Business guidance *for deeper regeneration*

→ *Regenerative Agriculture Metrics: Soil chapter*

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01. Soil context

1.1 Soil health

The focus on soil health in many regenerative agricultural initiatives is reflective of the importance of soils for the provision of many ecosystem functions. Soil health is often defined as the continued capacity of soil to function as a vital living ecosystem that sustains plants, animals and humans.[1]

Soil health widely describes a range of factors and outcomes. Soil is a complex mix of both biotic and abiotic components, a vital component of ecosystems that provides a range of functions in the agricultural landscape.

Historically, soil has received less study relative to its importance but companies are making rapid progress in understanding the soil microbiome and its ecological functioning, particularly in agroecosystems.[2,3] Key functions include ensuring sustainable plant production in agricultural systems through the provision and creation of healthy soils, regulating water quality by acting as both a source and sink of pollutants, carbon sequestration through soil organic matter content and even benefits to human health.[4]

Managing soils for the provision of these services can be challenging, involving trade-offs and synergies between maximizing different services. Farms could take several measures to increase nutrient availability to improve the productivity of soils for crop production, but this could lead to a loss of other important components of soil health, such as soil biodiversity or soil structure.[5] Alternatively, increasing some components of soil health can feed back into other components. For example, increasing soil organic carbon content can achieve water retention and reduce the weight of soil in a given volume (bulk density), an indicator of soil compaction.[6,7]

Measuring soil health can broadly include physical, chemical and biological components (Figure 1).[8] Measures of soil quality have often focused on chemical indicators that correlate with soil functions such as nutrient availability, cation exchange capacity, soil toxin levels and soil organic carbon (SOC).[9] For example, reviews of the impact of SOC indicate increases in productivity across different crop types.[10,11]

Other indicators of soil health look at the physical structure of soils (e.g., bulk density, infiltration rate). Measures of physical structure provide important information on water movement through soils and the conditions necessary for plant growth and minimizing erosion.[12] Biological indicators of soil health can include metrics associated with micro- (e.g., microbial activity), meso- (e.g., nematodes, mites) and macro-fauna diversity (e.g., earthworms). Soil biodiversity can be an important determinant of soil functions, yet assessments of soil health often overlook them and are highly variable by geographic and ecological context. For example, studies often measure microbial activity and diversity as a component of soil health although they can be important contributors to enhanced decomposition, nutrient mineralization and nitrogen fixation.[13] Similarly, the presence of macroinvertebrates in the soil can lead to a range of benefits to ecosystem functions in some contexts.[14]

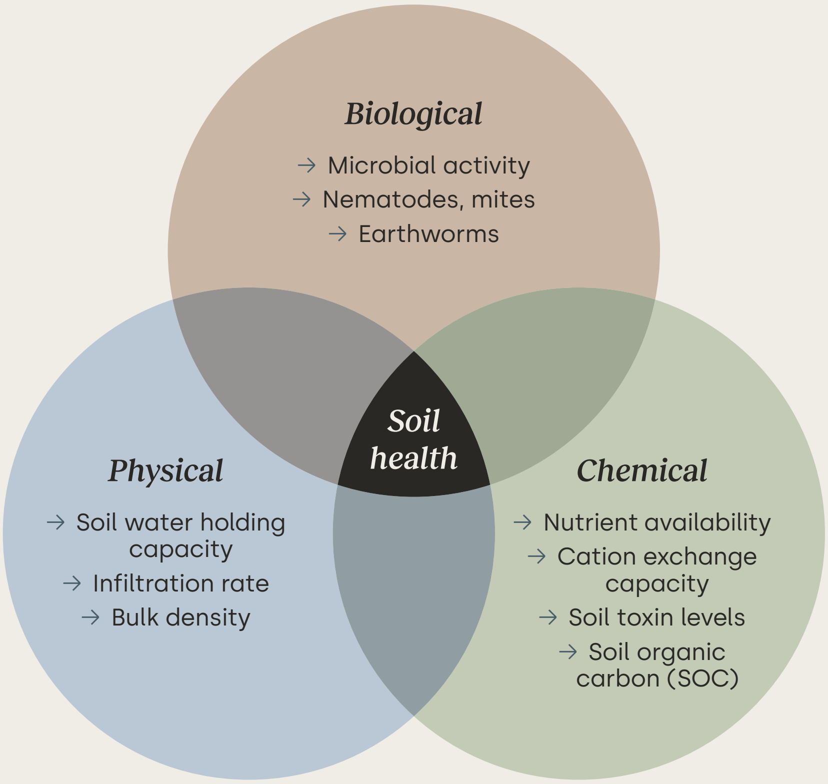
Collectively, measures of chemical, physical and biological components can provide an overview of the health of soils relative to reference states.

OP2B's working definition of regenerative agriculture

Related to agroecological evidence and principles, regenerative agriculture is a holistic, outcome-based farming approach that generates agricultural products while measurably having net-positive impacts on soil health, biodiversity, climate, water resources and farming livelihoods at the farm and landscape levels. It aims to simultaneously promote above- and belowground carbon sequestration, reduce greenhouse gas (GHG) emissions, protect and enhance biodiversity in and around farms, improve water retention in soil, reduce pesticide risk, improve nutrient-use efficiency and improve farming livelihoods.

Figure 1: Measures of chemical, physical and biological components can provide an overview of the health of soils

Figure adapted from Bayer, 2017



1.2 Soil context and complexity

Soils vary substantially across different geographies, ecological contexts and agricultural systems. The formation and types of soils that emerge depend on parent material (rock types, weathering processes), topology/elevation, climate (precipitation, temperatures), biodiversity in the region and timeframes.[16] These factors combine to create diverse soil types in their physical, chemical and biological properties.

These soil types and geographies correspond to large differences in soil chemistry and physical structure. For example, one study shows that soil organic carbon content varies even with sandy soil types globally, with the highest levels occurring in temperate and colder zone sandy soils and lower levels in arid areas. Soil biodiversity varies geographically. Some studies use earthworm abundance and presence as an indicator of soil health and functioning.[17] However, the richness and abundance of earthworm species varies geographically,[18] meaning their occurrence in different regions does not always correspond to similar changes in soil health. Indeed, in some areas they are invasive species and may correlate with decreases in soil function.

For many agroecosystems there is often poor knowledge of soil parameters. For example, there are large gaps in understanding soil biodiversity. Information is limited for many geographies and groups of species leading to limited understanding of how soil biodiversity links to different functions.[19] There is also a lack of standardized metrics for measuring soil biodiversity and metrics that aggregate a range of different taxa and species. Each provide different services and disservices in agricultural settings and thus can be hard to interpret (e.g., microbial biomass).[20,21]

These complexities mean that while there is broad agreement on the components of soil health that it is possible to measure (e.g., physical, chemical, biological), there are many different metrics that studies can use and it can be challenging to define universal metrics for assessing soil health that are applicable globally and across different contexts (i.e., the most applicable indicators may differ depending on contexts). The challenges in collecting much of this information compounds this as they currently require costly field collection and laboratory analysis for many indicators.

However, there may be some indicators that are more universally applicable across contexts but where the reference levels and appropriate thresholds will differ by geography and ecological zones. Studies often see SOC as a more widely applicable indicator of soil health – due to its correlation with many soil functions across contexts – but benchmark levels can differ by soil type, management and agroecosystem.[22] In contrast, the most relevant biological indicators are likely to differ by context, requiring a more flexible approach to indicator selection.[23]

1.3 The impacts of agriculture on soils

Global food demand is expected to increase by 25-70% by 2050.[24,25,26] This will require balancing increasing yields to spare land for nature[27,28,29] and managing the substantial negative externalities of a global agriculture system.[30]

Some farming practices can have severe detrimental effects on the health of soils. Though most forms of agriculture require some level of soil disturbance, excessive soil disturbance, vegetation removal and exposure of bare soils have led to widespread soil erosion and degradation. Over long time periods this can reduce the functioning of the system and agricultural production.[31] Risks of soil erosion are particularly high in some soil types and geographical contexts. Globally, soil erosion is a major impact from agricultural production, with rates of erosion potentially increasing globally and influenced by political and contexts.[32,33]

Practices can also influence the quality of the remaining soils by influencing their physical structure, biological and chemical health. For example, a mechanical disturbance of the soil can detrimentally impact soil biodiversity and physical structure. A recent global review indicates that agricultural land management usually leads to a significant decrease in SOC content.[34] Similarly, in the EU an assessment of bulk density – a key indicator of physical structure – indicates that land-use type was the biggest driver of variation in bulk density, with croplands having a 1.5 times higher bulk density than woodlands.[35]

The use of agricultural chemicals and pesticides can cause a risk to soil health as pesticides and toxins can accumulate in the soils over time. Pesticides may include insecticides, herbicides and fungicides. Most global pesticide use is for increasing crop production. A large variety of substances (both biological and chemical) can be involved, varying in their effects on targets, environmental toxicity, persistence and potential for bioaccumulation. Other pollutants linked with agricultural activity include pharmaceuticals and hormones used in livestock production.[36] The accumulation of pesticides and other pollutants in groundwater, surface water and soils can lead to detrimental environmental and human health impacts.[37] Note that the chapter on biodiversity includes metrics and guidance supporting the "reduced pesticides risk" outcome of regenerative agriculture.

Overall, modern agricultural practices can be detrimental to multiple components of soil health and companies need to take measures to mitigate these impacts.

1.4 Potential benefits of regenerative agriculture for soil-related outcomes

Many actions and processes associated with regenerative agriculture can lead to significant improvements in measurable soil-related outcomes and, consequently, to soil health overall. Improvements in soil health can result in the enhancement of ecosystem functioning[38] and resilient agricultural production,[39] as well as (in some cases) increases in yields.[40]

Reduced erosion

Some practices achieve reductions in soil losses by taking actions to reduce the potential for erosion and increase levels of soil aggregation.[41] Such actions include reducing tillage,[42] planting cover crops[43] and intercropping.[44] At the same time, the use of organic amendments may increase soil aggregation.[45] These practices can also improve the water infiltration rate and holding capacity of soils,[46] reducing the potential for erosion.

Reduced pollution

Studies show possible reduction in pollution from agriculture by reducing the overapplication of chemical fertilizers and pesticides, replacing these with organic amendments and improving agricultural practices to prevent the loss of these chemicals.[47] Riparian buffers can increase the efficiency of fertilizer use by reducing nutrient runoff in many contexts.[48] The implementation of integrated pest management techniques[49,50] can reduce the risk of pesticide pollution accumulating in soil from excessive application. The implementation of crop rotation can reduce pesticide requirements.[51] Many contexts have shown that reductions in tillage maintain soil quality and fertility.[52] Yet fertility and fertilizer requirements following no-till implementation can be highly variable.[53,54,55,56]

Improved soil biodiversity

Many regenerative agriculture practices can lead to increased levels of soil biodiversity, both invertebrate and microbial. In croplands, increasing the diversity of crop species, establishing crop rotation systems, cover crops for annual crops and establishing intercropping for perennial and annual crops are all associated with increased levels of soil biodiversity,[57,58] as is a reduction in pesticide risk.[59] Increasing areas of natural, semi-natural or restored habitats within a cropland matrix, as well as connecting these habitats, increasing land-use efficiency and increasing numbers of on-farm trees can also increase biodiversity in some contexts.[60,61,62] Note that the chapter on biodiversity discusses these actions and their predicted impacts in more detail.

Measuring and reporting progress on regenerative agriculture at a company level

One of the major challenges for companies is to credibly and transparently demonstrate their progress on regenerative agriculture. To do so, companies typically measure progress either in terms of surfaces transitioned to regenerative agriculture (e.g., 30% of the sourcing regions converted to regenerative agriculture by 2030) or in terms of the share of ingredients sourced from regenerative agriculture (e.g., 30% of ingredients sourced through regenerative agriculture by 2030).

