were found in > than 10% of academic literature reviewed:<br>1. No or low external inputs and the utility of on-farm inputs (26% of 229 papers)<br>2. The integration of livestock (19%)<br>3. Not using synthetic fertilizers (12%) or pesticides (12%)<br>4. Reducing or eliminating tillage (12%) | Did not propose a definition but explains that many practices associated with regenerative agriculture, including crop rotations, cover crops, and livestock integration, are generally (or in some contexts) considered to be "Good Agricultural Practice and remain integral to conventional farming" |
| **Outcome-oriented definitions** | 1. Enhancement of existing agriculture<br>2. Restoring and regenerating soil health and ecosystem functionality | 1. Identified thirteen thematic objectives in academic studies – mostly environmental, and again the most commonly stated relating to soil health<br>2. Identified to a lesser extent thematic objectives along the three dimensions of sustainability: people, planet, and profit | Outcomes that were found in > than 15% of academic literature reviewed:<br>1. To improve soil health (41%)<br>2. To increase biodiversity (21.5%)<br>3. To sequester carbon (17%)<br>4. To improve ecosystem health (17.4%)<br>5. To improve the social and/or economic wellbeing of communities (17.4%)<br>6. To increase farm profitability (15.7%) | 1. Restoration of soil health, including the capture of carbon (C) to mitigate climate change<br>2. Reversal of biodiversity loss |

### (b) Use of regenerative agriculture by various stakeholders

The practices most frequently mentioned by other practitioners differ from the literature. Table 5 presents practices and principles covering other practitioners that we reviewed. Different from academic papers reviewed by Newton (2020), the most commonly mentioned practices here include reducing or eliminating tillage (41%), the integration of livestock (41%), and the use of cover crops (31%).

It is important to emphasize that the selection of suitable good practices must be in accordance with the initial starting points defined by local context, farming systems and operational scale. Additionally, trade-offs between different farming practices may sometimes exist. For instance, replacing mineral fertilizers with animal manures can help build soil carbon, but the associated higher $N_2O$ emissions may offset the mitigation gains of soil sequestration.[185,186] Recognizing the co-benefits and trade-offs of different regenerative practices are extremely important for assessing the outcomes of regenerative agriculture, avoiding exaggerated claims of certain practices, and reducing the risks of greenwashing.

**TABLE 5: PRINCIPLES AND PRACTICES COVERING ACADEMIC LITERATURE, PRACTITIONERS AND OTHER STAKEHOLDERS**

## What practices and principles are commonly associated with "regenerative agriculture"?

| Management practices \ Organization or author | Reduce or eliminate soil tillage | Permanent soil cover with cover crops/ minimize bare ground | Crop rotation and divers-ification | Increase water percolation/ water resource management principles | Integrating animals | Green manures | Add compost | Avoiding or eliminating synthetic inputs |
|---|---|---|---|---|---|---|---|---|
| Cal State University | ✓ | ✓ | ✓ | ✓ | ✓ | | | minimize |
| Project Drawdown | ✓ | ✓ | ✓ | | | ✓ | ✓ | ✓ |
| Gabe Brown | ✓ | ✓ | ✓ | ✓ | ✓ | | | ✓ |
| Rodale Institute | ✓ | ✓ | ✓ | ✓ | ✓ | | | |
| Danone | ✓ | ✓ | ✓ | ✓ | | | | ✓ |
| General Mills | ✓ | ✓ | ✓ | ✓ | | | | |
| OP2B | ✓ | ✓ | ✓ | ✓ | | | | |
| Ikea Foundation | ✓ | ✓ | ✓ | ✓ | | | ✓ | |

In this case, practitioners were more aligned on the most mentioned outcomes: improve soil health (86%), sequester carbon (64%), increase biodiversity (46%), improve water resources (46%), and improve the social and/or economic wellbeing of communities (41%). Notwithstanding many positive outcomes, it is clear that many of the outcomes depend a great deal on context. Although broad consensus is that regenerative agriculture can lead to farm income generation, a recent review of the definitions of regenerative agriculture suggests that the majority of definitions focus on outcomes that aim to have positive impacts on nature and farming systems (Newton et al. 2020)[187] and only a few are placing an equal emphasis on socio-economic dimensions. However, emphasis on socio-economic factors is central to some definitions in wider civil society and if agroecology is included in the assessment, there is a greater emphasis on socio-economic dimensions.

