Ground Zero? Let's Get Real on Regeneration!

Report 1: State of the Art and Indicator Selection

Wageningen University & Research · Alliance Bioversity & CIAT · Nestlé · CGIAR · EiA Excellence in Agronomy · ofi · ETH zürich

G0 Ground Zero

Colophon

Ground Zero? Let's Get Real on Regeneration! is a collaboration of Wageningen University & Research (WUR), Nestlé Research, Olam Food Ingredients (Ofi), OneCGIAR, ETH Zurich and various partners across the tropics

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Executive Summary

The urgency with which the world needs to combat climate change has led to ambitious commitments by leading food companies such as Nestlé. Given that a large proportion of emissions in supply chains occur during the production of commodities, focus has converged on Regenerative Agriculture as a key strategy to achieve those goals. The Regenerative Agriculture agenda coalesces around three main goals:

- Reduce the Carbon Footprint
- Enhance Soil Health
- Enhance and safeguard Biodiversity

alongside commitments to enhance smallholder producers' incomes, to avoid child labour and to ensure a sustainable supply. The Ground Zero project aims to provide a framework of robust, easily measurable and verifiable indicators and methods for the assessment of the carbon footprint, soil health and biodiversity in cocoa and coffee production systems. The project is organised around four work packages (WPs): WP1 – Coordination; WP2 – Carbon Footprints; WP3 – Soil Health; WP4 – Biodiversity. Here we report on the state-of-the-art for each of these topics and in a final chapter we indicate the next steps that will be taken in the project.

WP2: Carbon Footprints

Robust methods are needed to benchmark current greenhouse gas (GHG) emissions from coffee and cocoa plantations and to track progress in reducing those emissions. Although measurement of net carbon (C) emissions requires accounting for C stocks, particular attention must be paid to the nitrogen cycle, and notably to the use of nitrogen fertilizer because of the large, potent nitrous oxide emissions associated with its use. From a global warming potential perspective in a 100-year time horizon, one kilogram of nitrous oxide is equivalent to 273 kilograms of carbon dioxide (i.e. 273 kg CO_2-eq/kg N_2O; IPCC, 2021). There may also be large emissions of methane during waste processing. The equivalent emission factor for methane is 27 kg CO_2-eq/kg CH_4 (Forster, 2021).

The Cool Farm Tool is a C accounting tool that has been widely-adopted by the major food companies and their suppliers. This tool was initially developed for use with arable farms and has recently been adapted for use with perennial crops. Accurate measurement of C emissions in perennial crops is more challenging than in annual crops for a number of reasons. First, much less research has been done, meaning that many processes are poorly understood. Second, there is substantial carry-over of C in the crop and associated agroforestry trees from year-to-year which needs to be accounted for.

Given the widespread acceptance of the Cool Farm Tool, we will focus on improvement of the tool in two ways. First, to improve the accuracy of input parameters used in the calculation of overall net emissions, by making detailed measurements of dynamic processes such as nitrous oxide and methane emissions. Second, to extend the functionality of the tool to enable improvements in management of cocoa and coffee farms that reduce their C emissions to be rewarded. For example, extra functionality will be added to the Cool Farm Tool to account for more efficient management of nitrogen fertilizers. This will be done in liaison with the Cool Farm Tool Alliance to ensure our aims are aligned and that outcomes of the research are accepted and endorsed for general use.

For widespread monitoring of progress towards zero C on smallholder cocoa and coffee farms, simple means of verification are needed. To this end we will explore the use of digital image capture using mobile phones as an approach to estimating above-ground C stock in cocoa and coffee and associated agroforestry trees. Further verification will be proposed based on the correct implementation of 'good agricultural practice' of crops to maximise efficiency of input use and minimise losses to the environment.

WP3: Soil Health

Soil health refers to the continued capacity of a soil to function as a vital living system that sustains plants, animals and humans. Enhancing Soil health is one of the key goals of regenerative agriculture, an approach to sustainable farming that has been embraced by major agri-food companies including Nestlé to achieve ambitious sustainability commitments for their supply chains. Important challenges for the implementation of the sustainability strategies relate to (i) lack of clarity on the means by which the objectives can realistically be achieved (due to incomplete or contradicting evidence underlying the assumed benefits from practices), and (ii) the lack of suitable indicators and methods for monitoring progress towards the objectives. To address these challenges, the Ground Zero project aims to provide robust, easily measurable and verifiable indicator sets and methods for evaluation and monitoring of regenerative agriculture in cocoa and coffee supply chains.

In this report we review current knowledge on the links between production practices and soil health in coffee and cocoa, considering priority objectives for soil health enhancement defined by coffee and cocoa experts. We also provide an analysis of existing indicators schemes and important data gaps and methodological challenges. Important knowledge gaps relate to the links between some of the practices and the outcomes in terms of multiple soil functions underlying soil health, as well as the synergies and trade-offs between soil health and productivity and profitability, biodiversity and greenhouse gas emissions. Those need to be addressed to improve recommendations on soil health enhancing practices. In terms of data gaps and methodological challenges, we conclude that there is a general lack of data on biological indicators in coffee and cocoa farms, and also a lack of scalable methods. There is also a need to further explore the suitability of more sensitive indicators to detect changes in soil organic carbon (SOC) based on SOC pools or other indicators of SOC turnover (e.g. POM-MAOM) or changes in microbial communities (e.g. PLFA). Finally, reliable information on practices and robust interpretation schemes and benchmarks are required for the interpretation of the indicator values. Various opportunities for collaboration with related research projects to overcome some of these issues are highlighted.

Considering (i) the priorities for soil health enhancement and (ii) lessons learnt from existing indicator frameworks, we propose a soil health framework to be tested in Phase 1 of the project. The hierarchical framework focusses on establishing the links between context, practices and outcomes (in terms of soil functions or criteria). It also seeks to address relations (synergies, tradeoffs) between soil health indicators and other sustainability goals such as crop yields, greenhouse gas reductions (WP2) and biodiversity (WP4). A set of physical, chemical and biological indicators of soil health is proposed, alongside the collection of information on practices and context. To account for the needs of different users and the strong variation in agroecologies and archetypes within and across coffee and cocoa producing regions, the framework offers the flexibility to include add-on indicators. Those add-on indicators assess functions that are only relevant in certain contexts (e.g., Cd mitigation), or that are not suitable for monitoring at scale. Similarly, we offer different indicators and methods, depending on the purpose and targeted users. In the future a digital tool could be offered to support decisions on indicator and method selection for different purposes and contexts.

WP4: Biodiversity

Tropical perennial crops like coffee and cocoa originate from and are cultivated in highly biodiverse tropical forests. The conversion of such forests to managed coffee or cocoa plantations leads to a reduction in habitat for plants, animals and other organisms and affects the provisioning of ecosystem services to people.

This report reviews the knowledge on biodiversity impacts in coffee and cocoa and the indicators that are or could be used for the assessment of progress towards more biodiversity positive production by the cocoa and coffee sector. The report informs further work towards closing some of the identified knowledge gaps and the testing of selected indicators. We consider the Principles, Criteria and Indicators framework to assess progress towards more biodiversity positive production. The overarching principle (or objective) is to improve biodiversity outcomes of coffee and cocoa production systems. Biodiversity can be considered from the ecosystem to species to genetic level. At these different levels, different criteria (e.g., improve habitat quality on farm) can be identified that contribute towards the main principle. These criteria are underpinned by land use and management practices. Progress towards the criteria is assessed using indicators. Indicators can be outcome-based, to assess the state of and change in biodiversity outcomes, or they can be practice-based, indicating the implementation of practices that are known or expected to lead to certain biodiversity benefits.

Practice-based indicators are frequently used to assess sustainability in agriculture. However, practice – biodiversity outcome relationships are often not well quantified. There is no cross-sector agreement on clear and measurable criteria for a typology for cocoa or coffee farming systems that can be linked to biodiversity implications in a quantitative manner. Most impact studies compare relative performance of broad production system types, though definitions are not consistent making comparisons across contexts difficult. There is more evidence for broader land use history impacts and for major system characteristics (e.g., monoculture versus agroforestry), than for the impacts of specific crop management practices (e.g., organic matter management, weeding, cover crop use, pesticides use). More data and understanding are needed on relevant system characteristics (including practices that can be monitored and are actionable by farmers) so that they can be more consistently defined and linked to plausible implications for biodiversity.

At farm scale, most existing indicator frameworks for biodiversity in cocoa and coffee production systems include indicators such as associated tree density, diversity and canopy cover, sometimes with target values. Yet, actual implementation by supply chain actors seems rare outside of certification schemes. Also, when defining targets, it is important to consider the current state of biodiversity, the ecological potential and the scale at which biodiversity outcomes are sought. Collecting data on biodiversity indicators on farm can be resource intensive. We will explore the potential for alternative approaches, from remote sensing-based monitoring to farmer reporting. Based on literature and expert input, criteria and associated outcome and practice indicators and methods were selected for testing to a) increase understanding on practice-outcome links in different system types and b) explore and start to test novel, potentially more efficient, assessment methods.

1 Background

The urgency with which the World needs to combat climate change has led to commitments by many leading companies to halve carbon emissions by 2030, and to achieve carbon neutrality by 2050. Given that a large proportion, often 70% or more, of emissions in supply chains occur during the production of commodities, focus has converged on Regenerative Agriculture as a key response. Regenerative Agriculture, although poorly defined (Newton *et al.*, 2020; Giller *et al.*, 2021), has its focus on reducing carbon emissions and improving soil health whilst maintaining productivity and enhancing biodiversity.

Thus the Regenerative Agriculture agenda coalesces around three main issues:

- Reducing carbon footprints
- Enhancing Soil Health
- Safeguarding and enhancing Biodiversity

Alongside commitments to ensure all smallholder producers receive a living income, to avoid child labour and to ensure a sustainable supply.

Challenges associated with the implementation of this agenda relate to: (i) a lack of clarity on the means by which the objectives can realistically be achieved (due to incomplete or contradicting evidence underlying the assumed benefits from practices), and (ii) the lack of suitable indicators and methods for monitoring progress towards the objectives. To address these challenges, the Ground Zero project aims to provide a framework of robust, easily measurable and verifiable indicators and methods for the assessment of carbon footprint, soil health and biodiversity in cocoa and coffee supply chains. In **Phase 1** of the project, focus is on comprehensive indicators that can be used for research purposes, aiming to provide evidence on the validity of general assumptions underlying claims on the links between regenerative practices and their outcomes. Outcomes of practices for which knowledge or data gaps have been identified will be prioritized. In **Phase 2**, a selection will be made of indicators suitable for routine monitoring on a wide range of commercial farms, potentially requiring modification of the protocols to allow their wider applicability. Ultimately, this project aims to come up with an integrated framework for the assessment and monitoring of the carbon footprint, soil health and biodiversity of coffee and cocoa farms globally.

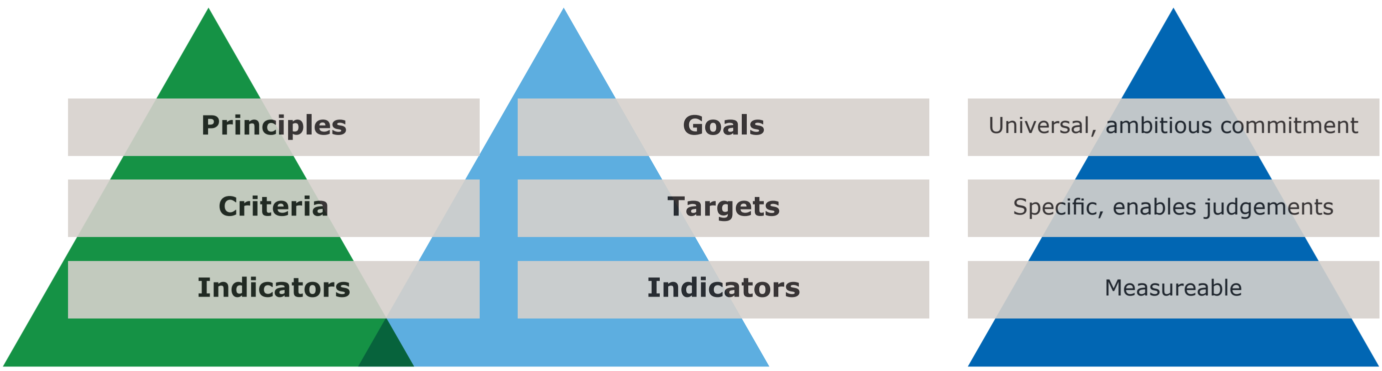
1.1 General Approach

Most frameworks used to assess progress towards sustainability are hierarchical in nature (Bell and Morse, 1998). Starting with general principles or goals which are often universal, ambitious commitments, a set of criteria or targets are identified which are more specific and enable choices and judgements to be made (Figure 1.1, Marinus *et al.*, 2018). Indicators are then chosen that can be measured to benchmark and monitor progress towards the criteria. Ideally causal links can be identified to provide a mechanistic understanding of the links between the selected criteria and the principles or goals that they underpin (Florin *et al.*, 2012).

A simple example for the Ground Zero project is:

- Principle/ Goal: Enhance soil health
- Criterion: Increase soil organic matter
- Indicator: Soil C content

Figure 1.1 Hierarchical frameworks help with indicator selection as they provide logical linkages between indicators and abstract concepts.



This sounds deceptively simple, although there are many pitfalls in measuring soil C contents, such as the depth to be sampled, issues of compaction and bulk density measurement, stratification of C with depth etc (see, for example, Wendt and Hauser, 2013). Further, soil C is what we describe as a 'slow ecological variable' which is a good integrating indicator which is of little direct use for monitoring change as changes are only observed over timescales of several years. Further, it is impractical and generally too costly to measure such indicators in every field of every farm.

A key role of the research to be conducted in the Ground Zero project is to question assumptions concerning the linkages between different indicators and the overall principle/ goal that is being addressed. This will be done through detailed measurements in experiments and in comparative research on coffee and cocoa farms across the world. By developing and evaluating best management practices and evidence of their effects on indicators in the field we will develop a system for tracking progress and rewarding farmers based on their robust implementation of these practices.

So deriving evidence to link principles and *criteria* to *practices*, and *practices* to *indicators* is central to the approach. Once we have identified practices that provide the expected benefits, a second step will be to explore *feasible ways* of monitoring implementation of *practices*.

For some *criteria* it may be feasible and practical to monitor *outcomes directly*. For example: increase diversity in non-cocoa tree canopy structure (for the principle: safeguard and enhance biodiversity in cocoa plantations), the *outcome* (number of canopy strata) rather than the *practice* (having trees of different canopy height amongst the crop) could potentially be assessed using remote sensing approaches. We will explore for which criteria this is feasible and which approaches would be most cost-effective.

1.2 Overall objectives

The overall objectives of the Ground Zero project are three-fold:

1. To benchmark carbon footprints, soil health and biodiversity in cocoa and coffee production and primary processing at source of origin.
2. To provide a series of robust, easily measurable and verifiable indicators and tools that can be deployed for monitoring and evaluation in cocoa and coffee supply chains.
3. To explore opportunities to achieve positive impacts on carbon footprints, soil health and biodiversity in cocoa and coffee production and primary processing at source of origin.

The project is organised around four work packages (WPs): WP1 – Coordination; WP2 – Carbon Footprints; WP3 – Soil Health; WP4 – Biodiversity.

The aim is to Benchmark and provide indicators and tools to move away from generic Tier 1 reporting guidelines to achieve more granularity. We are confident that tools can be developed to achieve local Tier 2 indicators to benchmark and monitor key variables (emission factors, soil health and biodiversity). Whether the granularity can be achieved to derive readily measurable indicators for Tier 3 reporting will be determined during the research.

In this report we present a background review of the state-of-the-art, and a preliminary proposal on monitoring and indicator selection for each of the three topics: Chapter 2 – WP2 Carbon Footprints, Chapter 3 – WP3 Soil Health and Chapter 4 – WP4 Biodiversity. We conclude (Chapter 5) with a discussion on the opportunities and challenges for rolling out such a monitoring approach through supply chains.

2 WP 2: Zero Carbon Emissions

2.1 State of the art

Nestlé have made ambitious commitments to cut their greenhouse gas (GHG) emissions by 50% by 2030 and to achieve net Zero by 2050. A large proportion (approximately 70%) of the GHG emissions associated with the end products sold occur during the primary production of agricultural ingredients, of which coffee and cocoa are important contributors. To monitor progress in reducing GHG emissions an accurate baseline of the current emissions in different coffee and cocoa production systems is needed, as well as assessments of measures to reduce emissions.

Current approaches to measure and monitor carbon footprints increasingly rely on the Cool Farm Tool as the default carbon calculator for most private sector actors [1]. The Cool Farm Tool was initially developed for arable farming in Europe (Hillier *et al.*, 2011), but has been adapted and refined for a wide variety of production systems including perennials (Ledo *et al.*, 2018, Vervuurt *et al.*, 2022). Despite the widespread use of the Cool Farm Tool, it lacks sensitivity to account for many interventions that can reduce GHG emissions, in particular on management of nitrogen (N), and interventions that can support improved biodiversity such as different types of agroforestry systems (Maney *et al.*, 2022). This is particularly true for perennial crops in the tropics like coffee and cocoa.

Attention to N management is crucial in estimating the net C footprint of production systems due to the strong GHG emissions associated with nitrogen cycling and in particular the emissions of nitrous oxide (N_2O) associated with fertilizer use. An example of the limitations of the Cool Farm Tool relates to the use of the IPPC Tier 1 default value of 1% for N_2O emissions from N fertilizer. Recent research suggests that 2.5% would be a more realistic value in both oil palm (Rahman *et al.*, 2019) and tea (Wang *et al.*, 2020), which confirms earlier suggestions of Veldkamp and Keller (1997). Given the warm temperatures, humid climates and abundant supply of organic residues to the soil in tropical perennial crops, such large N_2O emissions rates from N fertilizer are not surprising. The question remains whether the same holds for cocoa and coffee.