Reporting progress on regenerative agriculture needs to compare many nature-related indicators and metrics against the locally relevant context. Companies can do this by characterizing and substantiating the local context and practices of the current farming system that regenerative agriculture hopes to transition for better outcomes. The challenge to tackle for many soil-related indicators is having a baseline from which to transition and reporting outcomes based on the baseline system and a reference level indicative of healthy, resilient soils in that context. Companies will achieve the changes by changing practices that will vary by farm, while the common unit for reporting will be outcome metrics.

It is critical to measure the outcomes of regenerative agriculture using a holistic approach that considers environmental, social and economic outcomes to ensure a complete picture of the impacts.

Climate and carbon sequestration benefits

Agriculture typically results in a decrease in soil organic carbon content.[63] Regenerative agricultural practices, in particular organic amendments, conservation tillage, agroforestry practices and crop diversification lead to increases in SOC in croplands.[64] Contributing to climate change mitigation and wider environmental benefits, though these effects are not universal.[65,66,67,68] Cover-crop establishment may require at least five years from initiation before obtaining significant positive impacts.[69] In grasslands, grazing can have negative effects on SOC while agroforestry and organic amendments again have positive effects.[70] Nitrogen application can increase SOC sequestration and the application of manure may achieve this more effectively than with equivalent inorganic fertilizer.[71,72,73]

Interconnectivity between soil and water

Many regenerative agricultural practices can contribute to multiple beneficial outcomes, providing useful synergies for implementers and contributing to improved soil health overall. Many practices can benefit other outcomes of interest, such as water. Implementers should consider that there can be a strong bias in the evidence base for many interventions towards certain regions,[74,75] types of ecosystem(s) and land use. Interventions can have a mix of impacts with expected improvements being highly context dependent. Companies should therefore take measures tailored to local contexts and informed by scientific literature.

Key indicators and *metrics for soil health*

02.

02. Key indicators and metrics for soil health

2.1 Soil sub-group on corporate metrics for regenerative agriculture

As part of the Regenerative Agriculture Metrics (RAM) workstream, the soil sub-group convened technical experts from 22 member and partner organizations. The objective of this sub-group was to identify alignment on indicators and metrics to support the soil-related outcomes of regenerative agriculture and identify remaining gaps and challenges to implementation. This soil guidance follows WBCSD's **climate** and **water** guidance already published.

This chapter brings together the work thus far, accounting for existing metrics and those considered specific to soil, holistically. For example, increased soil health and reduced pesticide risk can contribute to improved water outcomes. Similarly, improvements in environmental flows and water quality can support positive biodiversity outcomes. We also cover how all environmental outcomes can ultimately affect farmer livelihoods and health outcomes.

2.2 State, pressure, response framework

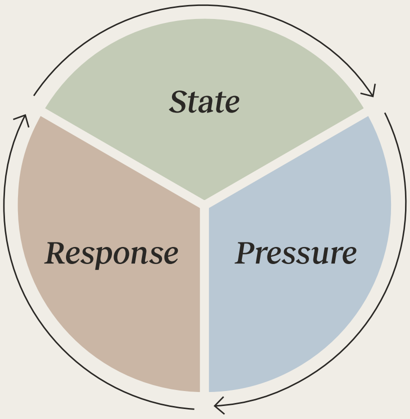
Companies and farmers often use the state, pressure, response framework (Figure 2) to help define indicators and associated metrics to measure impacts on the environment. Metrics of state are often the most reliable; however, they can be difficult to collect or attribute to company action and may be slower to change than response or pressure indicators. Thus, it is also possible to measure pressures that are influencing parameters or the responses that can reduce pressures or restore nature. Companies can use pressure metrics where there is a strong evidence base linking pressures to changes in the environmental parameters of interest. Response metrics can provide guardrails to ensure companies meet outcomes in a scientifically-rigorous manner. This workstream, however, focuses on state and pressure metrics.

State: Direct state of the environment in (i) the state of ecosystems (extent and condition), (ii) species (abundance and extinction risk) and (iii) ecosystem services (or the state of nature's contribution to people).

Pressure: Human activities that directly or indirectly change the state of the environment and ecosystem.

Response: Actions taken by companies or farmers to address pressures or to improve the state of nature on farmed land.

Figure 2: **State, pressure, response framework for soil-related metrics**



Outcome: Increased soil health

Component: Biological health

Component: Physical health

Soil macro-invertebrate species richness and abundance

Soil bulk density

Pesticide risk: Environmental Impact Quotient field use ratings

Percentage of farmed land with cover crops (%)

Percentage of farmed land with no tillage agriculture (%)

2.3 The process

Increased soil health was defined by the group as the single soil-related outcome for regenerative agriculture.

Framework mapping and criteria assessment

To align the outcomes and metrics with existing corporate reporting requirements, we conducted:

- a review of soil-related metrics included in relevant standards and frameworks (see **Annex C, Table 8**) and
- an assessment of a subset of the most aligned metrics across these frameworks against criteria to determine their scientific evidence base, ease of measurement, affordability, accessibility and applicability (see **Table 4**).

First, we screened various frameworks for measuring soil health including regenerative agriculture frameworks and tools, corporate sustainability and nature assessment (see **Table 9**) and target-setting and disclosure approaches. We then reviewed some leading frameworks used in legislation regarding soil health (e.g., EU Soil Law) and recommended metrics in the academic literature. These include:

- Sustainability frameworks: Taskforce on Nature-related Financial Disclosures (TNFD) Food & Agriculture Sector Guidance, Science Based Targets Network (SBTN), CDP, Global Reporting Initiative (GRI), International Sustainability Standards Board (ISSB) and the EU Corporate Sustainability Reporting Directive (CSRD);
- Regenerative agriculture frameworks: One Planet Business for Biodiversity (OP2B), Regen10 Outcomes framework v0, Sustainable Agriculture Initiative (SAI) Platform, Field to Market, Cool Farm Tool, Sustainable Markets Initiative and Textile Exchange.

The mapping exercise highlighted points of agreement and divergence among the frameworks. The review identified a large diversity of soil-related metrics aimed at measuring responses, pressures or the state of soil health.

There was limited alignment across frameworks on the majority of metrics and indicators (see full results in **Annex C**). However, when we grouped these metrics into the different components of soil health, we identified more alignment (**Table 7**). **Table 2** shows the results of the alignment mapping for a sub-set of metrics and indicators that showed the greatest alignment between frameworks.

Annex B provides the full mapping showing limited alignment for the most specific metrics and indicators – although it notes a few exceptions, such as soil organic carbon.

2.4 Recommendations for measuring soil outcomes of regenerative agriculture

To measure the increased soil health, the soil sub-group recommends three components of soil health to measure alongside key pressures. All of which are important in measuring the success of regenerative agriculture:

- Biological soil health
- Physical soil health
- Chemical soil health
- Pressures (e.g., fertilizer, pesticide, soil erosion)

We identified several indicators and metrics to measure these components. However, the group also acknowledges substantial challenges associated with the context specificity of soil health. Thus, we recommend the measurement of all these components using metrics and methods suited to the context.

Noting large differences in baseline and threshold levels between soil contexts, the following indicators and possible metrics support measurement aimed at increased soil health outcomes and are able to support the indication of improvement in the main pressures of agriculture on soil resources in many contexts (**Table 1**). Further details on their maturity are available in **Annex B**.

In addition, we recognize connectivity between the **climate**, **water** and biodiversity chapters and their relevance to soil health.

Table 1: Recommended soil components and possible metrics – June 2024

Pink text: Relevant soil health-related metrics recommended as **core** in other chapters.
Orange text: Relevant soil health-related metrics recommended as **additional** in other chapters.

Key indicators and metrics for soil health

Outcome	Type	Component	Important indicators in many contexts	Possible metrics	Rationale
Increased soil health	State	Soil health – physical	**Green water**	**Soil water holding capacity (%)**	Widely acknowledged that physical health and structure of soil is important in measurement. Agriculture can cause the loss of soil structure and compaction. However, relevant metrics, thresholds and baselines will differ by context, with limited alignment on globally applicable metrics that are feasibly collected. Bulk density, infiltration rate and green water availability are often used emerging indicators.
			Infiltration rate	mm/hr	
			Bulk density	Dry weight of soil in a given volume, g/cm^3	
		Soil health – chemical	**Soil organic carbon**	**MT CO$_2$e total** (included under soil carbon sequestration indicator in climate guidance)	Soil organic carbon was the most aligned metric in our analysis, being a relevant indicator across a range of contexts and required in many frameworks and initiatives. In addition to organic carbon content in soils, it is important to measure other aspects of chemical soil health (e.g., plant-available nutrients, soil toxins) where there is emerging alignment on indicators. However, relevant indicators, metrics, thresholds and baselines will likely differ by context, with substantial challenges associated with many metrics when applied across contexts.
				SOC/area or metric tons of carbon/ha	
				% organic carbon content	
			Level of availability of soil nutrients to plants	Amount (mg/kg) of plant available macro/micronutrient in soil sample (N, P, K, SOM)	
		Soil health – biological	**Soil invertebrate diversity**	Species richness and abundance of macroinvertebrates (incl. earthworms where relevant).	The biological health of soils is vitally important in improving ecosystem functions and productivity, yet there is currently little consensus on metrics that are useful and feasible to apply across contexts. Soil biodiversity is highly context specific, differs by soil type and is often poorly understood compared to above-ground biodiversity.
			Soil microbial diversity	Microbial biomass	
				DNA-based metrics	
		Soil erosion	**Soil erosion**	Metric tons/ha	Soil erosion is a key threatening process to soils in agricultural systems. Regenerative practices aim to increase soil health and reduce unsustainable rates of soil erosion. Methods exist to measure soil erosion quantitatively but can be challenging and costly to apply at scale or have high uncertainties associated with measurement.
				% bare ground cover	

Table 2: Existing metrics with connectivity to soil health

Pink text: Relevant soil health-related metrics recommended as **core** in other chapters.
Orange text: Relevant soil health-related metrics recommended as **additional** in other chapters.

Key indicators and metrics for soil health

Outcome	Type	Component	Indicator	Metrics	Rationale
Minimized water pollution	Pressure	Nitrogen & Phosphorus	**Nutrient loss**	**Nutrient Use Efficiency (NUE) %**	Water metrics link – a recommended core metric in water guidance. Excessive use of nutrient inputs can have detrimental impacts on some aspects of soil health.
Reduced pesticide risk		Pesticides	**Pesticide risk**	**Environmental Impact Quotient (EIQ) – Ecological component field-use ratings**	Biodiversity metrics link – recommended core metric in biodiversity guidance. Key pressure on soil health as pesticides can accumulate in the soil and be a risk to soil biodiversity.
Increased sequestered above- and below- ground carbon	State	Soil health – chemical	**Soil carbon sequestration**	**Total soil sequestration (MT CO$_2$e total)**	Climate metrics link – recommended core metric in climate guidance. Highly related to the soil organic carbon indicator in table above.
Improved environmental flows		Soil health – physical	**Green water**	**Soil water holding capacity (%)**	Water metrics link – additional metric in the water guidance. The water holding capacity of the soil is an important indicator of soil physical structure and related to soil functions and productivity.