Outside of academia, considering regenerative agriculture to be defined by outcomes is as common as defining it by principles and practices. In our review of 44 definitions (Table 6) of the term used by business, civil society, and philanthropy, 61% of organizations used a framework of outcomes or objectives. Within these, the most common were related to improving soil health, improving biodiversity, and reducing GHG emissions or sequestering carbon. Following this, improved freshwater usage, enhanced livelihoods for growers, increased resilience in agricultural systems, and improved yields or productivity were also mentioned by many. Some organizations go as far as to include concepts not found more widely, such as enhancements to ecosystem services or even improvements to nutrient density of food.[188,189] **It is worth noting that most organizations identifying improved soil health as an**

**outcome do not detail what this entails, and for the few that do it is solely identified as increasing soil organic matter or soil carbon.**

As Giller[190] states, soil health is ultimately a container concept which needs to be disaggregated to be useful, at least from an agronomic perspective. Some organizations who provide implementation guidance beyond a definition take soil health understanding to this disaggregated level. For instance, Unilever[191] states that soil health is a measure of soil organic matter, microbial biomass activity and diversity, pH and soil nutrient status, and soil structural stability. In order for these granular soil health outcomes to be robust, and ascertain whether soil is regenerating, it requires a clear baseline measurement and monitoring at a farm level. The absence of this level of detail in some outcome-based definitions of regenerative agriculture can and has become a potential source of criticism.

**TABLE 6: OUTCOMES COVERING PRACTITIONERS AND OTHER STAKEHOLDERS**

## What outcomes are commonly associated with "regenerative agriculture"?

| Outcomes \ Organization or author | Enhanced ecosystem services | GHG emission reduction | Improved biodiversity | Improved livelihoods | Improved freshwater use and oceans | Improved productivity | Improved ag system resilience | Improved soil health |
|---|---|---|---|---|---|---|---|---|
| Cal State University | ✓ | ✓ | ✓ | | ✓ | | | ✓ |
| Rodale Institute | | | | | | ✓ | | ✓ |
| IPCC | | | | | | | ✓ | |
| General Mills | ✓ | | ✓ | ✓ | | | | |
| Unilever | | ✓ | ✓ | ✓ | ✓ | | | ✓ |
| Pepsico | | ✓ | ✓ | ✓ | ✓ | | | ✓ |
| Ikea Foundation | | | | ✓ | | ✓ | ✓ | ✓ |
| Soil Health Institute | | ✓ | ✓ | | ✓ | ✓ | | ✓ |

## ⓒ Comparison to other related terms

Practitioners become sceptical of regenerative agriculture given the lack of a strict definition and concern over how it contributes to system-level outcomes. Specific arguments against the term include:

- Concerns over confusion with other terms (e.g. sustainable agriculture, conservation agriculture) and, therefore, the difficulty for researchers to test attribution of regenerative agriculture to specific outcomes.[192]

- Lack of recognition of initial starting points and local context in farming systems, meaning that regenerative agriculture stays only at a high-level narrative regarding the soil health and biodiversity crisis.[193]

- Disagreement over presenting this as something "new", as many practices are not new but rather based upon Indigenous knowledge and practices, agroecological practices, conservation agriculture, etc.[194]

Additionally, the lack of both agreed scientific definitions and transparency of implementation of regenerative agriculture increases the potential for misuse by food producers and greenwashing.[195,196] It also warrants a review of similar terms and practices related to regenerative agriculture to identify overlaps and divergence – see Table 7.

**TABLE 7: A COMPARISON OF REGENERATIVE AGRICULTURE RELATED TERMS**

# How do "regenerative agriculture" practices relate to other agricultural systems?

| Management practice \ Type of agricul-ture system | Reduce sznthetic inputs | Eliminate synthetic inputs | Reduce or eliminate soil tillage | Permanent soil cover with cover crops | Crop rotation and diversification | Integrating trees (agro-forestry) | Integrating animals | Pay farm workers a living wage |
|---|---|---|---|---|---|---|---|---|
| Regenerative | 🟢 | 🟡 | 🟢 | 🟢 | 🟢 | 🟡 | 🟡 | 🟡 |
| Regenerative organic | | ✓ (other than approved USDA) | ✓ | ✓ | ✓ | ✓ (optional) | ✓ | ✓ |
| Organic | ✓ | ✓ (other than approved USDA) | | | | | | |
| Conservation | | | ✓ | ✓ | ✓ | | | |
| Agroecology | ✓ | | | | ✓ | ✓ | ✓ | ✓ |
| Sustainable | ✓ | | ✓ | ✓ | ✓ | ✓ | | |