In addition, the key approaches to guide effective management of N fertilizer – the 4R principles of nutrient stewardship[2] – are not fully accounted for in the Cool Farm Tool. The 4R principles of 'right source, right rate, right time, right place' are the fundamental basis for effective and efficient use of fertilizers to ensure highly-productive plantations while minimizing losses to the environment. These principles can also be used for developing a strategy to reduce N_2O emissions (e.g. Chapter 6.4 in Velthof and Rietra, 2018). The Cool Farm Tool does not account for timing and placement of fertilizers, but only captures the quantity and type. The emission factor for N fertilizer is fixed, irrespective of quantity applied, whereas research has shown that emissions are non-linear and the emission factors increase with the application rate (Kim *et al.*, 2013). Efforts to improve fertilizer use efficiency through better application dosing, placement and timing are therefore not rewarded in terms of reduced footprints. In addition, current focus is on Integrated Soil Fertility Management (ISFM) to ensure efficient recycling of nutrients through managing organic resources and maintaining soil organic C (Vanlauwe *et al.*, 2010), which in turn ensures a healthy soil. The 4R principles fit well within the ISFM approach as both focus on ensuring nutrients are used efficiently.

There are many similarities in the way coffee and cocoa are produced and processed, but also important distinctions. Calculation of emission rates per kg of product requires inclusion of the nursery and establishment phase and decisions about how these are discounted across the cocoa production cycle from seedling production in the nursery to the full duration of the plateau production phase. This has been included in the new perennial module of the Cool Farm Tool but requires verification. Both crops require pruning and intense management for an optimal production phase, including integrated soil fertility management with recycling of organic residues complemented with mineral fertilizers. Nonetheless, there are important distinctions between the two crops. In intensive coffee production systems, N fertilizer is used in much larger quantities than in cocoa production systems. Cocoa has a thick mulch layer and is largely processed on individual plantations, including removal of the beans from the pods and fermentation in the field, meaning that the husks remain on the farm.
By contrast, coffee is often aggregated and processed at centralised washing stations or hulling factories, which aggregate large amounts of residues. The anaerobic decomposition of wet residues, such as pulp and waste

1 A number of similar tools exist – see Acharya and Lal (2021) for an overview
https://worldcoffeeresearch.org/resources/carbon-accounting-for-coffee-based-farming-systems

2 https://nutrientstewardship.org/4rs/

water, is an important source of GHG emissions. The Cool Farm Tool has a rather rudimentary approach to calculating the emissions from these wastes, with high sensitivity to seemingly arbitrary parameter thresholds (e.g. depth of the waste water pond) and lack of temporal dynamics of waste over its entire life cycle (i.e. duration of different processing steps). Cocoa is often produced under shade trees or residual trees from primary forest. The Cool Farm Tool includes biomass sequestration for different types of tropical forest types and has allometric functions for biomass accumulation of shade trees following the IPPC guidelines.

Thus, there is substantial scope to improve on the existing monitoring tools (see review by Acharya and Lal, 2021). This will require detailed background research to ensure that they are built on up-to-date and reliable data sources as well as in-depth knowledge of local production conditions.

2.2 Approaches to measure progress towards Zero C

A number of tools exist to calculate greenhouse gas emissions in agricultural systems. As described above, the Cool Farm Tool (CFT – https://coolfarmtool.org/) is the most widely used and accepted. As its name implies, the Cool Farm Tool is designed to calculate emissions at farm scale (Hillier *et al.*, 2011), and aims to provide farmers and food companies with a simple means of benchmarking. The Cool Farm Tool provides and uses tables of coefficients and factors for the GHG emissions associated with different inputs (e.g. N_2O from animal manures, fertilizers) and activities (e.g. machinery operations) to allow an overall assessment of GHG emissions. Although the Cool Farm Tool was originally designed for arable farming and livestock systems, it was extended for use with perennials (Ledo *et al.*, 2018) and specifically adapted to cocoa by incorporating field data (Vervuurt *et al.*, 2022) and was recently used to calculate GHG emissions in cocoa plantations in West Africa (Vervuurt *et al.*, 2022).

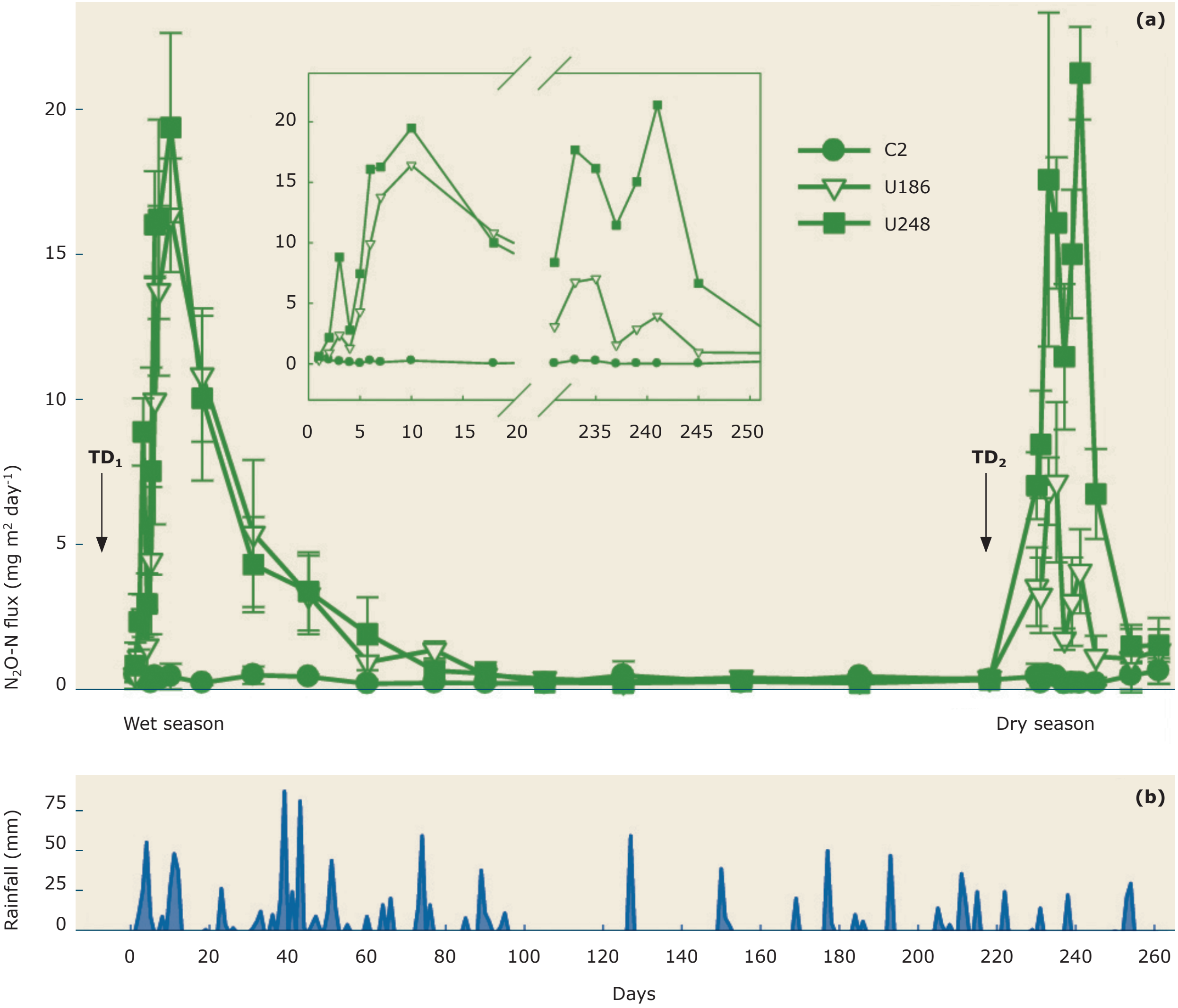
Agricultural systems are rarely in a steady state in terms of the C stocks above- and below-ground as agricultural management practices continually change. Therefore, a major challenge is to estimate rates of C accrual or loss from soils and in standing biomass. The complexity of the carbon and nitrogen cycles, which are the basis for calculating progress towards zero C, means that many variables need to be measured to arrive at a robust estimate of the C balance. The list of questions is long (see Appendix 1) and ideally these need to be answered for every plot on every farm. As this is simply not feasible given the 100,000s of farmers involved in global supply chains, simpler ways of estimating GHG emissions are needed. Different approaches can be taken, for example to select a sub-set of farms for detailed monitoring which are selected to be representative of the local population of farms. Ideally meaningful and robust indicators would be available that can be measured on every farm – which could be 'calibrated' by detailed research on a more limited number of farms. A key step towards this will be to run a sensitivity analysis of the Cool Farm Tool to identify the most important contributing variables to the overall outcome. Once these variables have been identified, a next step will be to seek proxies, hopefully with easily measurable indicators that can be used to track progress.

2.2.1 Direct measurements of GHG emissions

A challenge common to measurements of many processes in the nitrogen cycle is their dynamic nature. Rates of nitrification and denitrification, which together determine the release of nitrous oxide (N_2O) to the atmosphere are determined by the availability of mineral N (ammonium in the case of nitrification and nitrate in the case of denitrification), the temperature, the availability of organic substrates which drive microbial respiration and whether or not reducing conditions occur (Velthof and Rietra, 2018). Conditions which favour denitrification are thus where large concentrations of mineral N occur in soils rich in decomposable organic matter in warm and moist climates. So coffee and cocoa plantations provide potentially ideal conditions for denitrification. Given the strong environmental control of temperature, strong seasonal and diurnal fluctuations in the rates of microbial processes such as denitrification are observed.

Peaks of denitrification losses are expected to occur directly after addition of N fertilizer or organic matter to soil, where the majority of losses can occur within a few days. For this reason, an 'event-based' sampling approach is used where many samples are taken at close intervals around management events that are likely to trigger peaks in losses. Ideally samples are taken just before the management event, such as fertilizer application, and then at close intervals after the fertilizer is applied. An example is given in Figure 2.1 for oil palm where the large peak in nitrous oxide emissions was observed directly after fertilizer application. Obviously, to use such a strategy well some prior knowledge of events likely to trigger large emissions is needed, so that a sample can be taken immediately before the event occurs. In the case of weather events this is more problematic than when additions of organic or mineral fertilizer are made, although for example, sampling at the first rainfall event after a long dry spell would allow the capture of any N_2O emissions associated with the likely flush of N mineralization known as the 'Birch effect'.

Figure 2.1 Nitrous oxide emissions in oil palm demonstrating the need for an event-based sampling regime. (a) N_2O-N fluxes from the three treatments (U186 = 186 kg N in urea ha^{-1} $year^{-1}$, U248 = 248 kg N in urea ha^{-1} $year^{-1}$ and C2 = control [no fertilizer]) during a 261 day sampling period. TD1 (day 1) and TD2 (day 229) represent the first and second split of urea applications. The insert is an enlargement of the plot for improved visibility. Error bars indicate 1 SE (n = 4). (b) Rainfall during the sampling period.



Source: Rahman, Bruun, Giller, Magid, van de Ven, de Neergaard (2019) Global Change Biology: Bioenergy 214, 107-119

GHG emissions are often measured using static chambers (Figure 2.2). The base of the chamber is pushed firmly into the soil and then left in place in the field for some time to avoid extra soil disturbance that can stimulate mineralization of soil organic matter. The chamber is then closed at the time of sampling with a lid fitted with sampling ports and samples taken for analysis. Gas concentrations are measured either by taking samples using a syringe which are then injected into vials and sent for analysis at a central location, or samples are taken and analysed directly using an infra-red gas analyser. Samples should be taken consistently at the same time of day to ensure day-to-day comparability as there are potential diurnal cycles in the rate of emission. Both methods are widely used in research and have different advantages (Table 2.1). It should be noted that static chambers strongly underestimate NH_3 emission, because there is no wind or turbulence in the chamber. Nevertheless, such static chambers can be used to determine differences in risk of NH_3 emissions between fertilizers.

Figure 2.2 Simple static chambers can be made from locally-available PVC drainage pipes. The lids have two valves, one to allow pressure within the container to equilibrate and one for sampling gases using a syringe, or a gas analyser (diagram from K.S. Lourenço).

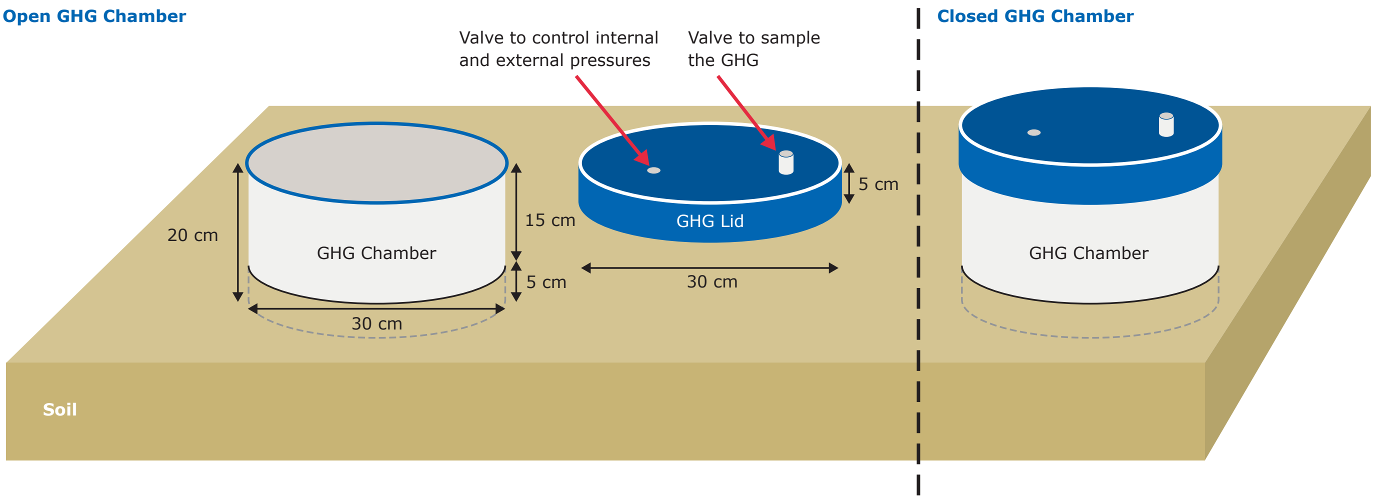


Table 2.1 A comparison of the methods for measuring GHG emissions used by the Group of Sustainable Agroecosystems at ETH, Zurich (ETHZ-SAE), Centro Internacional de Agricultura Tropical (CIAT), Cali, Colombia and Wageningen Environmental Research (WEnR).

Attribute	Fixed chambers – manual sampling (ETHZ-SAE and CIAT)	Fixed chambers – continuous flow (WEnR)
Which gases measured	CO_2, N_2O and CH_4	CO_2, N_2O, CH_4 and NH_3
Sampling schedule	Fixed chambers are carefully located in the field to take account of spatial variability. Gas samples are taken by syringe from each chamber at four intervals of 20 mins over an hour (0, 20, 40 and 60 mins after closure of the chamber). A linear regression is fitted to increase in gas concentrations over time and the slope of the regression provides the rate of emission for each gas measured accounting for chamber volume and area.	Fixed chambers are carefully located in the field to take account of spatial variability. Two measurements are taken directly from each chamber using the gas analyser at intervals of 15 - 30 min and the rate of emission for each gas is calculated accounting for chamber volume and area.
Accuracy	+++ A suite of 4-7 standards is used to assure accuracy and precision for each batch of samples	++ Interference between gases decreases accuracy, especially effects of high concentrations of CO_2 and H_2O on N_2O. Short closure time and if needed traps to remove/decrease CO_2 or H_2O can be used to improve accuracy
Precision	+++	++
Availability of results	Need sending to central location for analysis, so turn around depends on timing of batch analysis.	Immediate. Allows ready adaptation of measurement frequency in treatment comparisons.
Speed of analysis	GC is equipped with an autosampler and can handle about 150 samples per day plus standards. Postprocessing of GC raw data is handled with R.	About 1.5 minutes per sample (depends also on the number of gases that are measured). If emissions are high, a 'rapid box approach' can be used, by which a chamber is placed and continuous measurements for 5 – 10 minutes are carried out.
Cost	5 CHF per sample plus costs of vials and shipping etc.	Euro50k + 10k battery + 5k for teflon tubing, connection materials. Difficult to compare on a sample to sample basis. If all measuring stations are in close proximity some 70-100 samples can be analysed each day.
Feasibility at many locations	+++ sampling vials are shipped to different locations and sampling can be done independently	+ (because of costs of equipment)
Potential interferences	None	Could be sensitive to moisture and CO_2
Training	Straightforward	Straightforward – trouble-shooting requires experience if problems occur.

In the Ground Zero project we will conduct measurements of GHG emissions for two purposes:

First, to quantify N_2O and CH_4 emissions in typical cocoa and coffee production systems under current nutrient management strategies to provide an *accurate baseline of current emissions*. These measurements will be carried out over at least two years due to annual variability in the weather. Baseline measurements will be done at five locations (two for cocoa and three for coffee) using the manual sampling method, with samples sent to ETHZ, Group of Sustainable Agroecosystems (ETHZ-SAE) or to the Centro Internacional de Agricultura Tropical (CIAT), Colombia for analysis.

Second, to explore the use of different management methods to reduce GHG emissions. This work will involve field experiments with, for example, different 4R nutrient management strategies (both fertilizer and waste management) and more in-depth studies to unravel the controlling management factors (e.g. effects of interaction between residues and N fertilizer application). For this work WEnR has purchased an Innova Gas Analyser (see specifications in Appendix 2) which will be deployed to allow rapid turn-around in experiments.