Table 3: **A subset of the indicators and metrics for each component required for reporting under various regenerative agriculture related frameworks**

	Component	Indicator	Metric	Regen ag frameworks						
				Cool Farm Tool	Field to Market	OP2B	Regen10	SAI	Sustainable Markets Initiative	Textile Exchange
Outcome: Increased soil health	**Pressure – N & P**	Fertilizer use	Nutrient use efficiency (NUE)			🟩	🟫			🟩
	Pressure – pesticides	Pesticide use	Environmental impact quotient (EIQ)			🟩	🟩			🟩
	Soil erosion	Structural health of soil	# visual erosion signs (based on Sustainable Soils Alliance categories);				🟩			
		Soil conservation metric	Soil per acre lost to erosion from water and wind (t); tons/area		🟩					
		Soil erosion from water and wind	Metric tons/area					🟩		
	Soil health – physical	Green water	Soil water holding capacity m^3/m^3; % of volume of water/volume of saturated soil					🟩		
		Infiltration rates	mm/hr				🟩	🟩		
		Bulk density	Dry weight of soil in a given volume, g/cm3							🟩
	Soil health – chemical	Carbon sequestration	$MTCO_2eq$/area				🟫	🟩		
		Soil organic carbon (SOC)	SOC/area; metric tons of carbon/ha	🟦		🟩	🟫	🟩	🟩	🟩
		Agriculture soil carbon	Gross metric tonnage of carbon dioxide equivalent per year (Gt CO_2e/yr)							
		Level & availability of soil nutrients to plants	Amount (mg/kg) of macro/micronutrient in soil sample (N, P, K, soil organic matter (SOM))				🟩			🟩
		Level of soil pollution (soil toxins)	Amount of soil toxins copper, cadmium, zinc (requires additional soil testing and therefore incurs extra cost. EU Law: As, Sb, Cd, Co, Cu, Hg, Pb, Ni, Tl, V, Zn (μg per kg)				🟩			
	Soil health – biological	Soil invertebrate diversity	Presence of invertebrates				🟩			🟫
		Soil microbial diversity	Microbial molecular biomass							
			Soil microbial diversity							🟫
			DNA-based metrics							

🟩 Metric included

🟫 Companies must measure the indicator (e.g., soil organic carbon) but there is ambiguity on specific metric (e.g., SOC/area; metric tons of carbon/ha)

🟦 Based on geospatial layer

Table 4: A subset of the indicators and metrics for each component required for reporting under key sustainability initiatives and reporting frameworks

	Component	Indicator	Metric	Sustainability frameworks							EU		Literature	
				CSRD	GRI	TNFD	SBTi FLAG	SBTN	GHG SLR	FAO	EU Soil Law	LUSAS[76]	Bagnall et al. 2023[77]	Calvaruso et al. 2021[78]
Outcome: Increased soil health	**Pressure – N & P**	Fertilizer use	Nutrient use efficiency (NUE)			🟩				🟫				
	Pressure – pesticides	Pesticide use	Environmental impact quotient (EIQ)							🟫				
	Soil erosion	Structural health of soil	# visual erosion signs (based on Sustainable Soils Alliance categories);							🟫				
		Soil conservation metric	Soil per acre lost to erosion from water and wind (t); tons/area											
		Soil erosion from water and wind	Metric tons/area				🟫	🟫		🟫	🟩			
	Soil health – physical	Green water	Soil water holding capacity m^3/m^3; % of volume of water/volume of saturated soil							🟫	🟩		🟫	🟫
		Infiltration rates	mm/hr							🟫				🟫
		Bulk density	Dry weight of soil in a given volume, g/cm3										🟫	
	Soil health – chemical	Carbon sequestration	MTCO$_2$eq/area										🟫	🟩
		Soil organic carbon (SOC)	SOC/area; metric tons of carbon/ha					🟫	🟫	🟫	🟩	🟩	🟫	🟩
		Agriculture soil carbon	Gross metric tonnage of carbon dioxide equivalent per year (Gt CO$_2$e/yr)		🟩		🟩							
		Level & availability of soil nutrients to plants	Amount (mg/kg) of macro/micronutrient in soil sample (N, P, K, soil organic matter (SOM))							🟫	🟩		🟫	🟩
		Level of soil pollution (soil toxins)	Amount of soil toxins copper, cadmium, zinc (requires additional soil testing and therefore incurs extra cost. EU Law: As, Sb, Cd, Co, Cu, Hg, Pb, Ni, Tl, V, Zn (µg per kg)							🟫	🟩		🟫	🟫
	Soil health – biological	Soil invertebrate diversity	Presence of invertebrates							🟫				🟫
		Soil microbial diversity	Microbial molecular biomass											🟩
			Soil microbial diversity							🟫				🟫
			DNA-based metrics											

🟩 Metric included

🟫 Companies must measure the indicator (e.g., soil organic carbon) but there is ambiguity on specific metric (e.g., SOC/area; metric tons of carbon/ha)

Table 5: Criteria assessment results for recommended core metrics

	Pressure/ State/ Response	Component	Indicator	Example Metric	Criteria									
					Relevance to objective	Evidence base	Scalability	Generality	Breadth	Potential for Standardization	Potential for target-setting	Feasibility	Potential for gaming	Alignment
Outcome: Increased soil health	Pressure	N & P	**Nutrient loss**	Nutrient use efficiency (NUE)	1	3	2	2	2	3	2	2	2	2
		Pesticide	**Pesticide risk**	Environmental impact quotient (EIQ) field-use ratings	2	2	2	2	1	3	1	2	1	1
	State	Soil erosion	**Soil erosion**	Metric tons/ha	3	1	1	3	2	2	1	1	2	1
		Soil health – physical	**Green water**	Soil water holding capacity	2	2	2	2	2	2	1	1	2	1
			Infiltration rate	mm/hr	2	1	2	3	3	2	1	3	2	1
			Bulk density	Dry weight of soil in a given volume, g/cm^3	2	2	1	3	2	2	2	1	2	2
		Soil health – chemical	**Soil carbon sequestration**	MT CO$_2$e total	3	2	2	3	2	2	2	1	2	1
			Soil organic content	SOC/area or metric tons of carbon/ha	3	3	2	3	2	2	2	1	2	3
			Level & availability of soil nutrients to plants	Amount (mg/kg) of macro/micronutrient in soil sample (N, P, K, SOM)	1	2	2	2	2	2	1	2	0	3
			Soil toxins	Amount of soil toxins copper, cadmium, zinc. EU Law: As, Sb, Cd, Co, Cu, Hg, Pb, Ni, Tl, V, Zn (µg per kg)	2	2	1	1	1	2	1	1	2	2
		Soil health – biological	**Soil invertebrate diversity**	Presence of invertebrates (1 = no signs of invertebrate presence or activity, 3 = a few earthworms and arthropods present, 5 = abundant presence of invertebrate organisms)	2	2	1	1	1	1	1	3	1	1
			Soil microbial diversity	Microbial biomass	2	1	2	2	1	2	1	0	1	1

0	Does not meet the criterion
1	Partially meets the criterion but has limited potential for improvement or some limited challenges/issues
2	Partially meets the criterion and has substantial potential for future improvement or some considerable challenges/issues
3	Fully meets the criterion

For each component of soil health, we took a subset of the most aligned metrics to assess against criteria for metric design (see list of metrics in Table 5). For this exercise, we adapted metric design criteria for the context of regenerative agriculture from TNFD's criteria for assessing state of nature metrics.[79] These criteria address key points related to scientific evidence base, scalability, attribution, practical applicability for companies and potential for misuse of metrics. (Table 3 shows results for the recommended indicators, for criteria description details see Annex D.)

Case Study 1: McCain's Farm of the Future, Canada

McCain Foods is partnering with growers to re-imagine the way it grows potatoes with a commitment to implement regenerative agricultural practices across 100 percent of its potato acreage worldwide by the end of 2030. To do this, they are also supporting growers in optimizing the cost and benefits of the transition to ensure it is viable for the long-term.

The Farms of the Future program is paving the way for the shift from conventional to regenerative farming, ensuring sustainable potato yields while prioritizing soil health, water quality and its efficient use, biodiversity, and climate resilience. Integrating cutting-edge technologies, monitoring, and data-driven decision-making has been a critical priority.

McCain is committed to the operation of three Farms of the Future by 2025; farms used to demonstrate that the implementation of regenerative agriculture not only supports better crop yield and quality but can have significant benefits to farm resilience overall. Their path to progress includes a Regenerative Agriculture Framework, a farmer-centered guide, developed in consultation with growers and other agricultural experts which includes principles, priority practices, and thresholds to capture farming partners progress over time

Progress made in three years

In crop year 2023, the Farm of the Future in New Brunswick achieved five out of seven indicators at an advanced level or higher, showcasing an advanced overall status. They lead in **enhancing crop diversity** and **farm/ecosystem biodiversity** as well as **reducing toxicity of pesticides.** They've advanced in **minimizing soil disturbances, reducing adverse agro-chemical impacts and optimizing water use** and have engaged in **armouring soils and increasing soil organic matter.**

Figure 3: Showcasing progress with McCain's Regenerative Agriculture Framework including seven indicators

Armoured soils, preferably with living plants	The potato fields on the Farm had **living plants for 171 days,** accomplished by underseeding our grains, and applying cover crops following our potato seed bed preparation the previous fall. It is noteworthy that across our non-potato fields, the farm had armoured soils with living roots for the entire year.
Enhanced crop diversity	In total, there were 23 crop species grown, including 12 grasses and eight legumes. These were used mostly in multi-species mixes as underseed or cover crops **showcasing strong potential to increase potato yields while suppressing disease.**
Minimize soil disturbance	By adopting the use of a chisel plow and fall bedding, we **reduced tillage by two events** in the potato crop and embraced no-till practices for more than 50% of the non-potato crops. Deep ripping was used when soil was compacted in the first year before employing control traffic.
Reduced toxicity of pesticides	The Farm has achieved an **Environmental Impact Quotient (EIQ) of 189**, a reduction by 81% in our potato production system compared to 2021. This was accomplished largely due to the use of fewer, less harmful products and well-timed application. While the selection of newer and less harmful chemistry has come with an increased cost, we see a far greater associated reduction in EIQ (71%). Also, we actively reduced this expense through diligent pesticide management.
Enhanced farm and ecosystem biodiversity	**More than a quarter of the farm area (140 of 500 acres) is dedicated to natural habitat,** such as hedgerows and forested areas. In eight of our fields, we have introduced pollinator strips (6.16 acres total), micro ecosystems that attract and encourage pollinating insects. Additionally, we are quantifying the insect biodiversity, including pollinators, using expert taxonomists and DNA metabarcoding.
Reduce agro-chemical impact and optimize water use	All inputs were applied based on Decision Support Systems (e.g. DACOM, petiole testing), like in 2022. We have reduced the application of fertilizers and pesticides across our fields. Compared to other farms in the area, **nitrogen was reduced by 8%,** phosphorus by 40%, and potassium by 53% contributing to our deduction in greenhouse gas emissions. **Innovations like real-time plant nutrient sensing and "see-and-spray" for the precise spot application of pesticides** will further revolutionize our approach, reducing environmental impact while maximizing yields and providing a toolkit for McCain growers.
Increase soil organic matter	Soil health assessments have been completed and will be reassessed annually, including soil biodiversity assessments. **A total of 1,074 soil samples on a 50 m by 50 m grid serve as a baseline for soil physio-chemical properties including 504 biological samples.**

They have introduced several beneficial practices at a commercial scale that collectively enhance soil conditions and reduce environmental impact:

The adoption of cover crops should enhance soil health while reducing erosion.

The chisel plow as a form of conservative tillage before potatoes as well as no till planting of our rotation crops preserves soil structure.

Controlled traffic farming minimizes soil compaction, enhancing water infiltration, thereby increasing yield potential.

Fall bedding prepares soil for early spring planting, improving drainage and temperature control.

Measuring impact on soil health: Intensive soil health assessments have been completed across the 360 cultivated farm acres and will be reassessed annually, including soil biodiversity assessments. A total of 1,074 soil samples on a 50 m by 50 m grid serve as a baseline for soil physio-chemical properties including 504 biological samples resolved using DNA sequencing.

Soils are less compacted overall with cover cropping and reduced tillage demonstrating the potential for increases in soil organic carbon, and subsequently organic matter, enhancing soil health over time.

Efforts on farm are also producing insights on the complex diversity of soil animals, bacteria, and fungi being catalogued with DNA metabarcoding— leveraging biological insights for informed decision-making in sustainable agriculture. In addition, patterns indicate the specific benefits of cropping diversity where, for example, a higher cropping diversity is linked to a more diverse soil ecosystem in soil animals.

Opportunities for *implementation of metrics*

03.

03. Opportunities for the implementation of metrics

3.1 Reporting on practices

Regenerative practices applied within fields, between fields and across wider landscapes can help deliver the ecosystem functions needed to support resilient agricultural production systems. If scaled, they could help to deliver many of the outcomes for biodiversity, water, soil and climate listed above.