🟢 Found in most Regen Ag definitions   🟡 Found in some Regen Ag definitions

First of all, the term "agroecology", with internationally aligned agreement on definition through an organization like FAO, has a broader remit than most definitions of regenerative agriculture. It covers themes not generally considered by regenerative agriculture advocates, such as governance or culture and food traditions. It also covers those which are less prevalent or only implied in regenerative agriculture, such as ecosystem resilience and improving rural livelihoods.[197] However, some principles, such as diversity of species, are well aligned with most definitions of regenerative agriculture, reflected in either practices of regenerative agriculture (crop rotations) or its outcomes (increased biodiversity). Notwithstanding this, some viewpoints consider regenerative agriculture to be one that is the same as "agroecology" and "ecological farming",[198] becoming a source of confusion, especially amongst non-experts in this field.

Secondly, the term "conservation agriculture" also endorsed by FAO, has considerable overlap with definitions of regenerative agriculture that focus on principles and practice.[199] The three principles of "conservation agriculture", minimal tillage, permanent soil cover, and species diversification are well established as regenerative practices. Moreover the stated intended outcomes are to regenerate degraded soils, enhance biodiversity and natural biological processes to increase water and use efficiency, and improve and sustain crop production. FAO states these are universally applicable and can be implemented with locally specific practices.

Thirdly, the term "agroforestry" can be viewed as a form of tree and crop integration as included by some definitions of regenerative agriculture focusing on practices. According to FAO, agroforestry can be interpreted as a distinct agricultural system in its own right, while also delivering outcomes that are expected from regenerative agriculture.

Fourthly, the term "organic agriculture" has many explanations and definitions, but all state that the system relies on ecosystem management rather than external agricultural inputs – more of a process-based definition. It is a system that begins to consider potential environmental and social impacts by eliminating the use of synthetic inputs, such as synthetic fertilizers and pesticides, veterinary drugs, genetically modified seeds and breeds, preservatives, additives and irradiation.[200] Organic farmers must follow strict organic regulations to certify their product as "organic".[201] In comparison, there is not a consensus around regenerative agriculture as to whether external inputs should be phased out entirely, reduced, or simply optimized.

The only certified definition of regenerative agriculture is "regenerative organic agriculture". This certification scheme, launched by the Rodale Institute and managed by the Regenerative Agricultural Alliance focuses on three outcomes: 1) increasing soil organic matter over time and sequestering carbon below and above ground, which could be a tool to mitigate climate change; 2) improving animal welfare; and 3) providing economic stability and fairness for farmers, ranchers, and workers.[202] As suggested in its name, this definition considers regenerative agriculture as an extension of organic farming, and the first requirement for any grower seeking ROC certification is to already have USDA Organic certification, which implies the farmland has already been adhering to at least a three-year period of no use of prohibited chemical inputs. Beyond this, core regenerative practices that are required for certification are vegetative cover for a minimum of 25% of the year, a minimum of three crop rotations in the same area, minimizing tillage (no-till required for Gold standard), and rotational grazing (for livestock operations). Beyond this, operations must demonstrate at least three other regenerative practices, such as agroforestry, mulching, or silvopasture establishment, though this can be site specific.