Both in the baseline measurements and management study, measurement of GHG emissions from crop residue and waste management systems (e.g. composting, waste water management) need to be included. The assessments include calculation of indirect N_2O emissions, using IPCC-defaults and, if possible, site specific information on ammonia emissions and nitrate leaching. Where the INNOVA gas monitor is deployed this instrument can also measure ammonia concentrations. However, ammonia emissions measured with static chamber systems tend to underestimate real emissions. Nevertheless, the results can be used to assess if ammonia emissions are important and whether the IPCC defaults for ammonia emission for mineral fertilizers (FRACGASF – 10%) are applicable in cocoa and coffee plantations. An indication of nitrate leaching can be obtained by taking soil samples at different times (e.g. during the rainy season) and measuring nitrate concentration at different depths.

This result and a calculated N surplus on the soil balance (=input minus removal of N by harvested products) can be used to evaluate if the IPPC default leaching fraction (FRACLEACH) of 30% of the N applied also holds in cocoa and coffee plantations. Understanding of the amount and timing of any N surplus is also helpful to understand the fate of N through leaching, ammonia emissions, N_2O emission, N_2 emission and/or N accumulation in the soil.

2.2.2 Deploying and improving the Cool Farm Tool

The perennial module that has been developed for use with the CFT is called the Individual Biomass Module (IBM, Ledo et al, 2018). The IBM uses three logistic curves to estimate standing biomass related to age of the tree: woody biomass, leaf biomass and coarse root biomass. These curves are for potential production and calibrated on literature data. Perennial trees drop leaves during the growing season and that is assumed to be 1/3 of the present leaf biomass per year. Fine roots are similarly estimated. Based on the coarse root mass, fine root mass is estimated using a logistic curve. Both fallen leaf mass and fine root mass are assumed to decompose annually following a standard decomposition curve of which a decreasing amount remains in the soil. Pruning is included as a management input and pruning removes woody biomass from the standing biomass to litter. Litter can be removed from the field, shredded and left on the soil or composted. The approach was recently modified to include parameter sets for biomass estimated for shaded and unshaded cocoa and coffee cropping systems (Sanginés de Cárcer et al, 2022). The IBM is used to estimate the biomass increase for the year of interest, based on the age of the trees. The current management is forced on the tree growth curve. For example, the age of the majority of the trees is 15 years old according to the farmer who indicated that all of the cocoa trees are pruned every other year. The pruning management is now assumed to be applied from age 5 onwards and every other year, as that is the general age farmers start pruning trees. The biomass sequestered is the increase in year 15 according to the biomass curves (year 15 standing biomass – year 14 standing biomass), plus all the remaining biomass from the decomposed biomass pools (leaf litter, prunings if left on the field as indicated by the farmer, and fine roots).

The IBM R-script (Ledo, 2018, supplementary information) allows users to evaluate C sequestration and GHG emissions for practices specific to perennial crops. The evaluation of resource inputs such as fertilizers, pesticides and fossil fuels, and C sequestration by several groups of shade trees in different climate zones can be evaluated through the web version of the CFT application or using an Excel spreadsheet.

Collecting data for the CFT and the IBM model of farmer practices is mostly done through interviews. Local enumerators need to be familiar with the production systems and practices and have a background in agronomy to be able to adequately collect the data. A questionnaire with pre-filled lists of answers on inputs used (type of fertilizers, names of products etc) is highly recommended to facilitate both the interviews and data processing. These pre-filled lists need to be custom made for each

region. The parameters on which it is most difficult to collect quality data are farmer estimates on area under cultivation, the number, type and size of shade or remnant trees and pruning practices. Enumerators must be equipped with strict guidelines on what needs to be collected but also for which purpose, as that helps them to provide essential information for farmers to be able to provide accurate answers.

The R-script has been translated into C# by Wageningen Plant Research (Annette Pronk) to accommodate the evaluation of a large number of individual cocoa or coffee plots which are subsequently combined with the spreadsheet results in an online database and aggregated to farm level results. An evaluation has been done using this method for approximately 10000 smallholder cocoa farmer plots on three continents (South Asia, Africa and Latin America). This approach was used in 2020 to evaluate the GHG Emissions of approximately 500 coffee farmers in Nicaragua as a baseline and an endline evaluation was performed in 2022. The quality of the results depends on the quality of the input data which are the results of farmer interviews. Some questions may seem simple for researchers, but may be difficult to answer for smallholder farmers. This means that representative default values are needed to allow the tool to be applied. We plan to conduct a sensitivity analysis to understand better which input parameters are the most important to estimate accurately. A detailed list of information needed for the CFT (including the IBM) is provided in Appendix 2.

2.2.3 Novel methods to estimate above-ground C stocks

National forest inventory and satellite images are principal data sources used to calculate area change, above-ground C stocks, and are hence used to establish baseline reference emission levels. However, national forest inventories are often outdated and inconsistent because they lack adequate financial support as well as technical and skilled human resources to acquire and update the data. A variety of practical experiences from developing countries, e.g. Vietnam, Ethiopia, Tanzania, Cameroon, India and Mexico have demonstrated that local communities can play an essential role in forest monitoring and management program (Danielsen *et al.*, 2011, Pratihast *et al.*, 2012). Moreover, if communities are involved in measuring the above-ground biomass C pool (which can be used in calculating the C stock changes) in the farms they manage, they may establish 'ownership' of any C savings and greatly increase transparency in the sub-/intra-national governance of C financing.

2.3 Review of knowledge on the link between practices and components of C footprints in cocoa and coffee

2.3.1 Narrative summary of results and main findings

Overall, practices that enhance productivity while enhancing the efficiency with which added nutrients are converted into biomass and yield will reduce the emissions per unit of produce. This includes all agronomic practices which might be termed 'good agricultural practice (GAP)' or 'best management practices (BMP)' which contribute to better nutrient use efficiency. What is considered to be GAP or BMP varies across localities and needs to be agreed by local experts. There may be trade-offs with other regenerative principles (e.g. soil health, biodiversity) which emphasises the need for an integrated assessment. Agroforestry systems, by increasing tree cover, sequester and store more carbon than cocoa monocultures, but could result in trade-offs in terms of decreased productivity of understorey cocoa and coffee. A list of criteria and related practices is included in Table 2.2 below. Much of the research that will be done through the Ground Zero project will focus on testing the assumptions behind whether these suggested improved practices actually contribute to reducing the overall C footprint of cocoa and coffee production, and to what extent.

2.3.2 Summary table

Table 2.2 Some examples of links between criteria and practices

Criteria	Practices	Notes on (strength of) evidence for the relationship
Increase productivity of the cocoa or coffee crop	Better management practices, including pruning, crop sanitation, nutrient management etc	**Well-established.** The more above- and below-ground biomass the more C is stored.
Improve the efficiency of N fertilizer uptake and use by the crop	Focus on the the 4R's of nutrient management (Right source, Right rate, Right time, Right place)	**Well-established** (but most evidence in annual crops). The more N is converted directly into biomass and yield the less N is susceptible to loss. Good agronomic practices in terms of crop management (e.g. crop sanitation, pruning) are essential to ensure strong nutrient demand.
Maintain soil cover	A continuous mulch cover is critical for preventing soil erosion, promoting microbial activity, and saving water	**Well-established.** Practices include maintenance of a continuous litter layer, cover crops and intercropping.
Enhance residue recycling within the plantations	Attention to residue recycling to ensure maximum recycling of nutrients and minimise GHG emissions from waste management	**Well-established.** Efficient recycling minimizes the need for additional nutrients. Need further research to clarify best management approaches for waste management (e.g. composting etc)
Agroforestry systems, by increasing tree cover, sequester and store more C than monocultures	Increase the proportion of shade trees	**Well-established.** Maney *et al.* 2022 indicate: *"Carbon storage in cocoa-based agroforestry systems is significantly higher than in monoculture cocoa (Nijmeijer et al., 2019, Schneidewind et al., 2019, Schroth et al., 2016) and agroforestry systems can provide a cooler and more sheltered microclimate (Niether et al., 2020). Additionally, there is evidence that nutrient cycling in agroforestry systems can be comparable to natural systems (Nijmeijer et al., 2019; though see also Blaser et al., 2017)"*

2.4 Improving the Cool Farm Tool for assessing C footprints in cocoa and coffee

Due to the complex and multi-dimensional nature of C footprints, our main focus will be on improving and deploying the Cool Farm Tool (CFT) for both cocoa and coffee. To this end the majority of our focus to date has been on identifying knowledge gaps and areas for improvement of the CFT. It is possible that some management practices and intermediate measures that are known to enhance C storage, such as those described in Table 2.2 can also be used as indicators for progress towards zero emissions, which deserves further attention during the project.

2.4.1 Areas for improvement in the Cool Farm Tool

Potential areas for improvement of the Cool Farm Tool are summarised in Table 2.3. The Individual Biomass Module (IBM) used in the CFT assumes potential biomass production which is seldom the case. The included reduction factors for water and/or nitrogen are set at 1, that is no reduction factor is included, simply because it is not clear what the factors should be and how they can be implemented. Furthermore, the biomass curves are assumed to be for unpruned trees, which is also seldom the case. Pruning needs attention and additionally the implementation of pruning is important to evaluate. Other assumptions that need to be verified are the amount of leaf litter, which is assumed to be equivalent to one third of the total annual leaf biomass, as well as the assumed nutrient content of leaf litter which is important as it drives the decomposition pathway for C sequestration. The coarse and fine roots can contribute considerably to carbon stocks (Pronk *et al.*, 2002) and are currently based on literature but data is very limited and conditions under which measurements were taken (potential production, pruned or not) is seldom known. As literature sources for these data are limited, these variables need both calibration and validation. Due to lack of sensitivity analysis on the parameters it cannot be indicated which are the most important ones but it is clear that small overestimations of carbon sequestration can easily become out of hand over a period of 20 to 25 years, the normal economic lifetime of a productive cocoa or coffee tree. One critical issue with the IBM which needs to be addressed is the lack of a carbon balance. The calculations are quite complex as most output is converted to CO_2-eq, including N fluxes, so the final outcome does not depend only on direct emission of C. In addition, small errors may accumulate over time leading to substantial overestimates of C sequestration.

Table 2.3 Identification of current weaknesses and possible areas for improvement of the Cool Farm Tool for cocoa and coffee. Initial attention will be to understand the sensitivity of outcomes from the tool by conducting a sensitivity analysis, which will provide guidance on where greater focus is needed. In all cases attention will be paid to identifying simple methods or proxies that are feasible to use with farmers to guide their management.

Topics	Weakness	Proposed improvements
Relative importance of input parameters	There is uncertainty concerning which input parameters are the most important in determining outcomes. Small errors can be propagated over the plantation cycle.	Conduct a sensitivity analysis of the model for different types of plantation systems to guide the focus on model improvement
Biomass production	It is assumed that cocoa and coffee trees achieve potential biomass production	Use actual biomass production estimated per location? Derive water and nutrient limitation factors to constrain biomass production
Pruning	Biomass curves used are for unpruned trees	Derive an accurate approach for estimating effects of pruning on biomass estimates
Litter turnover	It is assumed that annual leaf litter turnover is 1/3 of the total leaf biomass.	Update the turnover value based on literature and recent experiments done in CocoaSoils (e.g. ongoing CocoaSoils work of Déo-Gratias Hougni)
Root turnover	Turnover of coarse and fine roots based on limited measurements	Conduct a detailed review of the literature to see if improvements can be made.
Management of fertilizer N	Emission factors of N-fertilizer use in perennial tropical systems appear to be double (~2%) those of annual crops (~1%). More importantly, the factor is independent of NUE so there is little incentive to (i) match N use to target yield, and (ii) improve placement and timing of application by spreading fertilizers to help avoid N peaks in the soil solution that drive N_2O losses.	Derive emission factors to address the 4R's of nutrient management (Right source, Right rate, Right time, Right place) to reward better management practices.
Integrated Soil Fertility Management (ISFM)	ISFM not currently considered but as part of regenerative practices many are recommending co-application of organic residues and mineral fertilizers. Mineral N addition to organic matter application may accelerate N_2O emissions from (de)nitrification processes.	Derive emission factors for mixing organic resources and mineral fertilizers. This will need experimental research.
Use of nitrification inhibitors	Nitrification inhibitors may be a useful management tool to decrease N_2O emissions. Biochar has been proposed as a nitrification inhibitor, although testing has been in laboratory experiments with unrealistically large application rates. Inhibitor use is currently a yes/no option, but guidance needs to be provided on what constitutes effective inhibitor practices (i.e. type, quantity, timing)	Derive emission factors for nitrification inhibitors based on detailed experimental research under field conditions, so that CFT provides better guidance on realistic application methods and quantities.
Organic wastes/ compost	Wet coffee pulp is often treated in several steps (e.g. left in heaps, composted in windrows in dry or wet conditions) of different duration before being re-applied back to the field. The duration of each step will impact emissions, but the CFT currently only allows one treatment option with no duration indication. In addition, users often generate errors with % moisture – dry matter equivalent conversion factors.	Derive emission factors for different methods for organic waste management and duration. This will need experimental research including various composting methods (anaerobic/ aerobic conditions, mixing C and N rich materials etc).
Washing of coffee beans and waste water management	Emissions related to post-harvest operations need to be included (e.g. washing of coffee beans). Emission factors for waste water in settling ponds include only an arbitrary factor (2 m depth). Methods to reliably measure COD in waste water over space and time do not exist.	Derive more accurate emission factors for post-harvest treatments and waste water treatment, including oxygenation. Emissions could be calculated based on (i) COD derived from mass balance of process steps and (ii) degree of oxygenation of the waste water.
Amendments (e.g. lime)	Current CFT emission factors are based on assumptions and few direct measurements. No emission factors are available for all amendments, some of which may exhibit net C sequestration.	Confirm current CFT emission factors are appropriate, or otherwise derive more accurate emission factors. Develop emission factors for new sources of amendments.
Intercropping	Currently calculations depend on assigning land area to different crops	Explore if additional parameters (e.g. yield) could be collected easily to provide more accurate assessment

3 WP3: Soil Health

3.1 Soil health: definition and concept

Soil health is "the capacity of soil to function as a vital living system, within ecosystem and land-use boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and promote animal and human health" (Doran and Zeiss, 2000). A shorter definition that is also widely used describes soil health as "the continued capacity of a soil to function as a vital living system that sustains plants, animals and humans"[3]. Soil health does not reflect the composition of soil per se, but rather its capacity to promote the pertinent social and environmental functions and benefits of the land (Janzen *et al.*, 2021). Soil health should thus be seen as a broad concept that needs to be contextualized by defining objectives and desired outcomes (Amponsah-Doku *et al.*, 2022a). Central to the concept of soil health is the capacity of a soil to supply multiple soil functions, which depends on physical, chemical and biological soil properties and processes and their interactions (Creamer *et al.*, 2022; Pulleman *et al.*, 2022). Those properties and processes are in turn defined by ecosystem boundaries (including pedoclimatic conditions), the land use history and the current use and management of the land.

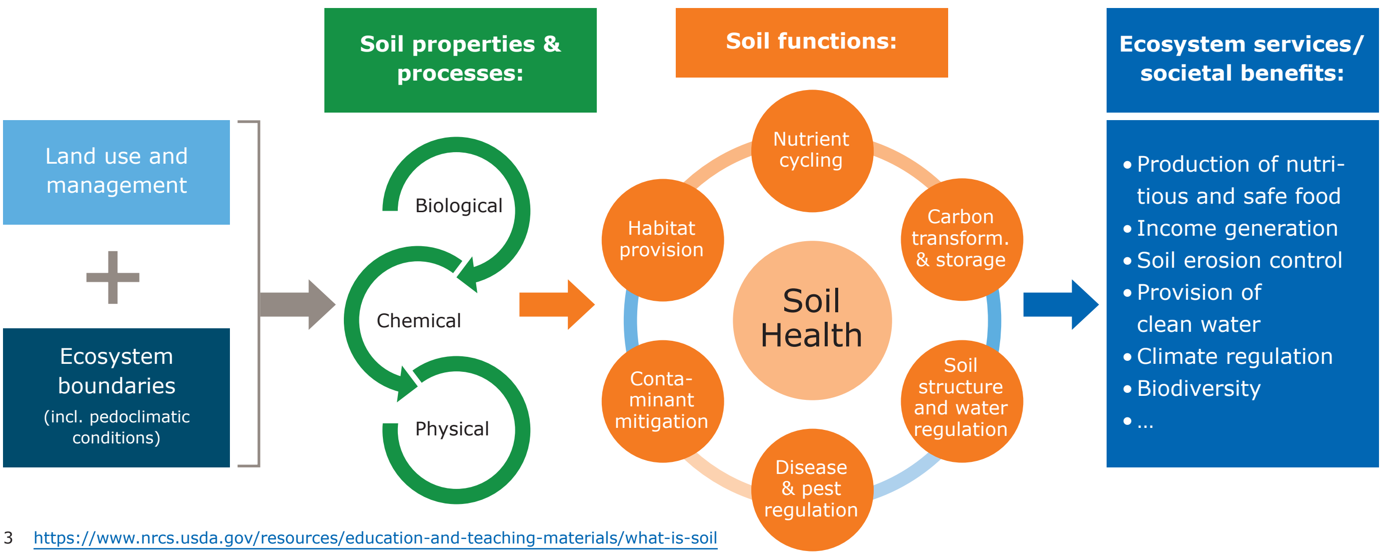
The most prevalent soil functions for agricultural land are primary production, nutrient cycling, carbon storage, water regulation, disease & pest control, contaminant mitigation and habitat provision (Creamer *et al.*, 2022).

Healthy soils thus contribute to important social, economic and environmental benefits or sustainability goals such as the production of nutritious and safe food and other raw products, income generation, soil erosion control, provision of clean water, climate regulation (greenhouse gas mitigation) and biodiversity (Lehmann *et al.*, 2020). Healthy soils also contribute to climate resilience of (agro) ecosystems through improved water infiltration, moisture retention, rooting conditions and disease suppression (Bongiorno *et al.*, 2019) (Figure 3.1). Ideally multiple soil functions are optimized by strengthening synergies among different functions and benefits, but trade-offs are likely to occur and may need to be optimized.