Key practices can include:

- Increasing diversity of crop species
- Crop rotations
- Intercropping
- Cover crops/reducing disturbance
- No- or reduced-tillage agriculture
- Conserving, restoring, creating and connecting areas of natural and semi-natural habitat (NSH)
- Buffer and riparian strips of NSH
- Nutrient management planning, 4R Nutrient Stewardship and/or Integrated Nutrient Management Planning
- Reducing overapplication and environmental risk of pesticides, including through integrated pest management (IPM)[80]

According to context, these practices vary in how they promote regenerative outcomes, including how they influence soil health. Alongside outcome metrics, it is useful to report on practices to show how the company is achieving the outcomes. This should include information on management and monitoring measures in place (e.g., % of farms with action plans for priority species or monitoring plans in place).

Reporting on practices informs adaptive management by indicating which practices are succeeding and where the company needs to make changes. There may also be benefits in disclosing practices where farmer incentive schemes (i.e., from downstream companies or banks) report comprehensively.

3.2 Target-setting

Indicators and their associated metrics can provide a basis for corporate target-setting on regenerative agriculture outcomes. Defining targets or thresholds is not in the scope of this guidance chapter but there are numerous resources to help companies define appropriate targets and monitor and disclose progress (outlined below).

Companies along the full agricultural value chain are likely to be developing targets and strategies to address impacts on nature and contribute to global goals for nature recovery (e.g., nature positive).[81] Both regulatory and voluntary corporate sustainability frameworks require (or strongly recommend) that companies set targets related to dependencies, impacts and risks then disclose them and report on progress (e.g., CSRD, TNFD, CDP, GRI, ISSB). While some initiatives do not prescribe how companies should set targets, SBTN details an approach to set science-based targets.

Here are some resources related to soil outcomes are available to help guide target and strategy development:

- ***SBTN Freshwater Guidance*** – Guidance for companies in setting science-based targets for freshwater direct operations and upstream activities. Includes guidance on water use and nutrient pollution target-setting.[83]
- ***SBTN Land Guidance*** – Guidance for companies in setting science-based targets for land including: i) no conversion of natural ecosystems, ii) land footprint reductions and iii) landscape engagement. The landscape engagement targets, in combination with efforts to reduce land footprints, can include engagement with sustainable agricultural practices to improve ecological and social conditions and reduce pressures on soils from traditional agricultural practices.
- ***EU Soil Monitoring Law*** – According to the EU soil strategy, the lack of dedicated EU legislation is a major cause for the state of soils in the bloc. The objective of the directive is to have all soils in a healthy condition by 2050, in line with the EU Zero Pollution ambition.
- ***EU Farm to Fork Strategy*** – The strategy sets out both regulatory and non-regulatory initiatives, with the common agricultural and fisheries policies as key tools to support a just transition. The strategy calls for reducing fertilizer losses by half by 2030.
- ***The UN Convention on Biological Diversity Global Biodiversity Framework*** – includes Target 7 to reduce pollution risks and the negative impact of pollution from all sources, by 2030, to levels that are not harmful to biodiversity and ecosystem functions and services. It provides a guidance and monitoring framework.[84]

Regenerative agriculture can play an important role as part of these strategies helping to reduce risks and minimize the impact of production systems on nature. We recommend the outcomes and metrics presented here for use as part of wider strategies for tracking farm- and landscape-level outcomes from regenerative practices and reporting progress at the corporate scale.

3.3 Remaining gaps and challenges

Improved data for measuring impacts on soil health

There are a range of resources and datasets available to help measure outcomes of regenerative agricultural practices (see **Annex E**). However, there are also large uncertainties and challenges in accessing data on different soil types and farming contexts. For example, there may be limited data on soil biology, particularly in some geographies, as can an understanding of the functions provided by different soil communities.

There is a need for further data and improved techniques for measuring soil health to help inform calculations of impact. Where companies consider direct measurement infeasible, they may use proxy measures as a first step toward more rigorous measurement and reporting.

Building an evidence base for practices

There is often a good evidence base for the outcomes of many regenerative practices on soil quality at a field or farm level. For example, reviews of the impacts of cover crops and reduced tillage on soil health in Mediterranean ecosystems show general beneficial effects on soil organic matter, microbial biomass and nutrient availability.[85]

However, many practices and soil contexts require further information. The research and agri-business communities also need more information to build the evidence base for regenerative practices in different contexts. A solid evidence base for the effectiveness of specific practices is essential when deciding to measure responses instead of pressure or state indicators, which can be more costly and time consuming to assess.

Understanding trade-offs between yield and environmental gains

As highlighted as a key guardrail for the use of these metrics (**Annex D**), it is important to consider yield and production statistics when transitioning to regenerative practices. In some cases, regenerative agriculture may lead to yield increases[86] (possibly more often in the long term than in the short term). However, this is difficult to test given inconsistencies thus far in defining regenerative agriculture.

While agricultural yields continue to increase in most areas of the world, stagnation is occurring in some regions, in particular affecting wheat and rice. Therefore, an understanding of the potential impacts of regenerative agriculture practices on yield is an important research area especially given increasing global demand for food.[87,88,89] This emphasizes again the need for more field references in different contexts. The RAM workstream seeks to align on a holistic set of metrics across environment, social and economic categories.

Interoperability of standards and frameworks

There is a clear need for a high degree of interoperability and connectivity with existing frameworks and platforms, including standards, reporting and disclosure. This work seeks to align and drive the incorporation of regenerative agriculture into these systems to strengthen corporate performance accountability systems for carbon, nature and equity.

Future directions for soil outcomes and current limitations

This guidance outlines a set of components and example indicators and metrics that companies could apply generally across many agricultural contexts to show progress on assessing their impacts on soil health. A standardized set of metrics facilitates consistent measurement, comparisons and aggregation.

However, the great diversity of potential contexts, in relation to a location's ecology, climate, geology, history, target products, management and landscape setting — mean that a one-size-fits-all approach is challenging to implement at present for soils. Different indicators, metrics and baseline/reference levels for different soil health aspects are potentially relevant or might be more practical or robust in specific contexts. The most appropriate indicators in different soil contexts require research to help guide users to identify the most appropriate metrics for their system and the relevant reference values for use for each indicator to set targets.

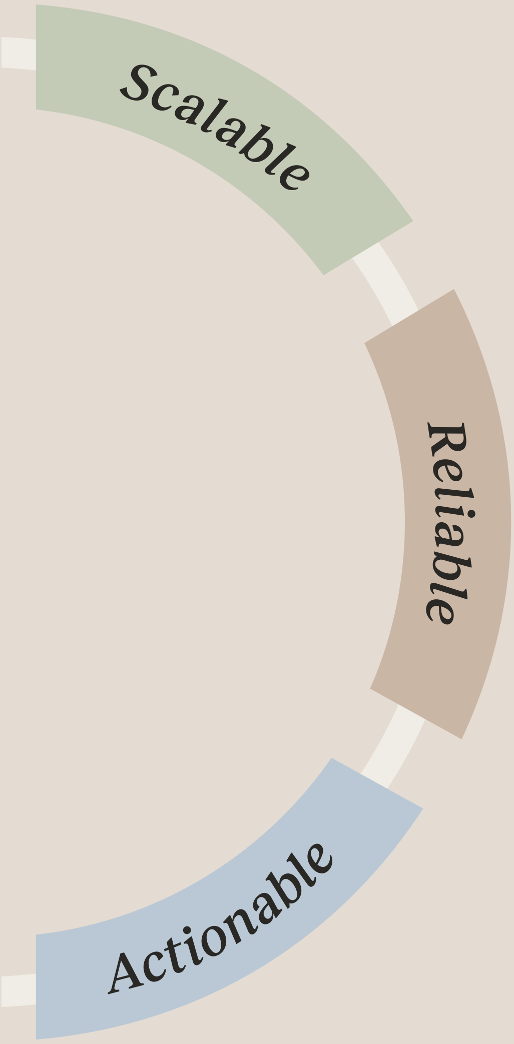
Many of the metrics currently available for measuring impacts on soil health require field sampling to gain robust data. There are often concerns about famer capacity if the burden for sampling falls on individual farms and farmers to collect data. This causes measurements to run into feasibility concerns depending upon how organizations operate in different farming contexts.

While some field sampling may always be necessary, research using earth observation to improve the robustness of modeling approaches and techniques to assess soils remotely could offer promising opportunities to improve the feasibility of measurement. Similarly, new technologies can open important avenues for soil health measurement. For instance, DNA-based techniques for soil health measurement are advancing rapidly and can allow insights into soil biological functions.

Case study 2: Genesis soil health sampling and cost consideration

Measure, monitor and improve the environmental impact of sourcing globally through representative field data.

Genesis is the world's first environmental impact agency based on soil health measurement for bio-based companies. Its methodology ensures real impact assessment at scale, sustainable sourcing and reliable corporate reporting from reliable data. Genesis supports the international industrial transformation of value chains over time for a truly regenerative terrestrial ecosystem.



Scalable: a representative view of global sourcing

Genesis employs a robust statistical approach based on survey methods to identify farms or parcels representative of the global sourcing (country, pedoclimatic context, production modes) for each strategic commodity. These samples of representative plots are subject to soil analysis.

Practical case

Representativity requires 11%. Baseline and monitoring of 90 plots to represent the European soybean supply chain of interest (800 plots, 7200 Ha, 2 production modes).

Reliable: data intelligence as a lever for action

Formulate sourcing specifications and establish achievable targets at a corporate level by correlating practices with their impact on soil health indicators and identifying.

Genesis data is accessible via an **online platform**, making it easy to share throughout organizations and supply chains and to track impact proofs such as Sustainable Development Goals (SDGs), CSRD reporting, hectares regenerated, soil carbon stock monitoring and biodiversity monitoring.

Practical case

Impact 7,200 ha in regeneration (monitoring off carbon storage).

Practical case

Development of a regenerative European soybean supply chain with two main production modes and comparison to traditional supply chains sourced from the US and Brazil.

Actionable: field data collected in situ

Soil health measurements comply with European recommendations and Genesis carries them out anywhere in the world.

For the set of representative parcels identified above, the company monitors soil functions using physical, chemical, pollution and biological indicators resulting from soil sampling analysis. An international network of partners selected by Genesis standardizes sampling protocols and laboratory analyses.

The company approaches external biodiversity through crop diversity, crop rotation, the presence of plant cover and the proportion of natural areas. It monitors these practices over time based on declarations and satellite imagery, along with other history of typical practices (tillage, fertilization, etc.).

Practical case

The company has identified two priority regenerative farming practices for sourcing specification

Next steps to *accelerate the transition to regenerative agriculture*

04.

06. Next steps to accelerate *the transition to regenerative agriculture*

The ultimate objective of this work is to enable companies to measure and report on the outcomes and impact of regenerative agriculture.

Our work with OP2B on regenerative agriculture metrics aims to address common challenges in the system relating to "measure and manage performance." Aligning on a common set of indicators will lead to outcomes that incentivize and accelerate progress on nature targets (as well as net-zero emissions and equity-related targets) and secure the necessary financing to propel the transition through transparency.

In 2024, WBCSD and OP2B will continue to facilitate the system-wide transition to regenerative agriculture as part of the broader drive for corporate performance and accountability on climate, nature and equity as well as action at the landscape level and an enabling environment.