# Appendix II

# References for Figure 1: How the food system is related to the planetary boundaries


| Box | Reference (in order of appearance in the box) |
| --- | --- |
| **Biodiversity loss (top left)** | 1. Maxwell, S.L. et al. (2016) "Biodiversity: The ravages of guns, nets and bulldozers," Nature, 536(7615), pp. 143–145. Available at: https://doi.org/10.1038/536143a.<br>2. Willige, A. (2019) *75% of crops depend on pollinators - they must be protected, World Economic Forum*. WEF. Available at: https://www.weforum.org/agenda/2019/12/protect-pollinators-food-security-biodiversity-agriculture/#:~:text=Pollinators%20like%20bees%20are%20essential,species%20are%20threatened%20with%20extinction<br>3. Secretariat of the Convention on Biological Diversity (2022) Science briefs on targets, goals and monitoring in support of the post-2020 global biodiversity framework negotiations. 2022. CBD/WG2020/4/INF/2/Rev.2. Available at: https://www.cbd.int/doc/c/c874/6eb7/813f0201cd67299c9eb10a4a/wg2020-04-inf-02-rev-02-en.pdf<br>4. Chapman, A. (2022) Could "lost crops" help us adapt to climate change?, PreventionWeb. Available at: https://www.preventionweb.net/news/could-lost-crops-help-us-adapt-climate-change<br>5. Pastor, A.V. et al. (2013) "Accounting for environmental flow requirements in Global Water Assessments." Available at: https://doi.org/10.5194/hessd-10-14987-2013. |
| **Agriculture is primary cause (middle left)** | 1. Ritchie, H. (2019) *Half of the world's habitable land is used for Agriculture*, Our World in Data. Available at: https://ourworldindata.org/global-land-for-agriculture<br>2. Pendrill, F. et al. (2022) "Disentangling the numbers behind agriculture-driven tropical deforestation," Science, 377(6611). Available at: https://doi.org/10.1126/science.abm9267.<br>3. Symonds, M. (2021) "Amazonia as a carbon source linked to deforestation and climate change.," Faculty Opinions – Post-Publication Peer Review of the Biomedical Literature [Preprint]. Available at: https://doi.org/10.3410/f.740469054.793587177.<br>4. Watts, J. (2017) *Third of Earth's soil is acutely degraded due to agriculture*, The Guardian. Guardian News and Media. Available at: https://www.theguardian.com/environment/2017/sep/12/third-of-earths-soil-acutely-degraded-due-to-agriculture-study#:~:text=A%20third%20of%20the%20planet's,away%20from%20destructively%20intensive%20agriculture<br>5. WWF, IUCN, Birdlife, SER, TNC and CGIAR. (2022) *Briefing note The post-2020 Global Biodiversity Framework: Proposal on Target 2 on Ecosystem Restoration*. Available at: https://www.nature.org/content/dam/tnc/nature/en/documents/GBF_Target2_NairobiOEWG_Briefing.pdf |
| **Novel entities (bottom left)** | 1. Asher, C. (2021) *Novel chemical entities: Are we sleepwalking through a planetary boundary?* Mongabay. Available at: https://news.mongabay.com/2021/09/novel-entities-are-we-sleepwalking-through-a-planetary-boundary/<br>2. Asher (2021) Op cit.<br>3. Persson, L. et al. (2022) "Outside the safe operating space of the planetary boundary for novel entities," Environmental Science & Technology, 56(3), pp. 1510–1521. Available at: https://doi.org/10.1021/acs.est.1c04158. |

| | |
|---|---|
| **Current agri practices (top right)** | 1. Hristov, J., Toreti, A., Pérez Domínguez, I. et al. (2020) *Analysis of climate change impacts on EU agriculture by 2050*, Publications Office of the European Union. Available at: https://data.europa.eu/doi/10.2760/121115<br>2. Roe, S. et al. (2019) "Contribution of the land sector to a 1.5 °C world," Nature Climate Change, 9(11), pp. 817–828. Available at: https://doi.org/10.1038/s41558-019-0591- |
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| **The agri sector is linked to health and social issues (right and third-down)** | 1. The Food and Land Use Coalition (no date) Business & Sustainable Development Commission (BSDC). Available at: http://businesscommission.org/our-work/the-food-and-land-use-coalition<br>2. FOLU (2019) Op cit.<br>3. Spector, T. et al. (2020) "Microbiome signatures of nutrients, foods and dietary patterns: Potential for personalized nutrition from the predict 1 study," Current Developments in Nutrition, 4 (Supplement_2), pp. 1587–1587. Available at: https://doi.org/10.1093/cdn/nzaa062_04 |
| **Chemical agri fertilizers (bottom right)** | 1. World Resources Institute (n.d.) *Eutrophication and Hypoxia* Available at: https://www.wri.org/initiatives/eutrophication-and-hypoxia/learn<br>2. Dunne, D. (2020) Nitrogen fertiliser use could 'threaten global climate goals', Carbon Brief. Available at: https://www.carbonbrief.org/nitrogen-fertiliser-use-could-threaten-global-climate-goals/#:~:text=Published%20in%20Nature%2C%20the%20results,major%20role%20in%20the%20uptick. |

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