3.1.1 The role of soil biota and biological aspects of soil health

Soils host enormous biodiversity (Orgiazzi *et al.*, 2016). Soil biodiversity refers to the quantity, variety and structure of all forms of life in soils, as well as related functions (Bispo *et al.*, 2009). Soil biota comprise viruses, bacteria, fungi, protozoa, nematodes, collembolans, mites, earthworms, soil-dwelling insects, and vertebrates such as moles and voles, organized in complex food webs (Orgiazzi *et al.*, 2016; Pulleman *et al.*, 2012). It is increasingly recognized that soil biota play a key role in mediating natural soil processes underpinning each of the seven soil functions shown in Figure 3.1 (Bünemann *et al.*, 2018) and are thus crucial to maintain healthy soils, although the relations between soil management, soil biodiversity, soil functions and crop production are not fully understood.

Figure 3.1 The general concept of soil health proposed for the project. See text for detailed explanation.



3 https://www.nrcs.usda.gov/resources/education-and-teaching-materials/what-is-soil

Soil organisms have been classified according to their taxonomic identification, their position in the soil food web and body size. Taxonomic identification can be problematic because of the huge diversity of certain groups and because a vast amount of soil organisms has not yet been identified. Relations between soil biodiversity and ecosystem functions, however, tend to depend more on structural and functional diversity than on species richness per se (Bloor *et al.*, 2021; Pulleman *et al.*, 2012).

Agricultural activities can have important effects on soil communities. Negative impacts of agricultural intensification on the structure (food web complexity) and diversity and abundance of soil communities have been known since several decades. Soil disturbances related to agriculture have stronger negative effects on higher trophic levels in the food web and on soil fauna with larger body sizes (Bloor *et al.*, 2021; Hendrix *et al.*, 1986; Tsiafouli *et al.*, 2015; Wardle, 1995), but those changes can have cascading effects on lower trophic levels effects (Pulleman *et al.*, 2012; Wardle, 1995). It has been shown that changes in soil food web structure and loss of so-called 'keystone species' that have a unique role in specialized soil processes and belong to physiologically and phylogenetically 'narrow' organism groups, can result in a drastic loss of function. Examples of such keystone species are Rhizobium strains that fix nitrogen with a specific legume (Pulleman *et al.*, 2012, 2022), fungal species that are capable of decomposing recalcitrant organic compounds, or bioturbators/ecosystem engineers such as earthworms and termites (Jongmans *et al.*, 2003; Paul *et al.*, 2015; Pulleman *et al.*, 2003). Yet certain management practices and/or land use systems contribute to re-establishing diverse soil communities and their activities, such as organic soil management, agroforestry or conservation agriculture (Hartmann *et al.*, 2015; Pauli *et al.*, 2011; Rousseau *et al.*, 2013). For further reading about the relations between soil management, soil biota and soil health see (Hoffland *et al.*, 2020; Pulleman *et al.*, 2012, 2022). For information about organism groups involved in specific soil functions see Biosis platform [4]. For an illustrated overview of different soil organisms, we refer to the Global Soil Biodiversity Atlas[20].

3.1.2 Criteria and practices for soil health in coffee and cocoa

As stated above, soil health is a broad concept that needs to be contextualized according to ecosystem and land use boundaries. With respect to soil health, the following criteria/objectives have been identified for coffee and cocoa production systems across diverse production regions globally (Table 3.1). The list is based on expert consultations targeting coffee and cocoa experts: it was notable that in all of the discussions threats to soil health were identified. On this basis they become key criteria and objectives that need to be addressed in order to enhance soil health.

Table 3.1 Criteria for soil health enhancement based on expert interviews and literature, and their relationship with the soil functions according to Figure 3.1.

8 criteria (based on priority objectives)

1. Soil erosion
2. Soil acidification
3. Nutrient availability and retention
4. Increase soil organic carbon/matter
5. Water retention and drainage
6. Soil biodiversity
7. Biocontrol of pests and disease
8. Cadmium (cocoa only and region specific)

↔

7 soil functions (based on Figure 3.1)

- Nutrient cycling and provision
- Carbon cycling and storage
- Water regulation
- Habitat for biodiversity
- Pests & disease regulation
- Contaminant (Cd) mitigation
- Primary productivity

4 http://www.biosisplatform.eu

During these expert consultations we also discussed the (sets) of practices that can be employed to achieve the objectives and important knowledge gaps and barriers to adoption. The completeness of the list of practices was confirmed based on complementary literature review (Amponsah-Doku *et al.*, 2022). The following practices are considered most relevant for the management of soil health in coffee and cocoa:

Proposed practices

- **Soil conservation measures** (contour planting, vegetative erosion barriers, terracing)
- **Permanent soil cover** (mulching, intercropping, cover crops, selective weed management)
- **Agroforestry**
- **Optimized fertilization** (based on 4R principles & soil/leaf testing)
- **Integration of organic amendments** (through recycling of local residue and waste streams, where possible)
- **Limit pesticides use/IPM**
- **Biostimulants/beneficial microorganisms**
- **Inorganic amendments** (lime, silicates, gypsum, biochar)

3.2 Review on the links between practices and soil health in cocoa and coffee

3.2.1 Strength of evidence

We reviewed the strength of scientific evidence for the links between the different (sets of) practices and their outcomes in terms of soil health, according to the different objectives/criteria. The results are summarized in Table 3.2 and a more detailed overview can be found in Annex 3.1 including references. We distinguished the following categories of supporting evidence: **Well-established** (ample supporting evidence); **Established but incomplete** (few available studies, but what's there is in agreement); **Inconclusive** (few studies and little agreement); **Unresolved** (ample studies but contradictory results). For some of the combinations of objectives and practices, the number of studies available for coffee or cocoa is too limited, so we indicated that the evidence is based on other types of cropping systems. The strength of evidence, or lack thereof, is one of the criteria used to inform the selection of indicators to be used for the project (especially in Phase 1, the research phase).

Table 3.2 Strength of evidence# for the links between supporting practices and each of the objectives/criteria for soil health. For further detail and references see Annex 3.1.

Practices / Criteria/functions	Soil erosion	Soil acidification	nutrient cycling and provision	Carbon cycling and storage	water retention	Soil biodiversity/ habitat provision	Biocontrol	Cadmium (cocoa)
Soil conservation measures	WE		WE		WE	EI		
Agroforestry	WE		EI	UR	WE	EI	IC	
Soil cover	WE		WE	EI	WE	EI	EI	
Optimized fertilization		WE	WE			EI	EI	IC
Organic amendments		WE	EI	EI	EI	EI	IC	IC
Biostimulants			UR/IC				IC	IC
Limit pesticide use						EI	EI	
Soil conditioners (including lime)		WE			EI			IC

WE = Well established (ample supporting evidence)
EI = Established but incomplete (few available studies, but what's there is in agreement)
IC = Inconclusive (few studies and little agreement)
UR = Unresolved (ample studies but contradictory results)

The evidence for the links between agricultural practices listed above and the different criteria for soil health is quite strong for the majority of practices and criteria (Table 3.2), although sometimes incomplete due to a low number of available (field) studies for coffee and cocoa. Fewer studies are available for cocoa than for coffee, and sometimes we refer to studies in other tropical tree crops, assuming that the same principles can be generalized to coffee and cocoa. As becomes clear from the overview in Table 3.2, strong synergies exist, as many of the practices listed can contribute to multiple soil health criteria/objectives. Yet, few of the available studies on agricultural practices have simultaneously assessed the impacts on multiple soil health criteria or objectives (Zwetsloot *et al.*, n.d.).

From a soil health perspective, the following practices can be considered no-regret options, provided that they are properly implemented and well-adapted to local conditions: agroforestry, use of cover crops, optimized fertilization and integration of OM inputs. The practices are formulated in a rather generalized way, and research may still be needed to optimize the practices and use of resources depending on local context. This is the case, for example, for the use of organic amendments. Trade-offs (as well as synergies) among soil health and other goals, such as greenhouse gas emissions, productivity, production costs, labour requirements may occur and should be carefully managed. Similarly, an important trade-off can occur when managing organic amendments for soil carbon sequestration. When carbon is stored as a result of the application of organic matter that is transferred from one place to another, this happens at the expense of carbon storage elsewhere. It does not add to reducing atmospheric CO_2 levels (Kögel-Knabner *et al.*, 2022)

Evidence is inconclusive or unresolved for a number of soil management practices or criteria, such as the use of biostimulants to improve nutrient cycling (inconclusive/unresolved), the impact of agroforestry on soil organic carbon sequestration (unresolved). The effects of different types of amendments, micronutrient fertilizers or biostimulants on cadmium availability in cocoa are inconclusive, which is not surprising given the complexity of the problem and that the issue is relatively new. The importance of soil health enhancing practices for natural control of soil-borne pests and diseases (inconclusive) has traditionally received very little attention in soil health assessments, perhaps due to the complexity of mechanisms underpinning soil suppressiveness and because practices and mechanisms cannot easily be generalized; they are rather crop, disease/pest and environment-specific. Yet, given the large yield losses of coffee and cocoa due to pests and diseases, and the challenges of climate change which can aggravate pest and disease outbreaks, this soil function deserves more attention especially for soil-born pests and diseases. Moreover, the indirect effects of improved soil health on pests and disease through improved nutrient cycling and plant nutrition affecting plant defense need to be better understood (Mur *et al.*, 2017).

With the growing popularity of nature-based practices the interest in the use of microbial inoculants and other biostimulants, like seaweeds or fermentation products to enhance nutrient cycling, crop nutrient use efficiency or pest and disease suppression has also increased (Rouphael *et al.*, 2020). The benefits of rhizobial inoculation in stimulating nodulation and nitrogen fixation in legumes are well-established (Giller, 2001; Vanlauwe *et al.*, 2019). Inoculation with Trichoderma spp. has shown benefits in control of plant diseases, particularly root rots (Avelino *et al.*, 2012). To the best of our knowledge there are no studies that have shown benefits of biostimulant application (including living microorganisms) or biopesticides in cocoa and coffee. Indeed, there are few independent scientific studies that assess biostimulants on crops and those published show no consistent benefits (Rouphael *et al.*, 2020). The success of inoculations with beneficial microorganisms like AMF tends to be extremely context and pest/disease specific and depends on the native soil community. The quality of the products is another factor that can limit their effectiveness (Pulleman *et al.*, 2022).

3.2.2 Key knowledge gaps

Following from the analysis made in Section 3.2.1 we identify the following knowledge gaps:

1 Implications of specific agroforestry designs (e.g. selection of tree species/traits and management) on nutrient cycling and soil carbon storage in different pedoclimatic conditions (ongoing project: Clima-LoCa; see Annex 3.3) (Niether *et al.*, 2020).
2 Effects of deep rooting (intercrops) on soil carbon storage and water and nutrient use efficiencies contributing to climate resilience.
3 Integration and optimization of the use of low-cost organic soil amendments, based on local residue and waste streams, to enhance use efficiency of mineral fertilizers (ongoing project: Rustica).
4 Agronomic effectiveness and underlying mechanisms of biostimulants, including locally produced so-called ‘biofertilizers’
5 Effects of soil amendments and micronutrient management on Cd availability and uptake in cocoa (ongoing project: Clima-LoCa).

Few studies in coffee and cocoa have assessed impacts of agricultural practices considering multiple soil functions

underlying soil health (Zwetsloot *et al.*, n.d.). There are also important knowledge gaps related to the synergies and trade-offs between soil health and productivity, profitability and greenhouse gas emissions that need to be addressed to improve recommendations on soil health enhancing practices. Those include:

6 Balance between SOC storage and mineralization (Janzen, 2006): How can the goal of nutrient cycling and other functions that rely on high microbial activity be reconciled with increasing SOC storage (Liptzin *et al.*, 2022).
7 Trade-offs and synergies between soil carbon storage and GHG emissions (CO_2, CH_4 and N_2O) directly from the field and indirectly from composting for example (see WP1).
8 Trade-offs and synergies between (components of) soil health and coffee/cocoa yields and input use efficiency/production costs (Wade *et al.*, 2020).
9 Trade-offs and synergies between cadmium mitigation in cocoa, soil fertility and crop productivity (ongoing project: Clima-LoCa).

3.3 Review of indicators for assessing soil health in cocoa and coffee

3.3.1 Soil health indicator schemes and requirements

Environmental indicators are measurable surrogates for environmental endpoints that are in themselves too complex to measure directly. Such indicators should give information about the (change in the) condition of an ecosystem and support environmental decision making (Pulleman *et al.*, 2012). Soil health cannot be measured directly because it is a broad, integrative, context-dependent concept. Yet, to be able to target management interventions and monitor progress towards the objectives, we need to assess soil health based on measurable proxies that together tell us something about (i) the capacity of the soil to support multiple functions and benefits, and ii) the actions to be taken to enhance this capacity. These measurements are called soil health indicators. There is broad consensus that multiple aspects (chemical, physical and biological) of soils and their interactions need to be considered to assess soil health. A second requirement for indicator schemes is that they can effectively support decision making by end users, which could include policy makers or (different groups of) practitioners. Third, to operationalize indicator schemes in the context of global food systems and supply chains, indicators must be scalable. This means: affordable, practical and applicable/adaptable to specific conditions, spatial and temporal scales, and objectives/users. Finally, indicator schemes should be robust and meaningful in terms of their interpretations according to the different soil functions or soil health criteria of interest.

3.3.2 Lessons from existing indicator frameworks and tools

An increasing recognition of the importance of soil health has led to the development of a myriad of soil quality indices and assessment frameworks, including national or regional monitoring programs for policy purposes and different soil quality assessment tools that target researchers and/or farmers (Bünemann *et al.*, 2018). Most indicator schemes focus on temperate climates and annual cropping systems or pastures. Soil health indicators can be measured at different scales from plot to farm to landscape and almost all existing approaches focus on agricultural fields, with the LDSF (Vågen and Winowiecki, 2023) being the exception that focuses on landscapes. Few existing approaches for assessment of soil health have been applied to coffee or cacao (or other tropical perennial crops), with a few exceptions (Araujo *et al.*, 2018; Rekik *et al.*, 2018; Rousseau *et al.*, 2013). Based on an analysis of 65 soil health/quality frameworks, Bünemann *et al.* (2018) concluded that there is a general lack of clear interpretation schemes of measured indicator values which limits their adoption by practitioners or decision makers. An inventory of existing indicator frameworks or tools that could be of interest as inspiration for our project is presented in Annex 3.2. A few of them include interpretation schemes and decision support tools (Moebius-Clune *et al.*, 2016; Ros *et al.*, 2022).

Bünemann *et al.* (2018) identified frequently used indicators in agriculture, showing that assessments are strongly dominated by chemical and physical indicators while assessments of biological indicators are limited. Soil-health assessments often include total organic carbon, pH, plant-available macronutrients, total N, electrical conductivity and cation exchange capacity. Some other chemical indicators that are measured less frequently are heavy metals, sodicity/salinity, micronutrients and soil organic matter pools. In terms of physical properties, the most popular ones are available water capacity, bulk density, texture, soil depth, soil hardiness, and aggregate stability. Less frequently measured physical parameters include hydraulic conductivity, pore distribution and infiltration. Biological indicators were included in less than 30% of assessment frameworks and included respiration, microbial biomass, N mineralization and earthworms (Bünemann *et al.*, 2018).

Total soil organic carbon or soil organic matter is the most widely measured indicator. This is not surprising given that soil organic matter is the primary food source for soil organisms and has a major influence on physical and chemical soil properties and processes. Its importance is also well understood by many farmers (Amponsah-Doku *et al.*, 2022). Yet, changes in total soil organic matter content are generally too slow for SOM to be a sensitive indicator of changes in soil health and the responses of soil biota to changes in soil organic matter (management) are not straight forward. With 'living' being part of the definition of soil health, it seems essential to measure biological indicators of soil health (Liptzin *et al.*, 2022). Biological indicators of soil quality have gained research attention and tend to respond more quickly to management changes (El Mujtar *et al.*, 2019; Pulleman *et al.*, 2012), although little evidence has been provided to link the indicators to aboveground productivity (Amponsah-Doku *et al.*, 2022). Including soil biodiversity in large scale soil assessments, can provide further empirical evidence on the interplay between agricultural practices, soil biota, and crop productivity, while rapidly advancing methodologies in biology will help to develop more robust indicators.

Besides the distinction between biological, physical and chemical indicators, some of the existing frameworks distinguish between inherent/static indicators that are important for soil functioning but do not depend on management (e.g., texture, mineralogy) but are important for interpretation, and dynamic indicators that do (Bünemann *et al.*, 2018; Lehmann *et al.*, 2020; Moebius-Clune *et al.*, 2016). When reviewing existing indicators being measured by supply chain partners active in coffee and cocoa (for example Rainforest Alliance) such as Nestlé's FAT tool or the Rainforest Alliance Scorecard, we see a strong focus on practice indicators, and some context indicators. But so-called outcome indicators that can be linked to soil health functions are (still) strongly underrepresented.

There is general agreement among existing indicator schemes that suitable indicators should meet the following requirements: be responsive to changes exerted by drivers (but not too sensitive to short-term temporal variation (e.g., weather effects), be practical (easy to measure, cost effective) and meaningful (i.e. they can be linked to the soil functions of interest) (Lehmann *et al.*, 2020; Liptzin *et al.*, 2022; Pulleman *et al.*, 2022). Table 3.3 is based on the list of requirements that was used in the United States by the Cornell Framework for Comprehensive Assessment of Soil Health (CASH) approach to select a set of 13 suitable indicators for nationwide soil health monitoring out of an initial list of 42 potential indicators (Moebius-Clune *et al.*, 2016).