This includes:

Accountability

- → Engaging with the relevant reporting frameworks and standard-setting bodies (including the Task Force on Climate-related Financial Disclosures (TCFD), TNFD, SBTN, GHG Protocol, CSRD, Science Based Targets initiative Forests, Land and Agriculture (SBTi FLAG) Guidance, CDP and others) to support 1) alignment on metrics that are scientifically robust and practical for corporate use and 2) guidance for implementation (on materiality, value chains, data challenges and more).
- → Framing regenerative agriculture outcomes and metrics within the broader context of sustainable land use as outlined in the **Nature Positive Roadmaps** for the agri-food system.[90,91]

Landscape action

- → Clarifying the financing needs and opportunities to de-risk the transition for farmers and other smallholder farm archetypes to regenerative agriculture in Europe. This includes identifying opportunities for co-investment and building on the existing business case. In addition, the work includes understanding the costs of the transition and demonstrating the business case in smallholder farms.
- → Catalyzing public-private investment opportunities by convening roundtables to bring to light public/private investment opportunities for large-scale landscape projects.
- → Supporting comprehensive farmer financing mechanisms by developing a guide on investment options to de-risk farmer transitions to regenerative agriculture.
- → Supporting the 2023 United Nations Climate Change Conference (COP28) **Action Agenda on Regenerative Landscapes** which aims to aggregate, accelerate and amplify existing efforts and new commitments to transition large agricultural landscapes to regenerative landscapes. In 2024, the Action Agenda is advancing the mapping of existing and planned regenerative landscape efforts. It will do this by brokering partnerships throughout the food and agriculture value chain with financiers and the public sector and communicate efforts and results to amplify the landscape approach and mobilize additional action.

Enabling

- → Driving awareness of the regenerative agriculture business case in policy by improving positioning it in global fora (Convention on Biological Diversity (CBD) COP16 in 2024, New York Climate Week, etc.).
- → Financing regenerative landscape projects by developing clear policy asks for blended funding for regenerative landscapes, laying the groundwork for public-private partnerships in Europe.
- → Aligning on a strong position for regenerative agriculture in upcoming EU policy.

It is important to note that the leading corporate frameworks for nature-related and regenerative agriculture – and the scientific methodologies and data that underpin them – continue to evolve and improve. Companies should see this work as a starting point to help align the industry with the regenerative agriculture outcomes and metrics that are likely to be developed and improved in the future. We will revisit our recommendations periodically to keep up with the latest developments.

Annex A: *Glossary*

Nature-related

State of nature

Refers to measures of the direct state of the environment in three categories: the state of ecosystems (extent and condition), species (abundance and extinction risk) and ecosystem services (or the state of nature's contribution to people).[92]

Pressure

Human activities that directly or indirectly change the state of the environment and ecosystem. Following the Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES),[93] five key pressures contribute most to the loss of nature globally: land- and sea-use change, direct exploitation of organisms, climate change, pollution and invasion of alien species.[58]

Response

Actions taken by companies or farmers to address pressures or to improve the state of nature on farmed land.

Riparian buffer

Riparian refers to an area along a stream or riverbank. A riparian buffer is essential to preserving water quality on farmland.[95]

Agriculture-related

Agroforestry

Growing trees and shrubs with crops and/or animals in interacting combinations on the same unit of land.[96]

Soil-related

Bulk density

The density of a volume of soil as it exists naturally, it includes air space, organic matter, and soil solids.[97]

Soil organic carbon (SOC)

Soil organic carbon is the carbon component of soil organic matter.

Soil organic matter (SOM)

Any material produced originally by living organisms that is within or returned to the soil. It is composed of soil microorganisms such as bacteria and fungi as well as decaying material from once-living organisms and fecal material.

Taxonomy

Components

The interaction of physical, chemical and biological properties of soil influences soil health.[98] In this report, we group indicators as physical, chemical or biological, referring to them collectively as components.

Impacts

Ultimate state of nature effects sought.

Indicators

Values or characteristics that provide insight into a particular phenomenon or situation.

Metrics

System or unit of measurements.

Outcomes

Quantitative or qualitative parameters that measure achievement or reflect changes over time; may be short or long term.

Annex B:
Technical discussion of recommended metrics

Outcome: increased soil health

Component: soil health – chemical

- → Type of metric: state
- → Spatial scope: per unit area
- → Temporal scope: dependent upon expected rate of change but likely 3-10 years
- → Key links to other metrics: carbon sequestration, soil microbial diversity.

Soil organic carbon

Soil organic carbon (SOC) content is a key component of soil health. SOC is the carbon component of soil organic matter, which is composed of soil microorganisms such as bacteria and fungi as well as decaying material from once-living organisms and fecal material. SOC content is closely associated with agricultural productivity and also provides a range of soil functions such as water retention and water quality maintenance via structuring the soil an addition to carbon storage.[99] Estimates show global SOC stocks at 2 meters in depth to be 1,500-2,400 Gt C – two to three times that in the atmosphere – and cultivation has already been responsible for 140-150 Gt C in losses. Many practices associated with regenerative agriculture, such as organic amendments and conservation tillage, lead to predictable positive changes in SOC.[100]

Standardized methods exist for the SOC metric, such as that from the Food and Agriculture Organization of the United Nations (FAO).[101] Table 6 provides an overview of some of the methods available and their relative pros and cons.

Physical sampling and soil C content measurement is the usual recommended approach to quantify SOC, involving quantification of (a) fine earth (<2 mm) and coarse mineral (>2 mm) fractions of the soil; (b) organic carbon concentration (%) of the fine earth fraction; and (c) soil bulk density or fine earth mass. Organic carbon concentration is determined through dry combustion or other laboratory methods associated with a measurement of total carbonate content, requiring technical expertise with associated costs.

A large number of samples in an appropriate protocol can often be required as SOC stocks are highly spatially variable, with stratified and non-stratified approaches appropriate in different contexts. Companies can determine adequate sample numbers through minimum detectable difference calculations. It is necessary to take samples at a sufficient depth (as deep as possible and 30 cm at a minimum and the same depth per campaign). To avoid bias, it is essential to consider soil bulk density as it changes over time; SOC stocks must therefore be estimated on an equivalent soil mass basis. This requires information about how both SOC and bulk density change with soil depth. The FAO therefore recommends obtaining SOC and bulk density information from at least three discrete, contiguous and successive soil layers to provide a more precise equivalent soil mass basis.

The appropriate frequency for resampling should depend on rates of expected change. However, it is common for five years to pass between sampling rounds and even as infrequent as every 10 years. Furthermore, SOC stocks can vary intra-annually. This means sampling should occur either throughout the year or during the same season. Sampling campaigns should take no more than 60 days within one season. And companies should record sampling points to ensure they take samples in the same location in every sampling round to limit the uncertainty and spatial variability within a parcel.

While other approaches to SOC measurement or estimation do exist, we do not currently recommend their use. Although estimates based upon calculating full carbon budgets have been improving rapidly, these approaches require the construction of major infrastructure such as flux towers, making them impractical. Spectral methods for estimating SOC rely on the reflectance of light on soil in the infrared region of the electromagnetic spectrum. It is therefore possible to predict soil carbon percentages from spectral measurements if a spectral library of different soil types is available. However, remotely sensed measurements can currently only measure spectra in the top 1-5 cm of bare soil, which is inadequate in terms of depth and often impractical in terms of land use. While many models for estimating SOC do exist, there is no real consensus on modeling approaches, so predicted values exhibit large discrepancies across models, irrespective of model category and spatial or temporal scale.

Table 6: Key factors affecting the feasibility and robustness of different methods for estimating soil organic carbon

	Physical sampling	Remote sensing (spectral)	Flux (full carbon budgets)	Modeling
Logistical requirements	Requires physical visits and multiple samples per farm, in pre-established, representative locations	Calibration/library required, so may require in-situ visit anyway	Repeated measurements required	Low
Costs	High (mainly logistics)	Moderate	Moderate; extremely high if flux tower construction required	Relatively low
Technical requirements	Substantial: requires sampling and processing as well as minimum detectable difference calculations, spatial stratification	Moderate	High	Low to high if modeling required
Scalability	Not easily scalable	Highly scalable if calibration possible	Low	Little consistency
Accuracy of measurement	High	Currently unacceptably low	Variable	Low – little consistency
Future prospects	Unlikely to be modified	May become substantially more accurate and databases of calibrated data may increase in size	Flux tower network expanding but unlikely appropriate for use case	Possible improvements

The metric itself aligns greatly across frameworks, appearing in a large majority of corporate reporting frameworks and regenerative agriculture initiatives themselves. Companies can set targets at an aggregate scale and track improvements straightforwardly but not using absolute values as reference levels inevitably vary by farm context. Manipulation of the metric is unlikely, although some actions could elevate SOC above optimal levels.

Reporting of SOC is by unit area, often as metric tons of carbon per hectare. Initial reports should contain spatial boundaries of the farm or other area of interest, records and results of historical activities and land uses, a sampling plan including minimum detectable difference calculations, sampling round results including measured site coordinates and sampled soil depths, laboratory protocol, bulk density results and estimated SOC percentages. This should then be converted to metric tons of carbon per hectare or metric tons of carbon across the farm. Follow-up reports should be produced with the same information after each sampling round, as well as descriptions of the implementation of regenerative agriculture activities.[102]

Disclosure examples for annual reporting:

- Soil organic carbon: metric tons per hectare, throughout a farm or other identified and delineated unit

Soil carbon sequestration

Soil carbon sequestration is an important metric when it comes to the reduction of greenhouse gas (GHG) emissions from the agricultural sector, as explained in the **climate chapter** of this work. A recent study found that regenerative agriculture practices can reduce emissions from agriculture by 4.3 to 6.9 Gt CO_2e per year, accounting for a reduction of between 30% and 50% in current agricultural emissions.[103] The study also found that regenerative agriculture has the potential to increase soil organic carbon (SOC) sequestration by 0.5-0.8 Gt CO_2e per year in agricultural soils. This metric links tightly to the one above, namely SOC, where SOC is the stock of carbon in the soils where sequestration or loss of carbon can increase or decrease over time. The most widely used metric, MT CO_2 total, can be scaled across different levels and different ecosystem types but with the need to adjust reference values to reflect local ecoregional conditions.

Availability of nutrients

The availability of soil nutrients to plants is another commonly used indicator of soil health but often focused more on the productivity of the soil than on other aspects of soil functions. The methods used to measure can be considered cost-effective but heavily rely on field efforts.[104] This metric can be good to set targets and define baselines but care should be taken that this indicator is not misused and used in combination with indicators capturing other aspects of soil health and angles of nutrient availability (e.g., pH, SOC).[105] These metrics can change rapidly in the short term and not always due to factors in farmers' control. In addition, the application of N and P inputs to the soil would cause this indicator to increase, potentially at the expense of other aspects of soil health if inadequately managed.

Soil toxins

Levels of soil toxins are an important indicator to assess the impacts of agricultural practices on soil health and water quality. Various agricultural inputs can pollute soils, including heavy metals and pesticides. For example, the measurement of many toxins is an important indicator in the EU soil monitoring law, including As, Sb, Cd, Co, Cu, Hg, Pb, Ni, Tl, V and Zn (μg per kg). This indicator measures the state of key pollutants and farms could sample them together and scale them up to a higher level. But as with other indicators, context specificity is important. The relevant toxins, their reference levels and thresholds are likely to differ substantially by context. Some toxins are also particularly challenging to measure at scale, requiring field measurements and complex analyses. Different toxins can vary in feasibility of measurement. Measuring the state of pesticides in soil is highly challenging and costly. In this case the differences between agricultural contexts and the difficulty in gathering those data might make its application more challenging at the corporate scale. Managing soil for water quality could help facilitate toxin retention in the soil – many toxins may be buffered or biotically transformed, while others may be retained and bound to organic matter.[106]

Component: soil health – physical

Bulk density

Soil compaction is a serious issue associated with intensive agricultural practices and can lead to reduced soil productivity and function.[107] Bulk density is a commonly used metric to understand the effects of soil use on physical health.[108] Increased soil bulk density is related to increased soil compaction, which consequently impacts some soil functions (e.g., nutrient availability and plant root growth).[109]

Soil bulk density is an indicator that companies can measure and report separately but also use to calculate soil organic carbon under many methodologies where they must consider changes in bulk density over time to avoid bias in SOC estimates (i.e., estimating SOC stocks on an equivalent soil mass basis). Variation in this indicator depends on soil type and bio-geographic contexts, so companies should report them with the relevant contextual information, such as baselines for that soil type and bio-geographic context.

The most common methodology is direct measurement using physical sampling. Here, there are standardized methodologies, part of protocols for measuring SOC. These are relatively inexpensive compared to other soil health measurements in the field. However, collecting this data will still require site visits, technical expertise for sampling planning and laboratory analysis, making it challenging to scale.[110,111]

Other measurement techniques are available but have robustness concerns associated with measurement. For example, radiation-based techniques are non-invasive and can have reasonable accuracy for time-series measurements but this varies by context and has substantial equipment costs and feasibility concerns. Regression-based modeling is also possible and companies could more easily scale it but requires substantial data inputs and has low accuracy.

Infiltration rate

Another metric for physical soil health is infiltration rate, which measures the rate of infiltration of water into the soil, providing an indication of soil stability and physical structure.[112,113] Although needing supplementation with other metrics to capture chemical and physical health in its entirety, the metric is relevant to various functions of soils, including plant production and water quality.[114] It is easy to capture methods for data collection at the farm level and standardize them across contexts, generally requiring field sampling. They are simple to conduct even with limited technical expertise. However, they can be time consuming and take large logistical effort for data collection to ensure representative sampling. For example, regular data collection would require high field effort to access enough water to inform multiple samples.

Green water availability

Green water availability is an important indicator of the physical structure of soils but only captures one aspect of physical soil health and would need to supplementation with other metrics (e.g., soil nutrients, carbon, etc.). It is possible to link it to the ability of soil to support better plant growth as it reduces leaching of nutrients and soil pollutants.[115] Water holding capacity is likely correlated with SOC in many situations.[116] We cover guidance on this as an indicator and metric in the **water chapter**.

Component: soil health – biological

The biological health of soil is an often underrepresented component of soil health, where metrics and indicators often focus on chemical health. A range of different biological indicators are possible in measuring different aspects of soil biodiversity. However, despite its importance, soil biodiversity is highly complex and understudied. There are bottlenecks that make measurement challenging, including limited understanding of soil taxa and their distributions and ecology, as well as a lack of standardized indicators to help assess baselines and track progress over time.[117]

Soil microbial diversity

Soil microbes are an important source of C, N and P and act as a sink of nutrients to support soil functioning.[118,119] These serve as agents of nutrient transformation and pesticide degradation and provide important functions in association with plant roots.[120]

Several metrics focusing on soil microbes and the functions they provide are commonly used for assessing soil health. Metrics include microbial biomass, enzymatic activity, nitrifer abundance, mycorrhizal abundance, C and N mineralization rates and microbial community composition.[121]

Microbial biomass is one commonly used metric and highlighted as an important indicator of decomposition rates, N fixation and nutrient mineralization.[122] However, the metric biomass has been criticized because i) more microbial biomass may not always be desirable as it mixes the functions of different microbe types, ii) more biomass does not necessarily equate with microbial activity and iii) results vary depending on the soil properties and methods used.[123] In addition, information relating to what optimal levels of microbial biomass are across contexts is challenging to obtain and the biomass metric gives an indication of the amount of microbial activity without distinguishing between types and functions of organisms.[124]

Microbial biomass is quite challenging to measure at present at scale and across sites without specialist expertise.[125,126] The main methods include: direct microscopy, culturing, chloroform, fumigation, Phospholipid fatty acid (PLFA analysis) and substrate-induced respiration (SIR) method.[127] Other metrics include microbial diversity, DNA-based measures, enzyme activity, etc. which have other pros and cons.[128] DNA-based measures that can assess the presence of different taxa would likely be more feasible in helping quickly assess samples, identifying specific taxa and linking to functions of specific microbial groups. Despite their high potential for future application, they are not widely available at present.

Soil invertebrate diversity

Some soil biodiversity metrics focus on invertebrate diversity, recognizing their important role in the provision of soil functions. The presence of invertebrates, particularly earthworms, is often seen as an important indicator of soil health and important for some aspects of ecosystem functioning.[129,130] Simple metrics (e.g., the presence of earthworms or invertebrates) are sometimes used and are seen as highly feasible to collect. For example, companies could scale up this metric to reflect the percentage of farms with a specific score for invertebrate presence. Naturally, however, the presence and abundance of earthworms and other macro-invertebrates differs greatly by context, making it challenging to apply such simple metrics at a global scale.

Indeed, different ecosystems and soil types will have a high variability in reference levels for different species' distributions and abundance and the species important for the provision of different ecosystem functions. There can also be limited knowledge of biodiversity in many soil ecosystems. There is also a risk of the misapplication of simple metrics that do not distinguish between different taxa or look at measures of abundance.[131] More advanced metrics that look at the abundance or presence of different macroinvertebrate species would require substantial effort and technical capabilities (including taxonomy), raising issues with scalability and the availability of reference data. Here, DNA-based approaches also offer opportunities for future advances and could help capture other components of soil biodiversity that are more challenging to survey (e.g., meso-fauna).

Component: soil erosion

- → Type of metric: pressure
- → Spatial scope: farm or per unit area
- → Temporal scope: depends on sampling frequency of required parameters
- → Key links to other metrics: soil organic carbon, nutrient loss

Soil erosion

Soil erosion is a key degrading process from agricultural practice and is a threat to sustainable agricultural production at multiple scales, from local to global; reducing erosion is important in maintaining functioning soils. A number of kinds of processes (water, wind, tillage) can cause erosion, which can make it challenging to both tackle and measure.

Erosion levels globally under conventional agriculture are likely an order of magnitude above baseline levels.[132] Severity depends on soil type, type of agriculture and biogeographic context and varies enormously globally. Bare soil is in general associated with the highest erosion rates, followed by arable land and then other agricultural uses, forests, agroforestry and other kinds of natural or seminatural vegetation.

Several types of methods exist to measure or estimate soil erosion rates, all of which present significant challenges (**Table 6**).[133,134] Plot-based approaches measure erosion directly via runoff but are not necessarily representative nor scale-dependent; we emphasize that extrapolation from plot to a larger scale to be inappropriate. This is also highly time-consuming and costly. Other techniques used include placing metal rods ("erosion pins") into the ground to measure decreases in soil height over time but this does not distinguish between erosion and soil compaction, remote sensing and newer approaches involving tracking environmental radionuclides that rely on several assumptions that have all been challenged.

Modeling soil erosion levels presents less feasibility challenges but potential for more uncertainty in measurement in some contexts. Modeling is based upon standardized equations for soil loss such as the Universal Soil Loss Equation (USLE) and estimates primarily water-based erosion. While process-based physical models exist, these do not necessarily have lower uncertainty than simpler empirical models such as the USLE. While the use of modeling approaches is increasing, they require

Table 7: Key factors affecting the feasibility and robustness of different soil erosion methodologies

	Plot-scale runoff measurement	Decrease in soil level (erosion pins)	Remote sensing (extrapolation from e.g., furrows)	Radionuclide tracking	Modeling
Logistical requirements	Physical visits	Physical visits	Low, unless calibration required	Complex	Low, unless calibration required
Costs	Low per plot; high in total	Low per plot; moderate to high in total	Cost of imagery and processing Low with coarse imagery, High with high quality imagery mostly required	High	Low-high depending on whether calibration required, and quality of imagery
Technical requirements	Moderate	Low-moderate	Moderate	High	Low-high depending on whether calibration required
Scalability	Very low, should not be extrapolated	Low	Highly scalable	Moderate – requires site visits	High but only in some areas of the world
Accuracy of measurement	Moderate but only accounts for water bound erosion	Low-moderate, does not distinguish between erosion and compaction	Low-moderate, only accounts for water-bound erosion, based on major assumptions High resolution needed in most cases	Low – substantial issues	Moderate but highly variable
Future prospects	Same	Same	Automation possible/likely	Prospects for future improvement	Prospects for future improvement

substantial time and technical skill. Furthermore, models have often had high levels of uncertainty associated with them because of a lack of adequate field-based data with which to validate them in many parts of the world; the models themselves are often only suited to particular locations and are frequently based on European and North American contexts.[135] Different modeling approaches can produce very large differences in estimates. However, while model parametrization and validation may require a number of pieces of information from each farm, many of these will either be known by land managers (such as cover crop presence and other land use practices) or will have to be collected as part of monitoring of other outcomes (such as soil organic matter content and soil texture). This could increase the feasibility and robustness of modeling as an approach.

The RUSLE2015 model,[136] for example, is based on the Revised Universal Soil Loss Equation (RUSLE) adjusted to the European continental scale, publicly available at 100 m resolution. However, appropriate measurements taken by users would allow more precise model parametrization of this model as well as (potentially) production of local finer-scale versions. As an outcome, erosion aligns across corporate reporting frameworks but we found it in less than half of the frameworks examined. Targets can be set for "acceptable" or "appropriate" levels of erosion per unit area but thresholds have been subject to criticism as not being science-based. Actors could exploit uncertainty associated with approaches to claim they have met targets without sufficient justification, meaning that both implementers and users will need to understand the uncertainty associated with this metric.

Disclosure examples for annual reporting:

- Erosion: metric tons per unit area per unit time, e.g., 3 metric tons per hectare per year.

Pressures

Other chapters provide information on key pressures on soil resources. The **water chapter** gives technical guidance on water extraction and pollution measures. The biodiversity chapter gives technical detail on metrics for pesticide risk.

Links to other metrics and environmental outcomes

These indicators and metrics aim to capture the major impact pathways through which agricultural activities influence environmental flows and water quality. Other topic chapters capture some pathways that impact soil resources:

- Pesticide pollution is highly damaging to some biodiversity components in the farmed landscape and in receiving water bodies but can also accumulate in the soils and impact soil biodiversity. The biodiversity metrics capture pressures caused by pesticide use.
- Excessive nutrient inputs will also impact the chemical health of soils. **The water guidance** through the nutrient use efficiency metric captures this.
- The water guidance includes soil water-holding capacity – a relevant indicator of soil health – as an additional metric to capture green water as an indicator of water quantity.
- A range of practices from regenerative agriculture can be expected to indirectly reduce pressure on water resources. We do not include these response metrics (e.g., extent of riparian buffers, cover crops, intercropping) here but feature in the calculation of some biodiversity metrics.
- Soil organic carbon content is highly related to carbon storage in soils, included in the climate guidance document.

For the pressure metrics included here, there is a clear link between changes in those pressures and expected changes in the state of water resources. Directly assessing state measures for water quantity and quality can be challenging and resource intensive. It may also be difficult to attribute findings to actions in individual farms, as in many cases upstream inputs in the wider hydro-basin will influence both baseline levels and trends over time. Attribution and interpretation of state metrics such as total suspended solids (TSS) can be more meaningful if measures are made at different points in space (i.e., upstream and downstream of the focal farm).

Aggregating metrics

Metrics measured at the farm level can be aggregated straightforwardly to other scales, such as for all operations within a defined landscape, hydro-basin or region; all operations producing a particular commodity; or at the corporate level. Where reference levels and thresholds may be different between contexts, reporting could present the proportion of farms achieving reference levels or where indicators are moving towards optimum levels. Companies should weight farm-level measures by farm area (or the area over which they have made measurements) when averaging to ensure an appropriate proportional contribution to the aggregate value from different-sized farms. They should also contextualize aggregate values expressed as ratios or percentages by providing total quantities (e.g., total area, nutrient application, water volume, etc.).

Temporal considerations

Companies should measure the metrics against the historical baseline that they define – for example, previous year or year the regenerative agriculture project started. For some metrics (e.g., soil erosion, nutrient availability) temporal variation in measurements is expected based on seasonal changes and varying weather conditions. Companies should collect metrics over timeframes appropriate to incorporating such variations and that allow meaningful comparisons and assessment of trends. It is also important to be aware of these influences to help interpret short-term changes in metrics and assess long-term trends that may be more responsive to regenerative practices on farm. Many of the metrics are amenable to reporting annually in line with corporate sustainability disclosure cycles but it is possible to report them over longer or shorter timeframes, i.e., to reflect seasonal or short-term changes in outcomes.