Table 3.3 Requirements for selection of suitable soil health indicators

Indicator requirement	Description
Pertinence	Ability to represent important soil functions
Practicality	Ease and cost of sampling and cost of analysis, need for and availability of specific infrastructure/equipment/skills
Sensitivity	Ability to detect change in response to management
Robustness	in terms of temporal and spatial variation unrelated to management, and reproducibility within/across laboratories
Practical	ease and cost of sampling and cost of analysis, need for and availability of specific infrastructure/equipment/skills

A long list of available soil health indicators and their relevance to each of the criteria and soil functions defined in Section 3.1.2 is shown in Annex 3.5. We categorized each indicator according to indicator type (biological, chemical, physical) and whether it provides information on outcomes, practices or context. Besides indicators that are based on soil properties or processes we also added some indicators that are measured in plants but that can reflect the effects of production practices on soil processes (e.g., foliar Cd concentrations). More detailed information is provided in a dynamic excel file that will be updated according to further feedback obtained from experts and stakeholders. The excel file is used to score different indicators based on the set of requirements listed in Table 3.3. We will thus be able to discuss and justify in a systematic and transparent way how we arrived at the medium list (Phase 1, researchers) and short list (Phase 2, supply chain partners) to be proposed for the Ground Zero project.

3.3.3 Data gaps and methodological challenges, and novel approaches to address them

Based on the long list of indicators presented in Annex 3.5 we conclude that many indicators are potentially available for all criteria that were prioritized for coffee and cocoa during expert consultations and literature review. However, challenges remain to their assessment in terms of sensitivity and robustness (e.g. soil organic matter content) and their potential for scaling (practicability, feasibility, reproducibility). The latter is especially challenging for some of the biological indicators that tend to be more laborious and costly and that require sophisticated lab equipment and trained operators. Soil organic matter/carbon is one of the most meaningful indicators across contexts that integrates multiple soil functions. However, soil organic carbon is not the most sensitive indicator (Liptzin *et al.*, 2022), due to its slow change given the large background SOC stocks in soils. SOC content also tends to show high within field variation which challenges its robustness. Finally, the interpretation of SOC changes over time requires information about the baseline conditions, and about the texture and mineralogy (context indicators), factors that determine to a large extent the potential of the soil to accumulate carbon (Dexter *et al.*, 2008; Hassink, 1997; Rasmussen *et al.*, 2018; Six *et al.*, 2002).

Regarding the lack of sensitivity of soil organic matter as a soil health indicator, significant advances have been made in the recent years regarding the identification of promising practical methods that provide information on SOC dynamics or pools rather than total stocks, including Particulate versus Mineral-Associated Organic matter (POM/MAOM) fractions (Cotrufo and Lavallee, 2022; Lavallee *et al.*, 2020), potential respiration (Leifeld and Kogel-Knabner, 2005; Liptzin *et al.*, 2022) or high throughput enzymatic analyses (Margenot *et al.*, 2018, 2017). Further work is needed to test their applicability, robustness and interpretation in the context of coffee and cocoa production systems. Regarding the potential for scaling, which depends on practical aspects such as costs, time, specialized lab equipment/staff, sample preparation and shipment, there are some recent developments that are worth exploring further in order to address some of the challenges. Some of them are already being addressed in ongoing projects (see Annex 3.3). Those include:

- The use of remote sensing, or proximate sensing using hand-held scanners for assessment of soil properties or processes in perennial crops remains limited, as was also confirmed during the stakeholder interviews (Ongoing project: Excellence in Agronomy, Benchmarks)
- Use of spectroscopic techniques such as lab-based NIRS, MIRS or XRF (Ongoing projects: Clima-LoCa, STDF, Excellence in Agronomy, Benchmarks)
- Use of high throughput enzyme analysis (Ongoing projects: Clima-LoCa, Excellence in Agronomy).

Finally, another methodological challenge relates to the lack of robust interpretation schemes, including benchmarks for measured indicator values across diverse contexts and soil types, and reliable and sufficiently detailed information about management practices. In this area we can explore the applicability of existing approaches such as CASH (Moebius-Clune *et al.*, 2016; Rekik *et al.*, 2018) and Open Soil Index (Ros *et al.*, 2022) and the ongoing EU project BENCHMARKS that is led by Wageningen UR. One of the issues is that coffee and cocoa are generally grown in regions that are relatively data poor. There are good opportunities for sharing knowledge and experiences with the CGIAR initiative Excellence in Agronomy, the latter specifically focusing on smallholder producers in the Global South (See Annex 3.3).

3.4 Proposed soil health assessment framework for the project

3.4.1 Contextualization

Lands cropped to coffee and cocoa are extremely diverse in terms of topography, parent materials, soil forms, intrinsic soil fertility and land use history. Yet, sufficient information is available in different production regions on the crop requirements/suitability criteria in terms of available nutrients, pH, soil depth, texture, drainage, irrigation requirements and the organic matter content of soils (Araujo *et al.*, 2018; Sadeghian, 2022, 2008; Sadeghian *et al.*, 2019; Snoeck *et al.*, 2016). Coffee and cocoa are frequently cropped in acid soils with high rates of aluminium saturation, which can negatively affect nutrient uptake and crop growth, while cocoa and coffee on strongly weathered tropical soils (or volcanic soils) can suffer from low P availability. High cadmium availability can be a problem for cocoa producers in certain parts of Latin America and the Caribbean where relatively high concentrations of cadmium are naturally present in the soil (Vanderschueren *et al.*, 2021). High rates of erosion can be a major challenge in some production regions where coffee and cocoa are grown on steep hillsides but are irrelevant in lowland areas on flat lands. Similarly farm archetypes show extreme contrasts, ranging from low-input smallholder farms of less than 1 hectare, to intensively managed plantations of thousands of hectares. For indicator schemes to be scalable, the relevance and adaptability to different agroecologies, farm sizes and production systems is extremely important.

Additionally, the availability of information or indicators that provides context for the soil's physical, chemical, and biological properties is extremely important. The idea that one set of standard indicators would be applicable and comparable globally, is highly unrealistic. Moreover, different indicator sets may be measured for research purposes (e.g., to provide evidence on assumed benefits from practices based on more detailed assessments on a subset of representative farms) versus large-scale monitoring purposes (e.g., to assess progress towards company commitments). Therefore, a framework that consists of a minimum set of indicators complemented with add-on indicators and methods for certain contexts or purposes, similar to the CASH framework (Moebius-Clune *et al.*, 2016), is recommended. Whether add-on indicators are measured in a given context depends on the prioritized criteria/objectives for soil health assessment (see Section 3.1.2). For example, the criteria 'halt soil erosion', 'prevent soil acidification', and 'reduce cadmium availability and uptake' are not always relevant.

3.4.2 Addressing key knowledge gaps

A major knowledge gap for soil health assessments are the trade-offs and synergies that certain practices can bring about when considering multiple soil functions, as well as the relations between changes in soil health (functions) and the desired benefits or goals at a higher aggregation level. The potential to address those knowledge gaps is an important aspect of the proposed indicator framework. Therefore ideally, the different indicators for the three different work packages should be measured in the same sites, alongside data on crop yields, crop nutrient uptake (allowing us to calculate applied nutrient use efficiencies), disease incidence, and other indicators that can be measure in plants and that provide a proxy for certain processes or benefits of interest at a more integrated level (see figure 3.2).

Figure 3.2 Schematic overview of the proposed soil health assessment framework for the project and that will be tested in the Ground Zero project, considering the criteria for soil health enhancement and their relations with practices (see Section 3.1.2).

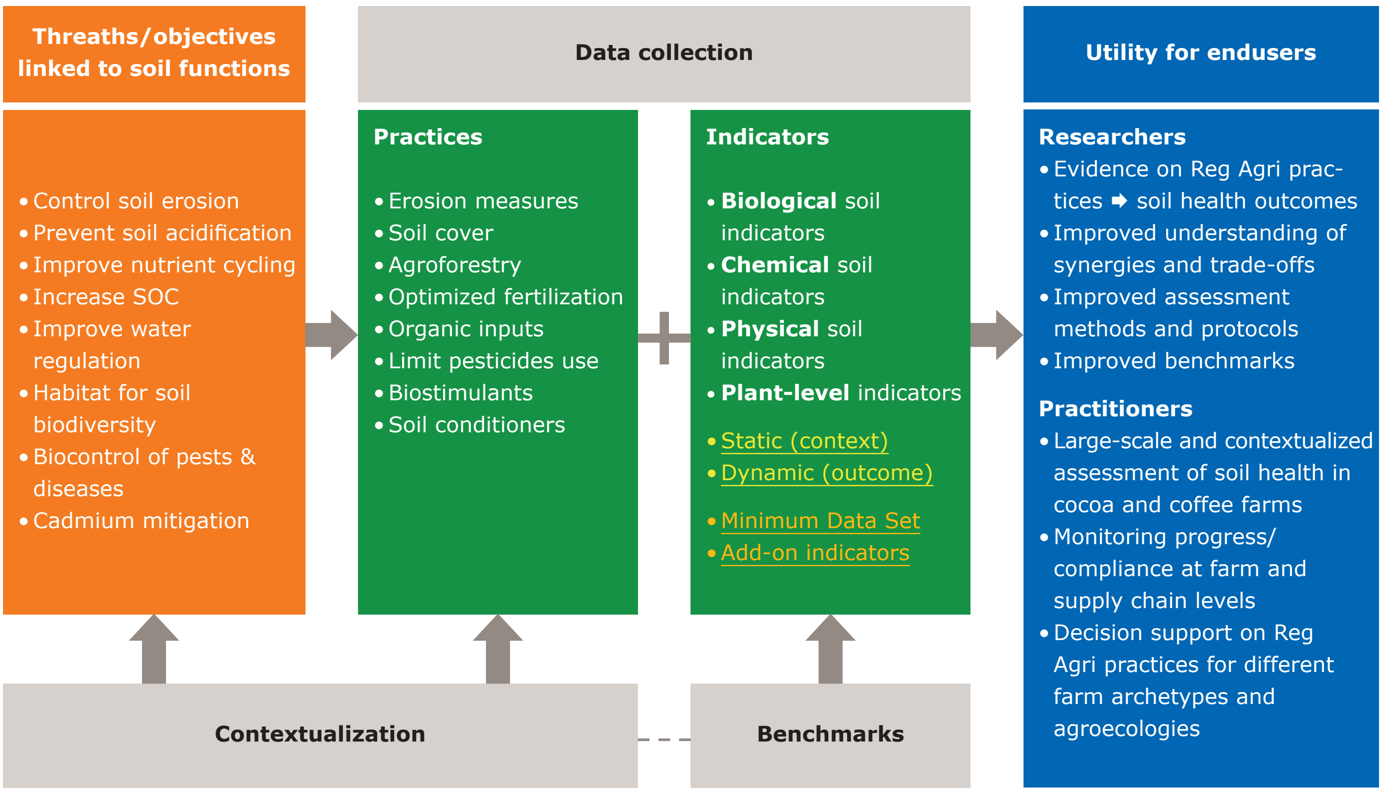


Table 3.4 List of indicators that could potentially be tested in the project (Phase 1; research phase). The first selection was based on the requirements for suitable indicators as shown in Table 3.3 (see Annex 3.4). Further refinement will be done after further expert consultations. In dark blue indicated the indicators that would have potential for assessment at scale, based on simplified methods, but some of them still need some further testing. Note that not all indicators are relevant for all contexts (they can be add-on or optional indicators).

Indicator type	Indicator (longlist)	Static/ dynamic	MDS / Add-on	Field or Lab method	Nutrient cycling	Carbon storage/ cycling	Water regulation (including soil erosion)	Pest control	Soil bio-diversity	Cd mitigation
Biological	Active fungal and bacterial abundances	D	MDS	Lab	1	1	0	1	1	0
	Earthworms density	D	MDS	Field	1	1	1	0	1	0
	Earthwom excrement counts	D	MDS	Field	1	1	1	0	1	0
	Enzyme activities	D	MDS	Lab	1	1	0	0	0	0
	Litter decomposition	D	MDS	Field or lab	1	1	0	0	0	0
	Nematode communities and maturity index	D	MDS	Lab	1	0	0	1	1	0
	Potential C mineralization	D	MDS	Lab	1	1	0	0	0	0
	Potential N mineralization	D	MDS	Lab	1	0	0	0	0	0
	Soil fauna community (abundances and richness)	D	MDS	Field	1	0	0	0	1	0
Chemical	Exchangeable Al, Al saturation, Available/ exchangeable macro and micronutrients, CEC, base saturation, soil pH	D	MDS	Lab	1	0	0	0	0	1
	Electrical conductivity	D	Add-on	Field or lab	0	0	1	0	0	1
	Total SOC, or SOM	D	MDS	Lab	1	1	1	0	0	0
	Total soil N and C:N ratio	D	MDS	Lab	1	0	0	0	0	0
	POXC	D	MDS	Lab	0	1	0	0	0	0
	Soil Cd	S	Add-on	Lab	0	0	0	0	0	1
Physical	Min. soil depth	S	Add-on	Field	1	1	1	0	0	0
	Texture (clay, silt, sand)	S	MDS	Lab	0	1	1	0	0	0
	Mineralogy (Al, Fe)	S	MDS	Lab	0	1	1	0	0	0
	Aggregate stability	D	MDS	Lab	0	1	1	0	0	0
	Slaking / dispersion test	D	MDS	Field or lab	0	0	1	0	0	0
	Available water content	D	MDS	Lab	0	0	1	0	0	0
	Bulk density, soil porosity	D	MDS	Lab	0	1	1	0	0	0
	Soil hardness	D	MDS	Field	1	0	1	0	0	0
	Surface crusting	D	MDS	Field	0	0	1	0	0	0
	Soil cover	D	MDS	Field	0	0	1	0	0	0
Physico-Chemical	POM-C and MAOM-C	D	MDS	Lab	0	1	0	0	0	0
	Carbon and nutrient stocks in litter layer	D	MDS	Lab	1	1	0	0	0	0
Physical-Biological	Visual soil assessment (VESS)	D	MDS	Field	0	1	1	0	1	0
Plant-level	SPAD analysis	D	Field	Field	1	0	0	1	0	0
	Indicator species	D	Field	Field	1	0	0	0	0	0
	Foliar nutrient contents	D	MDS	Lab	1	0	0	1	0	0
	Leaf Cd & Leaf Cd:soil Cd ratio	D	Add-on	Lab	0	0	0	0	0	1

Potential for assessment at scale

4 WP4: Biodiversity

4.1 Biodiversity, coffee and cocoa

'Biological diversity' means the variability among living organisms from all sources including, *inter alia*, terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are a part; this includes diversity within species, between species and of ecosystems (Convention on Biological Diversity, 1992).

Tropical perennial crops like coffee and cocoa are sourced from lands that were previously highly biodiverse tropical forests. The conversion of such forests to managed coffee or cocoa plantations leads to a reduction in tree and plant cover and diversity, affecting the plants, animals and other organisms that depend on forest habitat. It also affects the functioning of forest as an ecosystem providing services to people (e.g., water and climate regulation, carbon sequestration, wood and non-wood products etc.). Cocoa has been an important historical driver and direct cause of forest loss especially in Africa and Southeast Asia where it was introduced from Latin America in the 19th century. Coffee has led to deforestation in most of its production areas, including Ethiopia, its area of origin.

Cocoa or coffee production is typically established under a progressively thinned tropical forest canopy or on previously cleared forest land. Traditionally forest-based, complex-shade, coffee and cocoa agroforestry systems often become more simplified over time as competing vegetation is removed until just a few preferred tree species remain. Furthermore, a historical drive towards intensification to achieve higher crop yields in coffee (Vandermeer, 2011; Harvey *et al.* 2021) and cocoa (Ruf, 2011; Wade *et al.*, 2010) has led to a reduction in tree cover across these production systems.

Biodiversity is a broad concept that can be considered at different geographical scales and levels of organisation. Impacts of agricultural land use and practices are generally considered for:

- Habitats/ecosystems
  - Extent (e.g., size of forest, or wetland area, % natural habitat /ha or per farm)
  - Condition/quality (e.g., tree density, number of canopy strata in woody vegetation)
- Species (flora, fauna and other organisms)
  - Species abundance and/or relative cover
  - Species richness
  - Species composition (relative to a reference situation)
- Functions (functional traits of living organisms)
  - Diversity in functional traits such as plant leaf (e.g., chemical composition), phenology (deciduous vs. Evergreen trees; flowering time), root (e.g., specific root length), etc.
- Genes (e.g., varieties, crop wild relatives)

Good metrics for biodiversity should include the three elements, extent and condition of habitat and significance for conservation (of the habitat, species groups, individual species or gene). This report focuses on habitats and species, and (though to a lesser extent) the ecosystem services they support. Some plant features (or traits[5]) that relate strongly to characteristics of agroforestry systems, their functioning and implications for biodiversity are reviewed. We also consider a few biodiversity related functions as natural habitat and a diversity of agricultural systems support biodiversity and ecosystem services that, in turn, support agricultural production, including pest control, nutrient cycling and pollination, but also broader livelihood objectives and cultural services (see Zhang *et al.*, 2019 and references therein).

4.2 Criteria and indicators for biodiversity in coffee and cocoa production

In this report we use the Principles, Criteria and Indicators framework to assess progress. The overarching principle (or objective) is to improve biodiversity outcomes of coffee and cocoa production systems. Criteria related to improving outcomes for the different components of biodiversity contribute to this general principle. These criteria are underpinned by practices that influence these outcomes. Progress towards the criteria can be assessed directly using indicators that assess outcomes (e.g., forest extent, species richness) or indirectly using indicators for the implementation of practices that are known or expected to lead to positive biodiversity outcomes.

5 Plant functional traits (morphological, physiological or phenological features) *reflect species' ecological strategies and determine how plants respond to environmental factors, affect other trophic levels and influence ecosystem properties* (Perez-Harguindeguy *et al.*, 2013).

Criteria for better biodiversity outcomes and associated practices can be considered at the corporate level (i.e. covering the overall supply base of a company) or on the ground. *At the corporate level, indicators relate more to the presence and implementation of high-level commitments and strategies towards reduction in pressure on biodiversity or towards positive action, rather than actual outcomes for biodiversity*. These include for example, zero-deforestation commitments, policy to avoid sourcing near or in high conservation value areas, strategies to support more sustainable practices etc. Changes in biodiversity in the targeted areas are often difficult to attribute directly to those commitments and strategies. Therefore, criteria and indicators are needed for the actual state of biodiversity or for practices where the evidence on impacts on biodiversity is well-established. This report focusses on criteria for improved on-farm or landscape scale biodiversity outcomes, although two common corporate level criteria are also mentioned.

4.2.1 Criteria

The choice of criteria for positive biodiversity impacts on the ground (site to landscape) depends on whether the objective is to conserve or improve habitats (e.g., forests, trees on farm) or their functions (e.g., carbon sequestration, non-timber forest products), specific species or groups of species and their functions (e.g., rare birds, soil organisms, pollinators). The following general criteria are most commonly considered in perennial cropping systems:

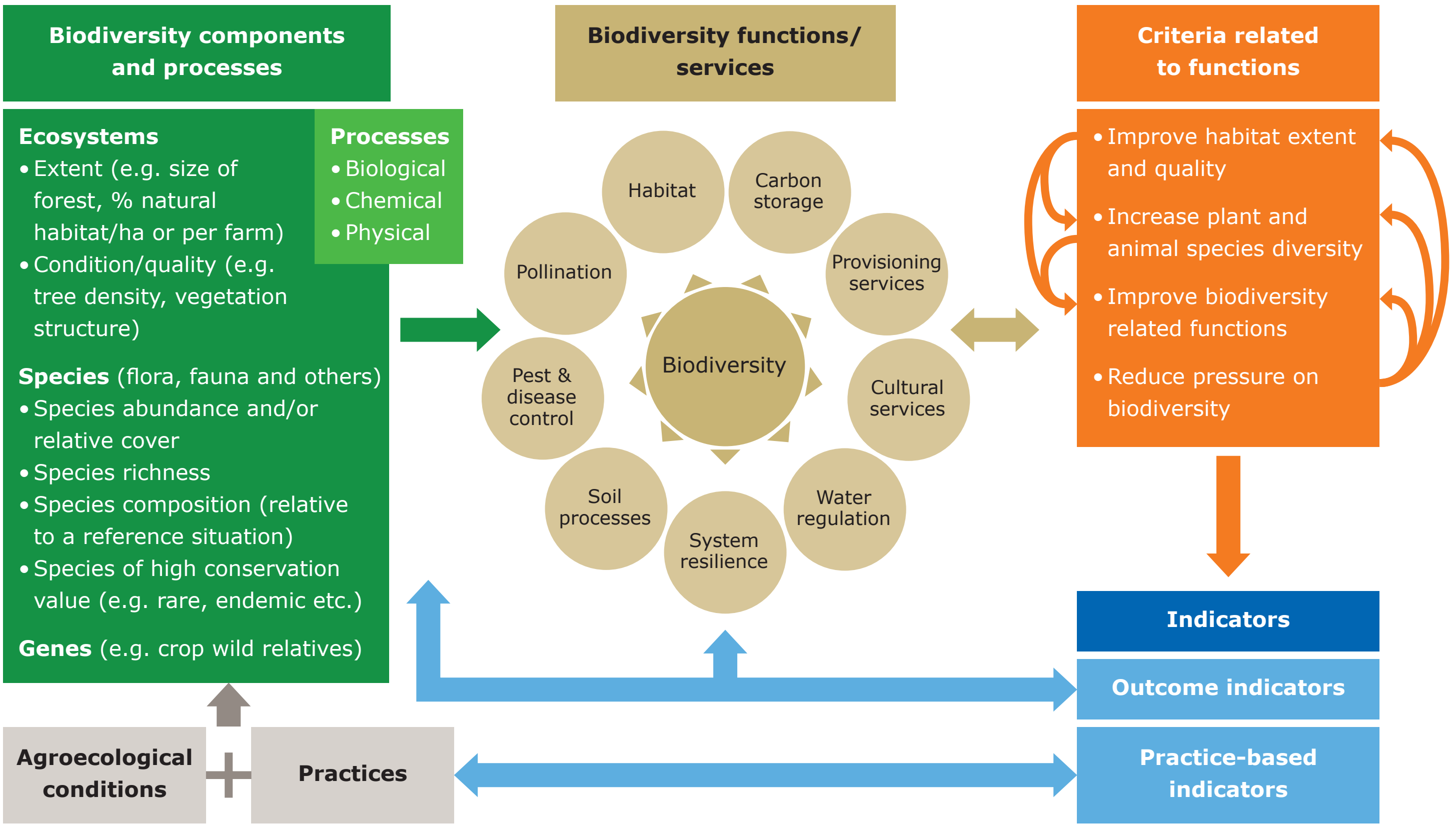
1. maintain or increase areas of natural habitat in plantations
2. maintain or increase landscape habitat connectivity
3. increase habitat quality of plantations
4. increase species richness (flora and fauna)/ forest-dependent species
5. reduce pressures on biodiversity from management practices
6. maintain or improve ecosystem services from biodiversity.

Some of these criteria can be further sub-divided according to specific objectives and contexts (Figure 4.1).

4.2.2 Indicators

Many approaches and metrics for biodiversity used in the private and financial sector, use indicators to assess (potential) supply chain risks to biodiversity in a particular area, rather than the impacts from interventions aiming to drive positive change (e.g. practices supporting a regener-

Figure 4.1 Links between biodiversity components and processes supporting biodiversity functions and services, feeding into the selection of (interlinked) criteria to improve biodiversity outcomes and functions and the identification of indicators for monitoring progress.



ative agriculture agenda). These biodiversity indicators are often developed from globally available biodiversity data and a generic impact coefficient is applied to infer impacts from a change in land use on biodiversity (often in Life Cycle Analysis (LCA)). This is generally a percentage loss in aggregate species richness (e.g., Means Species Abundance (MSA)) expected from the conversion of land to a different category of land use intensity, usually from a pristine reference state. These impact coefficients tend to use global data, are not crop or even cropping system specific and difficult to relate to actual change in land management and outcomes on the ground. Such indicators are not the focus of this review, but some details can be found in Annex 4.2.

Indicators should help assess the impact on biodiversity of changes in specific management practices in coffee and cocoa (e.g., associated tree diversity, crop residue management, inputs use) towards meeting company sustainability objectives (e.g., regenerative agriculture goals). Indicators for biodiversity impacts should be actionable on the ground, meaning they should relate to actions that farmers or plantation managers can take. Ideally, such biodiversity indicators should also be useable in reporting contributions towards global agreements on biodiversity or used in the emerging space of biodiversity credits (e.g., see https://carbon-pulse.com/184962/).

Indicators can be for ***outcomes*** (e.g., bird species richness) or for ***practices*** that are known or plausibly expected to lead to positive biodiversity outcomes (e.g., keep multiple native tree species in a coffee plot). Indicators for these two approaches are also respectively called **leading (practice) and lagging (outcome) indicators**. The distinction between the two can sometimes be a little fuzzy, for example a diversity of shade trees on farm is an outcome-indicator but also a practice-indicator (the different species are planted/kept). Indicators can be based on a single measure (e.g., the abundance of a species of bird) for a particular site, or an aggregate measure (e.g., an index combining all possible species in a particular area or associated with a particular land use type) used at a global scale.

Practices can be more cost-effective to monitor than outcomes, which is why practice-based indicators are often used. Often in the form of a questionnaire on a list of practices with responses aggregated into a final performance score. Another benefit of practice-based indicators is that they tend to be actionable by decision-makers, e.g., farmers (but also the company at portfolio level, see Table 4.1). Moreover, practice-based indicators have the advantage that they can provide insights into progress when there is a time lag between changing practices at local levels and their outcomes for biodiversity at a scale that can be monitored cost-effectively over larger areas, e.g., through remote sensing. Practice-based assessments should however be based on knowledge about outcomes or at least a strong theoretical impact pathway, and accompanied with (third party) verification.

A specific type of practice-based indicators is (aggregate) modelled, biodiversity impact metrics based on observations across many sites and studies. When sufficient data is available, these may provide some generalisable quantification of outcomes for (categories of) practices, but this requires agreed definitions of practices whose effects can be reflected in relative biodiversity outcomes (see Maney *et al.*, 2022 and Annex 4.2). These could then be used to improve current impact coefficients for different practices in e.g., MSA in LCA, but would still require monitoring for application of the practices.

The following section of this report seeks to identify which practices in cocoa and coffee production are known to provide biodiversity benefits and meet the criteria for positive impacts. Section 4.4 identifies feasible indicators to measure, quantify and monitor progress towards the achievement of these criteria towards improving biodiversity outcomes in coffee and cocoa production systems.

4.3 Review: the link between practices and biodiversity objectives in cocoa and coffee

We reviewed the available knowledge on the (sets of) practices that can be linked to these criteria, and some sub criteria, for biodiversity according to literature (Table 4.1 provides an overview, followed by a narrative summary and a more elaborate description with references is in Annex 4.1). We considered links between practices and biodiversity at plantation establishment, production system design and crop management, and the link between practices and ecosystem services supported by biodiversity, though this review was more limited.

Links can be well established (lots of supporting evidence), established but incomplete evidence (little evidence but what is there, agrees), inconclusive (little evidence and little agreement) or unresolved (lots of / good quality evidence but contradictory). The strength of evidence, or lack thereof, is one of the criteria that will be used to inform the selection of indicators for further research and indicators that could be applied across larger scales by Nestlé.

4.3.1 Summary table

Table 4.1 Linking criteria for better biodiversity outcomes to practices

Criteria	Supporting practices in coffee and cocoa (well-established or established but incomplete evidence)	Notes on evidence of effect of practices, strengths and limitations
Corporate level impact criteria		
No forest loss sourcing areas	Select low deforestation risk areas for sourcing. Implement zero-deforestation programmes (indicator would be reports or other evidence of implementation)	**Inconclusive:** despite commitments, deforestation in cocoa/coffee producing regions continues in many places (e.g., Côte d'Ivoire, Vivideconomics 2020) though commitments may require more time to achieve objectives
Maintain/ improve relative biodiversity values in sourcing areas	Implement programmes to support biodiversity friendly practices (indicator would be reports or other evidence of implementation of e.g., agroforestry)	**Inconclusive:** the impact of such programmes is generally not well monitored or the data is not available
On ground impact criteria		
No deforestation due to coffee/cocoa	Establish new plantations on degraded or non-forest land rather than convert forests	**Well-established.** There are also various local studies investigating site-specific impacts of forest to cocoa or coffee conversions (see references in Annex 4.1)
Maintain/increase % natural habitat in plantations	Maintain/restore part of farm/group of farms in forest or late secondary vegetation	**Well-established**
Maintain or increase landscape habitat connectivity	Maintain /increase % tree crown cover in and around plantations (agroforestry planned in space)	**Established in theory but incomplete evidence** (connectivity outcome may depend on target species – fauna and flora)
Increase habitat quality of plantations (vegetation structure diversity)	Agroforestry: • Maintain/ increase number of border or shade trees in cocoa/coffee systems • Include tree species of different heights • Include trees and shrubs of different species (incl. Native species) • Use cover and intercrops • Selective weeding • Use of landscape elements	**Well-established:** habitat quality increases with more structural and species diversity (ecological theory), which is improved in agroforestry systems (see Maney *et al.*, 2022 and references therein) However, effect size is hard to quantify because it depends on number of trees, canopy layers etc. There is no standard definition (and criteria) for different types of systems
Increase plant species diversity • Richness • Abundance • Similarity to reference habitat	• Integrate other crops (agroforestry/ intercropping) • Include native species • Use cover crops • Maintain (part of) natural undergrowth or epiphytic plants, using selective weeding	**Established at a general level** but effect size depends on number of other crops, native species and types/ level of ground cover achieved. Quantification is hindered by a lack of standard definitions (and criteria) for different types of systems)
Increase macro -fauna species diversity	• Agroforestry • Avoid hunting • Create corridors / landscape connectivity for macrofauna (e.g., apes, elephants, buffalos, tigers, puma)	**Established but incomplete evidence:** more diverse systems in principle support more faunal diversity through food and shelter but evidence is scattered, especially for forest specialist species (most data is on birds). The impact of hunting in and around plantations is not well quantified
Increase soil biodiversity	• Integrate crop and tree diversity (agroforestry/ intercropping) • Use cover crops • Increase organic matter input of high quality (pruning, litter, husks and other organic waste)	**Established in theory but incomplete evidence** The assumption is that a diversity of root systems will provide habitat for more diverse soil microorganisms and increased soil organic matter input of diverse quality provides improved food source for soil microorganisms See WP3 on Soil Health for further detail
Reduce pressures on biodiversity due to crop management practices (inputs)	• Use Integrated Pest Management • Reduce / appropriately time chemical use and use narrow spectrum chemicals (insecticides in particular)	**Established (in general) but incomplete evidence** for coffee/cocoa. Pest management practices are not well documented, especially in smallholder systems
Increase biodiversity related functions: carbon stocks	• Agroforestry • Keep/return crop and pruning residues to plots as high quality organic input (e.g., compost) • Use of landscape elements (incl. Riparian buffers)	**Established:** Agroforestry systems store more above ground carbon than monocultures, but quantification of the difference between system types is hindered by inconsistency in agroforestry definitions
Increase biodiversity related functions: pollinators and natural pest and disease control	• Integrate diverse plant species • Keep /return residues in plot • Use cover crops • Provide additional habitat (e.g., cut banana stems in cocoa for pollinators)	**Established but incomplete evidence**

4.3.2 Narrative summary

Practices affecting biodiversity outcomes in coffee and cocoa growing areas are determined at three major stages: plantation establishment, system design and crop management. Below is a summary whilst further details and references are in Annex 4.1.

Plantation establishment:

Conversion of intact forest or other native vegetation to cocoa or coffee plantations reduces the extent and condition of natural vegetation. Both when established under a (thinned) forest canopy or when entirely replacing intact or advanced secondary vegetation (***well-established***).

Coffee or cocoa systems developed under a forest canopy support greater biodiversity than monoculture systems, and cocoa and coffee grown closer to natural forest patches support a greater diversity of forest birds and mammals and a larger reserve of forest plant seeds (***established but incomplete evidence***, contribution to conservation may be context dependent).

Systems where associated trees are added into a no or low shade systems have lower biodiversity than those established under a forest canopy (***well-established***).

Yet, the baseline matters: increasing tree cover in existing no/low shade systems improves biodiversity because woody plant structural and species diversity is increased, whilst coffee or cocoa established in a forest, combining the main crop with selected forest trees, reduces biodiversity (and this generally reduces further over time except if managed not to do so) (***well-established***).

Therefore, developing any new plantations on already deforested land or in highly degraded forest is the most biodiversity friendly way to establish new cocoa or coffee plantations, and a requirement under the new European law on zero-imported deforestation (European Commission 2022). For degraded forest land, a criterion could be that establishing coffee/cocoa increases above ground biomass (AGB) without reducing biodiversity. There is, however, a potential trade-off with GHG emissions as establishing new plantations on degraded land could require larger amounts of fertilizer inputs.

System design and management:

No- or low shade systems provide less habitat and host fewer (forest) species than diverse agroforestry systems (***established but incomplete***, data is lacking on low shade systems and for certain taxonomic groups). By increasing vegetation structure and species diversity within

the agricultural ecosystem, agroforestry systems support greater biodiversity compared to monocultures (***well-established*** – ecological theory and empirical evidence).

Cocoa and coffee production systems exist on a gradient of vegetation structure complexity and shade management. Different types of system design (density of associated trees, species and their diversity, canopy cover) are likely to lead to different biodiversity (and coffee/cocoa yield and other ecosystem services) outcomes under different agroecological conditions and landscape contexts (***established but incomplete evidence***, literature comparing different types of agroforestry systems does not use consistent definitions in terms of tree density and diversity or other aspects of system design such as e.g., spatial arrangement of trees).

Crop management *(pest and disease management, pruning, nutrition and weeding)**:***
The use of insecticides, herbicides and fungicides and weeding tends to lead to a reduction in biodiversity (***established in general but incomplete evidence for coffee and cocoa***). Integrated pest and disease management can help reduce the negative impacts of insecticides on biodiversity, including through the adaptation of application methods and timing to maximise effect on harmful species and minimise effects on beneficial species (e.g., pollinators, natural pest enemies) (***well-established in agriculture in general***). Selective weeding and cover crops could likely help increase plant species diversity in plantations.

The effects of pruning (crop and/or associated trees and shrubs) on biodiversity in coffee and cocoa is ***inconclusive***. Keeping or increasing organic matter, including from (shade tree) pruning residues, in plantations supports litter- and soil biodiversity (***well-established***).

Biodiversity and ecosystem services (except yield)
More diverse systems are more likely to support a larger number of ecosystem services (Tilman *et al.*, 1997 ***well-established***). For coffee and cocoa systems, consistent positive relationships with biodiversity have been found for:

- Above ground biomass increases with higher associated tree species density and diversity in agroforestry systems (***well-established***)
- Floristic diversity within plantations and surrounding natural vegetation with increased pollination services (***well-established in coffee***, though unresolved in cocoa)
- Ground cover with erosion control (***well-established***)

There are also ecosystem services for which the relationship is likely positive but less well established, such as:

- Pest control services and natural vegetation near and within cocoa and coffee plots (***established but incomplete evidence***).
- Pollination services in cocoa and residue management (***established but incomplete evidence***)
- Associated tree species density and diversity and soil fertility (***inconclusive***)
- Disease control and biodiversity (***inconclusive***, disease dependent)

There may be tipping points and optimum values for elements of biodiversity in relation to ecosystem services (such as yield, pest and disease control, climate adaptation, carbon sequestration), but empirical data is lacking.