Thresholds for metrics

The purpose of this guidance is not to define thresholds for target-setting related to each metric and indicator. However, defining such thresholds will be useful as companies push to develop targets for regenerative agriculture and broader nature strategies that align with global sustainability targets. It will be important to factor in agronomic feasibility and potential trade-offs in these considerations.

There are various resources under development to help define appropriate thresholds and set compatible targets. For example, for soil erosion the United States Department of Agriculture (USDA) soil erosion threshold values exist to define acceptable limits for soil erosion. However, soil erosion levels will differ substantially depending on local site characteristics and such thresholds can be controversial.[137] However, as noted in Chapter 3, it is likely that for all soil health indicators, reference levels and thresholds will vary depending on the geographic, agricultural and ecological contexts.

Guardrails for appropriate use of metrics

Viewing the metrics and outcomes from regenerative agriculture as a whole

As highlighted above, it is important to view regenerative outcomes, indicators and metrics holistically. Metrics that are not heading in the desired direction are a prompt for further investigation, followed by adaptive management to change practice if required. It may be that actions are not having the desired consequences, that the practice or the indicator is not appropriate for the specific agricultural context or that practices have positive effects for some outcomes but negative ones for others.

Yield and economic returns are vital contextualizing metrics

For many regenerative practices, there is a good evidence base showing benefits to water quantity and quality at a field or farm level. Practices may lead to improvements in the long-term yield of agricultural production. However, in other cases, yields could decrease, particularly in the initial years of transition. When considering outcomes at the corporate scale, it is important to view yield measures alongside environmental metrics to highlight potential socio economic benefits or displacement effects. Note that the chapter on livelihoods covers metrics and guidance supporting socio economic outcomes of regenerative agriculture.

Metrics: limitations and variations

Individual metrics may not reflect all facets of the indicators and outcomes they link to and it is important to consider this when interpreting results. For example, changes in the availability of nutrients in the soil may increase following some agricultural practices but may also have knock on effects on other indicators (e.g., bulk density, soil organic carbon) that looking at this one metric alone would not capture.

Different organizations use many variations of these metrics; for example, some companies historically have reported agricultural water use in terms of production (metric tons) rather than spatially (hectares). We recommend a standardized approach outlined in this work on **regenerative agriculture** while recognizing variations on these metrics are likely to remain in use.

Landscape and supply chain considerations

The recommended spatial scope for measuring and reporting nature-related metrics is the farm boundary, unless otherwise noted. But it is essential to interpret nature-related metrics in light of the wider landscape or hydro-basin context. For example, it is necessary to contextualize changes in SOC depending on the soil type, agricultural practices and history of the landscape.

The metrics outlined here focus on the farm-level and do not generally consider the embodied impacts of farm inputs upstream in the supply chain. Consider changes made in the source or type of inputs used, e.g., for fertilizer, consumption or pollution of water in the production process, as context for interpreting metrics on-farm.

It is also important to reflect on how outcomes of actions on farms may vary depending on wider landscape trends. For example, the reduction in soil disturbance or pesticide use associated with regenerative practices may have differing benefits for soil biodiversity depending on how connected it is to habitat outside of the farm (note that we cover this topic under the biodiversity metrics).

Annex C:
Full mapping of soil metrics and indicators required within key frameworks

Table 8: Corporate sustainability framework and regenerative agricultural initiatives requirements on reporting metrics and indicators within different components of soil health

Components	Regen-ag frameworks							Sustainability frameworks							EU		Literature	
	Cool Farm Tool	Field to Market	OP2B	Regen10	SAI	Sustainable Markets Institute	TE	CSRD	GRI	TNFD	SBTi FLAG	SBTN	GHG SLR	FAO	EU Soil Law	Lucas	Bagnall et al. 2023[138]	Calvaruso et al. 2021
Practice – addition of soil amendments				🟩							🟩							
Practice – drainage		🟩																
Pressure – general	🟫			🟫			🟫	🟫		🟫				🟫	🟫			
Pressure – heavy metals				🟫						🟫				🟫	🟫		🟫	🟫
Pressure – N & P			🟫	🟫			🟫			🟫	🟫	🟫		🟫		🟫	🟫	🟫
Pressure – pesticides			🟫				🟫		🟫	🟫	🟫	🟫		🟫				
Pressure – soil erosion		🟫		🟫	🟫						🟫	🟫		🟫	🟫			
Soil carbon	🟦	🟦	🟦		🟦	🟦	🟦		🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
Soil emissions		🟦																
Soil health – biological				🟦			🟦							🟦	🟦			🟦
Soil health – chemical	🟦		🟦	🟦			🟦				🟦			🟦	🟦	🟦	🟦	🟦
Soil health – physical	🟦			🟦			🟦				🟦	🟦		🟦	🟦	🟦	🟦	🟦
Water – soil balance	🟦			🟦	🟦		🟦							🟦	🟦			🟦

🟩 Response metric 🟫 Pressure metric 🟦 State metric

Table 9: A review of soil-related metrics included in relevant standards and frameworks

Categories	Indicator	Metric	Regen. ag. initiatives							Corporate reporting framework									Scient. literature	
			Cool Farm Tool	Field to Market	OP2B	Regen10	SAI	Sustainable Markets Institute	TE	CSRD	EU Soil Law	FAO	GHG SLR	GRI	Lucas	SBTi FLAG	SBTN	TNFD	Bagnall et al. 2023[139]	Calvaruso et al. 2021
Pressure – heavy metals	Level of soil pollution (soil toxins)	Amount of soil toxins copper, cadmium, zinc (requires an additional soil test therefore incurs extra cost				🟫					🟩	🟫							🟫	🟫
		EU Law: As, Sb, Cd, Co, Cu, Hg, Pb, Ni, Tl, V, Zn (µg per kg)																		
Pressure – N & P	Soil pollution	Applied nitrogen (N) and phosphorus (P) (kg ha-1)			🟩							🟫							🟫	
	Fertilizer use	Nutrient use efficiency (NUE)			🟩	🟫			🟩			🟫					🟩			
	NUE yield	NUE yield = N uptake x N use efficiency							🟩			🟫								
	Quantity of unused materials & substances	Nutrient balance for N, P, K (as ratio)				🟫						🟫								🟫
	NUE of a system (sNUE)	Yield N / (Yield N + N loss)				🟫						🟫								
	Extractable P																		🟫	
	C/N ratio														🟩					🟫
Pressure – pesticides	Soil pollution	Avoided pesticide use per hectare (as proportion of the total cropland area owned, leased managed or sourced from by the entity) by pesticide toxicity level										🟫						🟫		
	Pesticide use	Environmental Impact Quotient (EIQ)			🟩	🟩			🟩			🟫								
	Reduction in use of highly hazardous pesticides (HHP)	Kg active ingredients (i.e.) of highly hazardous pesticides (HHP) applied per ha of harvested land							🟩			🟫								
	Pesticide use	Report the volume and intensity of pesticides used by the WHO toxicity hazard level												🟩						
Pressure – soil erosion	Structural health of soil	# visual erosion signs (based on Sustainable Soils Alliance categories)				🟫						🟫								
	Soil conservation metric	Soil per acre lost to erosion from water and wind (t)		🟩																
	Soil erosion from water and wind	Metric ton per area					🟩				🟩	🟫				🟫	🟫			

🟩 Metric included

🟫 Companies must measure the indicator (e.g., soil organic carbon) but there is ambiguity on specific metric (e.g., SOC/area; metric tons of carbon/ha)

🟦 Based on geospatial layer

🟧 Most aligned

Table 9: A review of soil-related metrics included in relevant standards and frameworks *(continued)*

Categories	Indicator	Metric	Regen. ag. initiatives							Corporate reporting framework									Scient. literature	
			Cool Farm Tool	Field to Market	OP2B	Regen10	SAI	Sustainable Markets Institute	TE	CSRD	EU Soil Law	FAO	GHG SLR	GRI	Lucas	SBTi FLAG	SBTN	TNFD	Bagnall et al. 2023[139]	Calvaruso et al. 2021
Soil carbon	Soil Conditioning Index (SCI- from the USDA NCRS tool) used to represent soil carbon metric	-1 and 1 for each field. A positive value indicates increasing soil carbon, a neutral value (between -0.05 and 0.05) indicates maintaining soil carbon and a negative value indicates losses of soil carbon. The magnitude of the index reflects confidence in the directionality and does not indicate a higher or lower quantity of carbon in the soil.		🟩																
	🟧 Ecosystem condition	🟧 Changes in soil organic carbon stocks (over 5+ years relative to a baseline)															🟫	🟫		
	Soil organic carbon	geoFootprint API	🟦																	
	Agriculture soil carbon	Gross tonnage of carbon dioxide equivalent per year (Gt CO_2e/yr)												🟩		🟩				
	Carbon sequestration	$MTCO_2$eq/area					🟩												🟫	🟩
	🟧 Soil organic content (SOC)	🟧 SOC/Area; Eu Law: g/Kg: metric tons of carbon/ha			🟩		🟩	🟩	🟩		🟩	🟫	🟫		🟩		🟫		🟫	🟩
	Soil Health Institute 1) Soil organic carbon concentration	Grams of C (g) per kilogram (kg) of soil on an oven-dry basis							🟩											
Soil emissions	N_20 emissions from soil (as part of greenhouse gas emissions metric)	Nitrous oxide emissions from soils (based on soil texture among others) is used to calculate greenhouse gas emissions together with energy use, methane emissions (from flooded rice fields) and emissions from residue burning		🟩																

🟩 Metric included

🟫 Companies must measure the indicator (e.g., soil organic carbon) but there is ambiguity on specific metric (e.g., SOC/area; metric tons of carbon/ha)

🟦 Based on geospatial layer

🟧 Most aligned

Table 9: A review of soil-related metrics included in relevant standards and frameworks *(continued)*

Categories	Indicator	Metric	Regen. ag. initiatives							Corporate reporting framework									Scient. literature	
			Cool Farm Tool	Field to Market	OP2B	Regen10	SAI	Sustainable Markets Institute	TE	CSRD	EU Soil Law	FAO	GHG SLR	GRI	Lucas	SBTi FLAG	SBTN	TNFD	Bagnall et al. 2023[139]	Calvaruso et al. 2021
Water – soil balance	Soil water infiltration	Drainpipe test				🟫														
	Soil moisture at planting	Dry, medium, high	🟦																	
	Water holding capacity	m3/m3					🟩				🟩	🟫							🟫	🟫
		EU Law: % of volume of water/volume of saturated soil)																		
	Readily available soil moisture (RAM)	Mm or between -10 and -200kPa water tension							🟩			🟫								🟫
	Infiltration rates	mm/hr					🟩					🟫								🟫
Soil health – biological	Health of soil biology	average # soil health indicator species (e.g., earthworms) per land use type				🟫														
	Earthworm abundance/ diversity/ structure																			🟫
	Nematode abundance/ diversity/ structure																			🟫
	Presence of invertebrates	Score from 1-5 1 = no signs of invertebrate presence or activity, 3 = a few earthworms and arthropods present, 5 = abundant presence of invertebrate organisms				🟩			🟫			🟫								
	Microbial molecular biomass																			🟩
	Soil microbial diversity	TBD based on emerging indicators							🟫			🟫								🟫
	Soil basal respiration	(mm^3 O_2 g-1 hr-1) in dry soil									🟩									

🟩 Metric included

🟫 Companies must measure the indicator (e.g., soil organic carbon) but there is ambiguity on specific metric (e.g., SOC/area; metric tons of carbon/ha)

🟦 Based on geospatial layer

🟧 Most aligned

Table 9: A review of soil-related metrics included in relevant standards and frameworks *(continued)*

Categories	Indicator	Metric	Regen. ag. initiatives							Corporate reporting framework									Scient. literature	
			Cool Farm Tool	Field to Market	OP2B	Regen10	SAI	Sustainable Markets Institute	TE	CSRD	EU Soil Law	FAO	GHG SLR	GRI	Lucas	SBTi FLAG	SBTN	TNFD	Bagnall et al. 2023[139]	Calvaruso et al. 2021
Soil health – chemical	Soil salinization	EU Law: Electrical Conductivity (deci-Siemens per meter)									🟩	🟫				🟫			🟫	
	Structural health of soil	%SOM per Ha				🟩						🟫								
	Soil pH	geoFootprint API	🟦									🟫								
	Soil Health Institute 2) carbon mineralization potential	Milligram CO_2-C per kilogram of dry soil per 24 hours							🟩			🟫								
	Soil pH	Negative log10 of the activity of hydrogen ions (H+). (Range of 0-14;							🟩		🟩	🟫			🟩				🟫	🟩
		Most soils fall in range of 3-9; ideal range for plant growth 6.0-7.5)																		
	Level & availability of soil nutrients to plants	Amount (mg/kg) of macro/micronutrient in soil sample (N, P, K, SOM)							🟩		🟩	🟫							🟫	🟩
	Cation exchange capacity (CEC)	Cmol(+)/Kg (range approx. 1 to 50)													🟩				🟫	🟩

🟩 Metric included

🟫 Companies must measure the indicator (e.g., soil organic carbon) but there is ambiguity on specific metric (e.g., SOC/area; metric tons of carbon/ha)

🟦 Based on geospatial layer

🟧 Most aligned

Table 9: A review of soil-related metrics included in relevant standards and frameworks *(continued)*

Categories	Indicator	Metric	Regen. ag. initiatives							Corporate reporting framework									Scient. literature	
			Cool Farm Tool	Field to Market	OP2B	Regen10	SAI	Sustainable Markets Institute	TE	CSRD	EU Soil Law	FAO	GHG SLR	GRI	Lucas	SBTi FLAG	SBTN	TNFD	Bagnall et al. 2023[139]	Calvaruso et al. 2021
Soil health – physical	Soil compaction										🟩	🟫				🟫	🟫			🟫
	Bulk density	Dry weight of soil in a given volume, g/cm^3							🟩		🟩								🟫	
	Soil composition	geoFootprint API	🟦																	
	Soil Health Institute 3) aggregate stability (physical)	Percent water-stable at 10 min – SLAKES[140] test using smartphone							🟫											
	Soil texture	Relative percentages of sand, silt and clay particles; particle size distribution							🟫						🟩				🟫	🟫
	Soil structure (physical)	Score from 1-5 1 = loose, powdery soil without visible aggregates, 3 = few aggregates that break with little pressure, 5 = well-formed aggregates – difficult to break							🟫											🟫
	Color, odor & organic matter	Score from 1-5 1= pale, chemical odor and no presence of humus, 3 = light brown color, odorless and some presence of humus, 5 = dark brown, fresh odor and abundant humus							🟫											
	Structural health of soil	Soil depth (shallow/ shallow intermediate/ intermediate/ deep intermediate/deep)				🟫														
	Structural health of soil	Visual Evaluation of Soil Structure (VESS) score (Sq1-5)				🟩														

🟩 Metric included

🟫 Companies must measure the indicator (e.g., soil organic carbon) but there is ambiguity on specific metric (e.g., SOC/area; metric tons of carbon/ha)

🟦 Based on geospatial layer

🟧 Most aligned

Annex D:
Metrics criteria assessment

WBCSD's technical partners first developed a set of metrics criteria against which to evaluate each potential metric:

Metric criteria		Explanation
1	Relevance to objective	Is the metric likely to drive effective change in the right direction.
2	Evidence base	Is the evidence base linking metric to objective adequately robust.
3	Scalability	Is it possible to aggregate the metric farm, landscape, corporate scales.
4	Generality	Is it possible to meaningfully apply it in all geographic and agricultural contexts (either in a single version or in biome/subsector variants)?
5	Breadth	How fully does the metric cover the relevant sub-objective/indicator – would it need supplementing with other metrics in order to fill gaps?
6	Potential for standardization	Is it possible to clearly define the metric methodology and standardize it for consistent application [also relates to verification].
7	Potential for target-setting	Is the metric amenable to defining baselines and targets.
8	Feasibility	Are effort/cost/capacity requirements compatible with widespread implementation.
9	Potential for gaming or creating perverse outcomes	Are there significant risks that the metric could be misleading or misapplied, resulting in undesired outcomes. This includes if the metric is likely to be attributable or responsive to farm-level changes.
10	Alignment	How well aligned is the metric with existing reporting frameworks?

We then scored each potential metric based on how well they met these criteria, see **Table 4**.

Annex E:
Key resources

Regenerative agriculture frameworks	
Biodiversity Monitor for the Dairy Farming Sector	A joint initiative of FrieslandCampina, Rabobank and the Dutch chapter of the World Wide Fund for Nature (WWF Netherlands) which aims to quantify biodiversity results to reward dairy farmers through supply chain partners and other stakeholders.
Cool Farm Tool	A farm management software that allows a farmer to calculate their GHG emissions based on simple data entry on their farm. There is also a tool to calculate water use and impacts, as well as biodiversity. The water module, requires inputs on farm characteristics, soil type, crop grown and water sources and irrigation used. It then computes water use statistics for the user.
Field to Market Sustainability Metrics Overview Documentation	This initiative helps farms assess their sustainability performance using a series of indicators across various environmental themes. It has metrics for biodiversity, land use, soil conservation, water irrigation use, water quality and carbon emissions.
OP2B Framework for Regenerative Agriculture	An international, cross-sectoral and action-oriented business coalition on biodiversity with a specific focus on regenerative agriculture. In 2021, OP2B with its members and partners proposed an initial set of four objectives and eight indicators for measuring progress on regenerative agriculture.
Regen10 Zero Draft Outcomes-Based Framework	A global endeavor committed to achieving regenerative outcomes for people, nature and climate. When complete, the framework will provide a holistic set of outcomes, indicators and metrics to understand and measure change that happens over time on farms and across landscapes.
SAI Framework for Regenerative Agriculture	This initiative aims to drive alignment on the use and measurement of regenerative agriculture practices. It defines 4 impact areas: soil health, water, biodiversity and climate. It then uses the criteria within these to identify the most "material" risks for a given farm/organization. It identifies 10 outcome metrics to measure progress against the 4 impact areas. It then provides a list of practices for use to help deliver against these impact areas, which companies should monitor to assess progress.
Sustainable Markets Initiative	A taskforce assigned to help scale regenerative farming. It has identified four levers to create change: A) funding, re-risking and new sourcing models, B) priority common metrics for environmental outcomes, C) government policy requirements to reward farmers for transition and D) ways to make environmental outcomes pay. Priority metrics include: GHG emission factors, soil organic carbon, natural and restored habitat in agricultural land, blue water withdrawal and nitrogen use efficiency.
Textile Exchange Regenerative Agriculture Outcome Framework	This framework helps the fashion, textile and apparel industry align on outcomes for regenerative agriculture by providing a range of farm and corporate level metrics. It splits the farm-level outcomes into those related to social and economic equity (e.g., human rights, sharing costs and risks, rights of indigenous community), animal welfare (e.g., good health and welfare) and ecological health.

Corporate sustainability frameworks	
CDP-Water	A not-for-profit charity established in 2000 to facilitate environmental disclosure. It aims to focus investors, companies, cities and governments to build a sustainable economy by measuring and acting upon their environmental impacts. There are three questionnaires available for companies under the CDP's global disclosure system: climate change, forests and water security.
CSRD	This EU initiative on corporate sustainability reporting requires all large companies and listed companies to disclose risks and opportunities from social and environmental issues, as well as their impacts.
GRI	This commonly used reporting framework provides disclosure requirements for various environmental and social topics, including water- and biodiversity-specific frameworks. It also includes a specific standard for agriculture, aquaculture and livestock.
International Sustainability Standards Board (ISSB)	This organization is developing a framework for sustainability-related risks and opportunity disclosures. It has issued the International Financial Reporting Standards (IFRS) 1 and 2 on general requirements and climate related disclosures in 2023. It is in the process of developing standards for other sustainability topics. It recommends using the Climate Disclosure Standards Board's (CDSB) guidance for water, which remains useful until the ISSB issues guidance on the topic.
Science Based Targets Network (SBTN)	Provides guidance on setting targets for nature. It has split the process into 5 steps: 1) assess organizational impacts, 2) interpret and prioritize results, 3) measure, set and disclose targets, 4) act to deliver the targets and 5) track progress. Guidance is available for the first three stages at present. There is also specific guidance for setting SBT for freshwater.
Task Force on Climate-related Financial Disclosures (TCFD)	A market-led initiative launched by the Financial Stability Board (FSB) in 2017. It aims to support stakeholders in assessing risks related to climate change through promoting disclosure of climate impacts and risks.
Taskforce on Nature-related Financial Disclosures (TNFD)	A market-led initiative launched in 2021. The initiative builds upon the related Task Force on Climate-related Financial Disclosures (TCFD), aiming to give the same focus for nature and biodiversity. The framework ultimately aims to support a shift in global financial flows away from nature-negative outcomes and toward nature-positive outcomes. The TNFD includes metrics of core disclosures as well as sector specific metrics.
TNFD Food & Agriculture Guidance	This draft provides the sector specific core and additional disclosure requirements and guidance for the TNFD, specific to the food and agriculture sector. It will finalize this guidance in 2024.

Soil-related resources	
National Datasets on Soil Types and Contexts	Fine scale soil maps at the county level in the USA, EU and UK. Similar datasets will be available for many other nations. e.g., USA – USDA Web Soil Survey - **Web Soil Survey - Home (usda.gov)** e.g., British Geological Survey Soil Observatory Map e.g., European Soil Data Centre – **ESDAC – European Commission (europa.eu)**
ISRC World Soil Information	A central database of soil-related resources and profiles information globally.
ISRIC Soil Geographic Databases	A catalogue of freely downloadable primary soil information available for geographic information system (GIS) use.
FAO Soils Portal	A catalogue of useful soil resources including classification systems, sampling and laboratory techniques, global maps of soil types, threats (e.g., salt affected soils). This includes global maps of soil organic carbon sequestration potential and global organic soil carbon as well as information on soil quality parameters.
FAO international Code of Conduct for the sustainable use and management of fertilizers	A globally accepted standard of conduct relating to all aspects of the management of pesticides.
GEMStat	The Global Freshwater Quality Database (GEMStat) provides data on the state and trends in global inland water quality for multiple sampling locations worldwide. It is a part of the water program of the United Nations Environment Programme.
The Green, Blue and Grey water footprints of crops[141]	A UNESCO-IHE report on the green, blue and grey water footprint of different crops and derived products. It provides information on water footprints in m^3/ton.[142]
Water Footprint Assessment Manual	This guidance on the assessment of water footprint includes overall water use (incl. water consumption from blue and green water), as well as direct and indirect water use. The guidance is for the overall water footprint of consumers or products throughout their life cycle but includes useful resources on calculating blue and green water footprints, as well as green and blue water evapotranspiration.
WATERSTAT	A range of datasets on the water footprint associated with different products and countries is available through the Water Footprint Network. This includes information on the blue and green water footprints of crops, farm and animal products. The resource also includes datasets on blue water scarcity and pollution due to nitrogen & phosphorus.
Setting Enterprise Water Targets	Assessments of water materiality and risks across the value chain inform this guidance on setting enterprise water targets at the local level. A toolbox is also available to help with this process.
WWF Water Risk Filter	The filter is a free and leading tool for helping assess water risks. It includes information on river basins prone to water scarcity, low water quality, as well as regulatory and reputational risks.

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About Regen10

Regen10 is a global endeavor committed to achieving regenerative outcomes for people, nature and climate. Originally funded by IKEA Foundation and the Rockefeller Foundation, Regen 10 has recently secured further funding from the McKnight Foundation to support its work. Alongside WBCSD, partners include 1000 Landscapes for 1 Billion People, the Food and Land Use Coalition, Global Alliance for the Future of Food, the International Union for Conservation of Nature (IUCN), Leaders' Quest, Meridian Institute, Sustainable Food Trust, Systemiq and World Farmers' Organisation.

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