Biodiversity versus yield objectives
In comparisons of cocoa and coffee yields, agroforestry systems are generally found to be less productive than monocultures for the main crop (***well-established***). Associated trees may compete with the main crop for resources, they may harbour pests and diseases or create conditions that foster disease development (e.g., some fungal diseases). Conversely, associated trees and shade may also support pollinators, natural enemies to pests and provide barriers to the spread of vectors of disease (see section 4.2). Moreover, yield gaps may (need to) be made context specific, depending on the capacity of the farmer to invest in intensification and/or on the need to produce more than just cocoa or coffee on their farm. System productivity (cocoa and associated trees products) is greater in agroforestry systems than monocultures though as they can provide additional crops besides cocoa and coffee (***well-established***). In both crops, most studies find that shade is unlikely to compromise annual productivity at levels up to around 40% shade, with taller shade tree canopies leading to better outcomes (***established but incomplete evidence***). Such intermediate shade levels are suggested to provide the most optimal outcomes for different ecosystem services, yields, incomes, and overall sustainability in smallholder systems (***inconclusive***), though local climatic conditions may affect this (see Annex 4.1 for more detail).

Overall, the evidence-base on biodiversity-yield relationships in coffee and cocoa is scattered and impacts ***unresolved*** because of the many different contextual and management factors that affect outcomes in different places.

Whether in monoculture-type systems or agroforestry, the objective should be to try and maximise ecosystem services that support crop or system yield, to reduce the need for inputs that support yield but have negative impacts on natural services. The balance is likely to vary depending on the system and its biophysical and socio-economic context. Well-designed cocoa and coffee growing systems, with associated trees either as border trees or as shade trees supporting biodiversity, should fit local biophysical and socio-economic conditions and minimise trade-offs with other objectives, such as coffee or cocoa yield, or include the consideration of yields for associated commercial crops (e.g., timber, fruit) and/or the potential to reward farmers to maintain higher degrees of tree cover than optimal for cocoa productivity.

4.3.3 Knowledge gaps on the link between practices and biodiversity in cocoa and coffee

Few practice – biodiversity outcome relationships are well quantified. Most studies compare the relative performance of production system categories, without quantifying differences which tend to be system-definition and context dependent. There is less evidence for the impacts of specific cocoa and coffee crop management practices than for broad practices such as plantation establishment history and major system design characteristics (e.g., monoculture vs. agroforestry categories). There is little data on biodiversity in monocultures and how practices in such systems can maximise biodiversity without compromising yields.

Quantification is hindered by a lack of standard definitions (and criteria) for different types of cocoa and coffee systems.

Knowledge gaps exist regarding:

- Implications of specific system designs (e.g., different associated tree configurations, canopy structure, species etc.) for biodiversity in farms and broader landscapes
- Implications of specific management practices such as ground cover management (weeding, cover cropping), organic matter, nutrients, irrigation, pesticide use etc. for biodiversity
- Evidence on the impact of different elements of biodiversity (e.g., woody and herbaceous species) other than tree density and canopy cover on coffee and cocoa yields
- Trade-offs and synergies between biodiversity and cocoa/coffee (system) productivity objectives in well managed (high input?) agroforestry systems
- Trade-offs and synergies between biodiversity and ecosystem services provision and yield in low intensity cocoa and coffee systems
- Aspects of succession in agroforestry systems, how to use and manage natural succession and implications for biodiversity and system productivity over time
- The potential for improving biodiversity outcomes in low to no-shade production systems.

4.4 Review: indicators for assessing biodiversity in cocoa and coffee

In this section we seek to link biodiversity related criteria to indicators. We reviewed existing indicators and literature assessing indicators for biodiversity in cocoa and coffee and potentially relevant indicators or indicator frameworks for other agricultural systems. Table 4.2 provides an overview, followed by a narrative summary (additional detail is provided in Annex 4.2).

At farm scale, most indicators relate to non-coffee/cocoa vegetation structure and composition as these are more directly impacted by management (retaining, planting or removing trees and herbaceous plants). Fauna is generally more indirectly affected by management, through impacts on their habitat, except through direct contact with insecticides or hunting. Plant features or functional traits beyond tree height and canopy size (e.g., phenology, rooting systems) are not often considered.

4.4.1 Summary table

Only farm level criteria and indicators are included in Table 4.2. For some criteria, assessing both the practice and outcome indicator will help fill some of the knowledge gaps that would support the use of mainly practice-based indicators (See knowledge gaps in Section 4.3) (and potentially feed into an aggregate indicator). Table 4.2 is a long list of farm and landscape level indicators, and not all indicators may be retained in subsequent steps. It only includes on ground, not portfolio level, indicators.

Experts were consulted on the indicators (and associated criteria) in Table 4.2 to help select the most relevant and feasible indicators (Table 4.3).

Specific targets for each indicator may be developed depending on whether the objective is to achieve a certain level (e.g., a defined agroforestry type) or to monitor progressive improvement (e.g., change in tree cover or species numbers) or maintenance of well-performing systems. When defining targets, it is important to consider the baseline, which may depend on context (e.g. having a norm or target of at least five species of trees on coffee farms across the sector could lead to a reduction in tree species diversity in areas with naturally higher on-farm species diversity).

Table 4.2 Long list of criteria for improvement of biodiversity outcomes in coffee and cocoa and associated indicators for selection and shortlisting for the project

Criteria	Outcome/lagging indicator	Practice/leading indicator	Notes, including existing applications
No-cocoa or coffee driven deforestation		Deforestation history of farm areas (and x area around)	Deforestation monitoring is becoming common practice
Maintain/ increase % natural habitat (above ground) in plantations	% farm covered in forest or late secondary vegetation	• Reported area of (semi-) natural habitat on farm • Non-cocoa/coffee tree density on farm • Tree cover history	Rainforest Alliance Standard and Regenerative coffee scorecard Tree cover history: 10 trees now if previously fewer is better than 10 trees if previously more
Maintain or increase landscape habitat connectivity	• % crown or shade cover non-cocoa/coffee • Distance between crowns inside and outside the plot	Main land use type around plantation (classes e.g. forest, perennial crops, annual crops, settlement)	• Rainforest Alliance Standard • CocoaMAP FIT (only % shade cover)
Increase habitat quality of plantations (vegetation structure diversity)	• Non-cocoa tree/shrub-sizes and height • Number of canopy layers (inferred from height) • Undergrowth cover % • Litter depth	• Number of non-cocoa/coffee trees and species maintained on farm • Maintenance of different tree sizes • Cover crop use	• Rainforest Alliance Standard and Regenerative coffee scorecard • CocoaMAP FIT
Increase plant species diversity • Richness • Abundance • Similarity to reference habitat	• Number of non-coffee/cocoa tree/shrub species per ha • % native species of trees and shrubs included • Presence/ number of epiphytic plants and climbers • Undergrowth cover	• Number of non-cocoa/coffee tree species on farm • Number of native species • Cover crop use • Management of epiphytes, climbers • Weeding practices	• Rainforest Alliance Standard and Regenerative coffee scorecard • CocoaMAP FIT Needs locally relevant and regionally specific list of species to guide identification?
Increase macro -fauna diversity	• Wildlife numbers and species • Indicator species occurrence (e.g., birds, endangered species) Can be modelled if sufficient ground-data for the area	Agroforestry (criteria need to be defined) as a proxy Plausible impact can be modelled if sufficient data on species vs. co-variates that vary with management	Field assessment needs specialist knowledge and is resource intensive Applied in local sourcing area studies supported by some companies. E.g. Biodiversity Progress Index based on birds for Nespresso's AAA Sustainable Quality Program
Increase soil biodiversity	• Species and abundance (see WP3) • Biomass	• Organic matter input (pruning, litter, husks and other organic waste) • Use of Integrated Pest Management	
Increase biodiversity related functions: support (natural) succession	• Presence of tree and shrub species of different ages • Natural regeneration	Manage species and ages of shade trees for different benefits over time, including through natural regeneration	Can be inferred from monitoring previous vegetation indicators over time/ reporting by farmer
Reduce pressures on biodiversity due to crop management practices (inputs)	Increases in populations of organisms that are affected by pest and disease control measures and other inputs	• Use of Integrated Pest Management • Timing, amounts and type of chemicals used	Rainforest Alliance Standard and Regenerative coffee scorecard
Increase biodiversity related functions: carbon stocks	• Above ground biomass (see WP2) • Below ground biomass (see WP3)	• Number/size/species of non-cocoa/coffee trees on farm • Residue management (including from pruning)	AGB: CoolFarm tool uses generic models for coffee and cocoa (high/low density) and equations for common categories/ species of associated trees
Increase biodiversity related functions: pollinators and natural pest and disease control	• Abundance • Species richness	• Cover crops use • Intercropping • Use of Integrated Pest Management?	Use practices that are known to support pollinators in plot

4.4.2 Narrative summary: indicators and methods

The choice between outcome/lagging indicators and practice/leading indicators may be determined by the elements of biodiversity to be assessed and associated implications in terms of tools and data needs and the practical feasibility for assessment across sourcing areas. Practice-based and outcome indicators for habitats and species should be scientifically sound, practical, at an appropriate scale and useful. Both approaches need baseline assessments.

Practice indicator monitoring may be more data/tool efficient in the longer term (using remote sensing or farmer reporting). However, an initial effort is needed to improve our understanding of biodiversity impacts of different management systems/practices and collect data on relevant associated outcome indicators and the context in which they are observed.

The selected indicators should be able to grasp the particularities of cocoa and coffee systems and the potential types of system structure and composition and management practices (from complex agroforestry to simpler low to no shade systems) and relate those to implications for several species groups and their dynamic interactions with their habitats.

Most existing indicator frameworks for biodiversity in cocoa and coffee production systems focus on practice indicators such as of retained natural forest habitat on farm, tree density, diversity and canopy cover on farm. The retention of native species is also sometimes used as an indicator (see Annex 4.2 for examples of existing frameworks). These indicators are seen as relatively cost-effective to implement, though actual implementation seems rare, outside of certification schemes.

Practices that increase habitat extent and quality through more native habitat and diverse types of vegetation on farm are seen to support more faunal biodiversity (see e.g., Gillison *et al.*, 2013). Indeed, animal surveys in cocoa or coffee plantations and associated landscapes are often used as outcome indicators to test hypotheses around the quality of habitat provided by agricultural ecosystems. These can be types of system design (e.g., different types of agroforestry systems and monocultures) and management practices (e.g., residue management, the use of chemical inputs etc.).

Leaf litter is not commonly used as an indicator for biodiversity in cocoa or coffee, yet it can be linked with both above ground vegetation characteristics and faunal habitat. Its composition can provide information on diversity differences among sites (Yang *et al.*, 2014). Leaf litter also serves as nesting material and provides shelter for (invertebrate) fauna, and litter depth has been found a good indicator of faunal diversity (e.g., Gillison *et al.*, 2013).

Finally, with regards indicators relating to distance to natural vegetation: for most companies, closeness to forest is seen as a potential risk of deforestation, while in terms of biodiversity impact it is seen as an opportunity: the closer to a forest the cocoa farm is, the more likely it is to host forest dependent species, especially if it is an agroforest.

4.4.3 Methods: some challenges and opportunities

Methods for indicator assessments vary from remote to on-the ground approaches, including satellite imagery, aerial photography, on-the ground surveys by technical specialists, trained extension officers or farmers, or more novel approaches such as farmer self-reporting using mobile technology (with proper triangulation), environmental DNA (eDNA) research, metabarcoding, acoustic monitoring for wildlife etc. Acoustic species monitoring requires intensive training of artificial intelligence to support identification of large numbers of species. E-DNA is increasingly being promoted as a method to assess species diversity, though samples need to be collected and analysed, which presents challenges when they need to be shipped across country boundaries. These technologies are promising but still mostly in the realm of research for now.

Faunal field surveys tend to be resource intensive if meant to provide an accurate picture of status and trends. Standard methods to monitor wildlife populations are resource intensive, logistically demanding (need to repeat measurements over the year to account for seasonal behaviour patterns) and method-sensitive (Ahmad *et al.*, 2021). Focussing on one, locally relevant, indicator (or group of) species can help reduce assessment efforts. Birds are often used as indicator species to assess the impacts of land use change on biodiversity and contributions to conservation, though their assessment still requires significant on-ground effort. Camera trap surveys can circumvent some of these limitations but present extrapolation challenges and potential risks in terms of leaving valuable camera equipment out in the field for longer periods.

Vegetation surveys generally require less frequent monitoring though still require significant resources. The identification of species can be problematic and often requires specialist knowledge. Instead of species, plant functional traits could be used as biodiversity surrogates, especially if combined with overall vegetation structure (mean canopy height, woody basal area and litter depth), according to Gillison *et al.*, (2013).

Citizen science is underutilised in ecological surveys, whilst it has been tested and found a reliable method in wildlife studies even in remote areas with low levels of formal education (Meijaard and Sheil 2007, Padmanaba *et al.*, 2013, Ahmad *et al.*, 2021). An additional advantage of using engaging farmers in monitoring is that their knowledge underpins their management decisions (e.g., Cerdan *et al.*, 2012), including their responses to information, advice and other attempts to change their practices to better meet the demands of company sustainability objectives.

4.4.4 Gaps in relation to indicators

Different taxonomic groups and species may react differently to changes in land use, but it is not feasible to develop indicators for each of these groups. Choices for specific species or groups of species should be based on local context.

There is currently no agreement on a typology of practices for cocoa or coffee farming systems relevant to biodiversity implications. The general categorisation of monoculture versus agroforestry is too coarse to be able to detect more gradual changes in practices by farmers (see Annex 4.1). Another common categorisation of cocoa and coffee systems is low versus high input systems. These terms could pertain to both monoculture and diverse-shaded systems (depending on the types of inputs referred to) and say little about potential biodiversity implications of changing practices within them. Also, there is no globally agreed typology of cocoa or coffee system that would allow more robust comparison among studies.

Data on impacts of crop management practices such as e.g., retained ground cover, organic matter (waste) management, the use of insecticides or herbicides is lacking. There is limited data on biodiversity related functions (e.g., pollination (especially for coffee), pest and disease control, carbon sequestration).

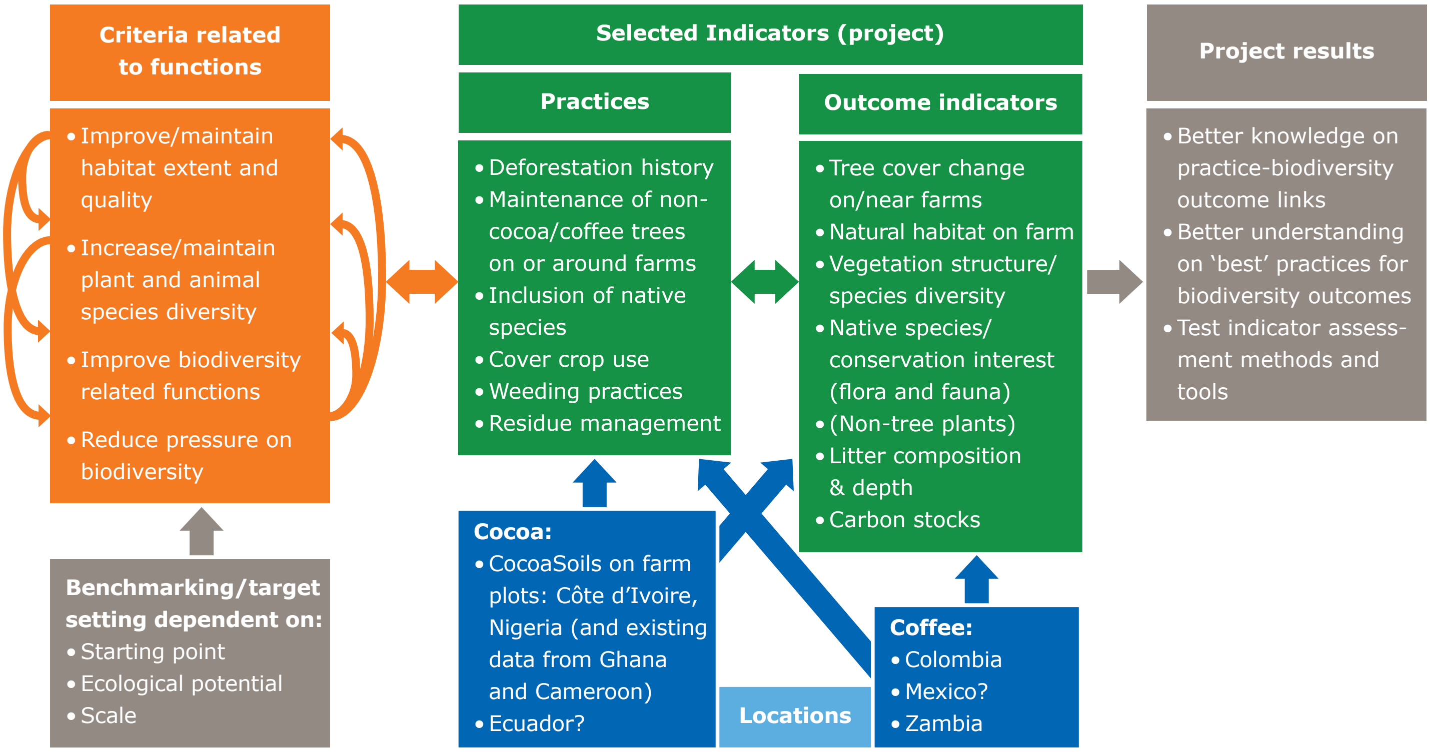
Therefore, more targeted data and understanding is first needed on relevant system characteristics (practices that can be monitored and are actionable by farmers e.g., densities of shade trees, % native species etc.) and their plausible implications for biodiversity (see Section 4.3).

4.5 Proposed indicator framework for the project

Coffee and cocoa production areas are very diverse in terms of climate, topography, soil types, natural biodiversity, and land use history. Different indicators may be most relevant and different benchmarks most appropriate for different areas, depending on their current and potential biodiversity state, ecological potential and company objectives in terms of biodiversity outcomes. Indicators can be for research, i.e., to investigate assumed benefits from practices in more detailed assessments in a set of representative areas (farms and surroundings), or for monitoring purposes, i.e. to assess progress towards specific objectives across sourcing areas.

The set of indicators selected for potential application and testing in the project (Table 4.3) largely match those currently used in research and practice, based mainly on habitat extent and condition and species diversity, but seek to test and improve the knowledge on practice-outcome links, as well as investigate efficient methods for assessment and monitoring (Figure 4.2). We will also

Figure 4.2 Summary of indicators that will be assessed and tested within the project and their link to the major criteria for better biodiversity outcomes.



explore how the results of the field assessments may eventually be used to improve aggregate indicators for specific (categories of) practices.

Filling knowledge gaps on other aspects such as impacts of practices on soil biodiversity, pollination and natural pest and disease control require resources beyond the scope of this project, though we will explore the possibility to explore these through student projects. The final selection of indicators to be tested in the project will be determined in consultation with Nestle. Results will also inform the selection of indicators that could be rolled out more broadly.

Indicators related to vegetation structure are difficult to test in an experimental set-up: trees need time to grow. Also, there may be a time-lag between a habitat improving and the associated fauna returning. Therefore, we generally explore these relationships by substituting space for time. I.e., comparing (preferably nearby!) areas under different management practices. Table 4.3 provides some of the detail of indicators and methods that will be tested on different types of farms in different countries. Testing will take place in CocoaSoils on-farm trial plots in Côte d'Ivoire and Nigeria (vegetation structure and composition only) and selected project farms in Colombia (coffee and cocoa) and Côte d'Ivoire (coffee).

Table 4.3 short listed indicators to be applied in the project. Methods applied during the project are in green.

Indicators	Best quality method	Alternative (may need testing)	Locations
Deforestation history of farms (or group of farms) (context indicator)	Overlay historical canopy cover data with farm areas		All selected farms
Land cover around farms (context indicator)	• Field assessment • High resolution image analysis (feasibility to be explored)	Farmer reporting	All selected farms outside CocoaSoils trial plots
% farm covered in forest or late secondary vegetation	• Field assessment (outcome) • High resolution image analysis, larger farms of clusters (feasibility to be explored)	Farmer reporting	All selected farms outside CocoaSoils trial plots
% crown or shade cover non-cocoa/coffee	Field survey		All selected farms
Density of non-cocoa/coffee tree (per ha)	Field survey	Farmer reporting (practice)	All selected farms
Diversity of shade tree species (richness and abundance) or functional traits	Field survey and calculation of richness indices	• Farmer interview (practice) • Farmer remote reporting (practice)	All selected farms
Species diversity of understory plant (herbs)	Field survey	Farmer interview on weeding practices	CocoaSoils trial sites only
% native species of trees and shrubs	Field survey	• Farmer interview (practice) • Farmer remote reporting (practice)	All selected farms
Above ground biomass (trees size x species)	Field survey		All selected farms
Number of canopy layers	Field survey		All selected farms
Undergrowth cover %	Field survey		All selected farms
Presence/ number of epiphytic plants and climbers	Field survey		All selected farms
Litter depth and composition	Field survey		All selected farms
Wildlife and (functional) species diversity	• Macro-fauna numbers / frequencies and species • (Tentative: functional insect densities and species)	• Farmer interview on occurrence and frequency of large fauna • (Tentative: trapping and identifying insects at guild or morphospecies level) Research: Link to vegetation and weeding/inputs management	All selected farms
Indicator species occurrence (e.g., birds, endangered species)	• Species numbers / frequencies • (Tentative: presence of relevant flying insects) Research: Link to vegetation and weeding/inputs management	Farmer interview (location specific indicator species)	All selected farms
Use of cover crops	Field survey Research: Link to wildlife	Farmer interview	All selected farms
Management of epiphytes, climbers	Field survey	Farmer interview	All selected farms
Weeding practices	Field survey Research: Link to wildlife	Farmer interview	All selected farms
Residue matter management (practice for litter indicator)	Research: Link to residue management	Farmer interview	All selected farms

5 Conclusions and Next Steps

The urgency of the challenge to reduce carbon footprints and enhance the sustainability of production, including safeguarding soils and biodiversity, is highlighted in the Intergovernmental Panel on Climate Change (IPCC) 6th Assessment Synthesis Report[6]. To this end, major companies are stepping up and making commitments to reduce GHG emissions in their supply chains and ensure sustainable supply of products for consumers. In this document we summarise the current state-of-the-art on knowledge related to measuring and monitoring the impacts of coffee and cocoa production oncarbon footprints (with special attention to GHG emissions), soil health and biodiversity. As our review shows, there is an abundance of frameworks and indicators proposed, particularly in the area of soil health, but no clear consensus on which approaches and methods should be deployed. Moreover, there is a need for indicators for the soil biological aspects of soil health, but the scalability and interpretation of biological indicators is problematic.

Our review has arrived at a fairly long list of issues for further investigation related to accounting for carbon footprints and indicators for soil health and biodiversity. Under Phase 1 of the Ground Zero project we have initiated research, in collaboration with the Cool Farm Alliance, to address some of the uncertainties in input parameters for the Cool Farm Tool (see Table 2.3). This includes detailed measurements of GHG emissions to provide an accurate baseline for cocoa and coffee farms. We are also testing indicators for soil health and biodiversity on a small number of cocoa and coffee farms in Latin America and Africa.

The challenge remains to distil our current knowledge into a simplified monitoring framework that can be rolled out across large numbers of cocoa and coffee farms, which is the focus of the second phase of the Ground Zero project. Finding indicators that are both measurable on many farms, and meaningful in terms of assessing the direction of change with sufficient sensitivity to provide guidance for farmers and other stakeholders is not a trivial venture.

As discussed in Section 1, we aim to evaluate the impact of 'best (or better) management practices' on indicators in the field in order to develop a system for tracking progress and rewarding farmers based on their robust implementation of these practices. In doing this we will derive evidence to link *principles* and *criteria* to *practices*, and *practices* to *outcome indicators*. Once we have identified practices that provide the expected benefits, a second step will be to explore *feasible ways* of monitoring implementation of the *practices*. In addition, for some *criteria* (notably those associated with biodiversity) it may be feasible and practical to monitor *outcomes* directly.

Rather than waiting for the outcomes of our research to provide guidance, our review highlights that there is well-established evidence that supports the benefits of some management practices. An obvious example would be the use of soil conservation measures to prevent soil erosion in hilly areas. We will prioritise further identification of such 'no regret' interventions and provide frequent updates on these throughout the course of the Ground Zero project. Implementation of improved management may provide win-win solutions that benefit both cocoa and coffee production as well as being good for the environment. There will also be cases where there are trade-offs between production and environmental goals. A solid understanding of such trade-offs is required to ensure equitable cost and benefit sharing so that smallholder producers do not bear all of the costs and are rewarded for contributions to societal goals.

6 https://www.ipcc.ch/report/ar6/wg2/resources/spm-headline-statements/

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List of Annexes

Annex 3.1 Strength of evidence[1] for the links between supporting practices and soil health, according to prioritized objectives (detailed table)

1. Halt soil erosion

Erosion measures: ***well-established***

- Effects of contour planting establishment of vegetative erosion barriers and terracing to control erosion in coffee and cocoa planted on slopes (Bekele Jiru, 2019; Meylan et al., 2013; Verbist et al., 2010).

Agroforestry: ***well-established***

- Shade trees or wind breaks protect soil against the erosive forces of intense rainfall and strong winds. Trees also provide soil cover in the form of prunings and litter (Meylan et al., 2013; Paningbatan et al., 1995).

Soil cover: ***well-established***

- Maintenance of a permanent soil cover, through planting of intercrops or cover crops, or mulching with locally available organic residues, is an effective way to control soil erosion, especially during renovation and rehabilitation of coffee or cocoa (Iijima et al., 2003; Nzeyimana et al., 2017).

Note 1: in practice contour planting is not widely adopted since it may complicate mechanization or increase labour costs for harvesting.

Note 2: intercropping of cash or food crops tends to be more suitable for smallholder farmers than cover crops, as the harvested product helps to provide food and income to the household.

2. Prevent soil acidification

Optimized fertilization: ***well-established***

- Strong soil acidity affects the availability of nutrients, particularly that of phosphorus and other macronutrients and can result in Al toxicity. The (over)application of nitrogenous fertilizers, especially ammonium-based leads to a decrease in pH.

Inorganic soil amendments: ***well-established***

- Lime and silicates are generally effective in raising soil pH, although limited mobility of lime in soil may be a challenge in perennial crops in the absence of soil tillage (Amponsah-Doku et al., 2022).

Organic amendments: ***well-established***

- Organic amendments such as composts or biochar (e.g., made from coffee husks and cocoa pods) can reduce soil acidity and Al availability (Amponsah-Doku et al., 2022; Pouangam Ngalani et al., 2022).

Note: Application of lime in acid soils can enhance microbial activity, increasing carbon dioxide emissions in the short term, although longer term effects on soil organic matter dynamics are less clear (Aye et al., 2016; Wang et al., 2016)

3. Improve nutrient cycling and retention

Optimized fertilization: ***well-established***

- Balanced fertilization, based on the principles of 4R (right source, right rate, right time, right place) and considering specific soil conditions, improves the nutrient use efficiency by the crop (Amponsah-Doku et al., 2022).

Agroforestry: ***Established but incomplete***

- Nutrient cycling in agroforestry systems is improved through the recycling of litter and through a nutrient pump effect through deep roots (Babbar & Zak, 1994; Hartemink, 2005). However, the species selection and management of shade trees are important factors determining complementarity vs competition for resources. Knowledge on shade species traits and management is incomplete (Blaser et al., 2017; Niether et al., 2020).
- Leguminous shade trees incorporated into coffee or cocoa agroforestry systems can contribute significant amounts of nitrogen (N), although the amount of N supplied through biological N fixation can vary widely depending on the species and soil conditions REF coffee (DaMatta F.M & Rodriguez Lopez, 2007; Partelli et al., 2011).

Use of soil cover: ***Well-established***

- Mulching, cover crops and intercrops can improve nutrient cycling and fertilizer use efficiency, especially when legume cover crops or deep rooting grasses are used (Bucagu et al., 2013; Mendonça et al., 2017; Rose et al., 2019) and as long as competition with coffee plants for water, light and nutrients is avoided (Delgado et al., 2021).

Organic amendments: ***Established but incomplete***

- The combined use of organic inputs and mineral fertilizers can increase crop response to fertilization and fertilizer-use efficiency, due to an additive effect related to improvement of soil health (Vanlauwe et al., 2010). However, information on the dynamics of different types of organic amendments is still limited and effective fertilization recommendations for coffee and cocoa production systems are limited (Amponsah-Doku et al., 2022a; Lambert et al., 2020; van Vliet & Giller, 2017).

1 We distinguished the following categories of supporting evidence: **Well established** (ample supporting evidence); **Established but incomplete** (few available studies, but what's there is in agreement); **Inconclusive** (few studies and little agreement); **Unresolved** (ample studies but contradictory results).

*Reference applies to cocoa; reference applies to coffee; reference applies to tropical tree crops; reference applies to other crops.

- The use of compost from local residue and waste streams, including cocoa pod husks, coffee pulp and coffee husks, has shown improvements in soil properties and plant growth (Amponsah-Doku et al., 2022; MULIA et al., 2019; Takala, 2019).
- Positive effects of biochar have been reported for cocoa and other tropical perennial crops (Zwetsloot et al 2020), although the effects vary depending on the quality of the biochar. Large volumes and high costs limit the scalability of biochar in coffee and cocoa.

Biostimulants/biofertilizers: ***Inconclusive***
- It is well known that the use of commercial rhizobium inoculants may enhance nodulation and biological nitrogen fixation in legumes.
- Other beneficial microorganisms may promote nutrient use efficiencies and plant health by increasing the availability, uptake or utilization of nutrients already present in the soil without actually adding more nutrients. Scientific studies showing that inoculants (mainly plant growth-promoting rhizobacteria and arbuscular mycorrhizal fungi) promote nutrient acquisition or crop yields in mature coffee or cocoa stands are lacking. There is evidence, however, that the combined application of compost and inoculation with AMF can improve the performance of young coffee plants at nursery stage or during establishment (Moreira et al., 2018; Urgiles-Gómez et al., 2021)
- Coffee and cocoa farmers increasingly use home-made 'biofertilizers' based on activated microorganisms and fermentation processes. Bio-stimulants, like seaweed-based products (Carvalho & Castro, 2019) may have potential to promote plant growth. Despite the growing popularity of biofertilizers and biostimulants, scientific studies showing their effectiveness and consistency under field conditions are extremely scarce and underlying mechanisms are poorly understood.

4. Increase soil organic matter/carbon

Agroforestry: ***Inconclusive***
- The evidence on the potential for agroforestry to sequester carbon as soil organic matter remains unclear as few studies are available, with results ranging from no effect of agroforestry on SOC stocks, or an increase or a decrease, compared to coffee monocultures (Negash & Starr, 2015; Noponen et al., 2013; Tumwebaze & Byakagaba, 2016) . Effects tend to be system and site-specific (Tumwebaze & Byakagaba, 2016).

Soil cover: ***Established but incomplete***
- Meta-analysis (Poeplau & Don, 2015) of a large number of studies has provided evidence that winter cover crops offer great potential for soil carbon sequestration in temperate climates but studies from tropical perennial crops are scarce.
- In a monocrop stand of oil palm, mulching alone could enhance SOC content by 52% at 13-years after planting, whereas the corresponding improvement in an intercrop stand (with cocoa) was 77%, above its conventional cultivation SOC without mulching (Manorama et al., 2021).
- Effects of deep rooting intercrops (e.g., Brachiaria (*Urochloa*) grasses in interrows of coffee) on soil organic carbon storage require further research (Silva et al., 2021a).

Organic soil amendments: ***Established but incomplete***
- Compost and returning cocoa pod husks to the soil on cocoa farms and to help build and maintain soil organic matter (Amponsah-Doku et al., 2022). Biochar can be an effective way to increase soil C, in a very stable form. However, large volumes and high costs limit applicability of biochar in coffee and cocoa

Note 1: Ultimately, the effect of management practices on soil organic carbon sequestration depends on initial soil conditions. Degraded soils with very low soil organic matter have a greater capacity to store carbon than soils that are already high in soil organic carbon.

Note 2: Carbon removal through soil C sequestration requires that atmospheric CO_2 is fixed through photosynthesis and stored in the soil. No atmospheric CO_2 is converted and stored as a result of the transfer of organic matter from one place to another, and it does not add to reducing atmospheric CO_2 concentrations. Therefore, it is essential to differentiate between the application of any of OM to soils from sources external or outside a land unit (e.g. amendments like manure, compost, biochar) and C sequestration based on OM inputs that have been produced in-situ (Kögel-Knabner et al., 2022; Niether et al., 2017).

5. Improve water retention (infiltration, storage)

Agroforestry and soil cover: ***Well-established***
- Agroforestry systems, cover crops, intercropping and mulching generally improve water infiltration and retention, and can improve drainage due to positive effects on soil physical properties and water retention (Siqueira et al., 2014). However, care should be taken to avoid too much competition with coffee plants for water, light or nutrients (Delgado et al., 2021; Neither et al. 2017) showed that cocoa agroforestry systems and monocultures have distinct moisture dynamics, and that cocoa and shade trees in agroforestry systems use water resources complementarily.
- Planting interrows with Brachiaria grass (*Urochloa* spp.) has been found to improve soil structure and is highly efficient in enhancing soil structure, water infiltration and plant available water in certain types of soil, such as those found in the Cerrado region of Brazil (Silva et al., 2021b).

*Reference applies to cocoa; reference applies to coffee; reference applies to tropical tree crops; reference applies to other crops.

Organic and inorganic soil amendments: ***Established but incomplete***

- Amendments like compost, biochar (Fischer & Glaser, 2012; Joseph et al., 2021) can improve soil structure and water holding capacity of the soil, reduce Al toxicity favoring root development and water uptake, or reduce the mobility of heavy metals. In the Cerrado region of Brazil, gypsum application has been shown to increase the rooting depth of coffee, thus reducing water stress (Silva et al., 2021).

6. Enhance soil biodiversity

Agroforestry and soil cover: ***Established but incomplete***

- Agroforestry and cover cropping or mulching have been found to contribute to more diverse soil communities, including soil and litter fauna (Barrios, 2007; da Silva Moço et al., 2009; Pauli et al., 2011; Rousseau et al., 2013). This is line with improved microclimatic conditions, higher amounts and more diverse organic matter inputs from crop residues and through the interactions with growing roots. However, evidence for coffee and cocoa systems is limited (Amponsah-Doku et al., 2022; Snoeck et al., 2010). Further research is also required to determine if these changes result in significant shifts in ecosystem function (Buyer et al., 2017). When it comes to soil biodiversity, functional diversity (i.e., groups of organisms that provide specific processes or functions (so-called keystone species) is more relevant than taxonomic diversity (e.g., species richness) (Pulleman et al., 2012; 2022).
- Arbuscular mycorrhizal fungal spore density and diversity was significantly lower in the young cocoa agroforests than in the old cocoa agroforests. Levels in the nearby secondary forest were not significantly different from old cocoa (Snoeck et al., 2010).

Limit pesticide use: ***Established but incomplete***

- Reduce pesticide use and where needed use narrow-spectrum pesticides and biopesticides helps to protect soil community. However few field data are available on the effects of different (combinations of pesticides) on beneficial soil organisms.

7. Stimulate natural control of soil-borne pests and diseases

Effects and measures cannot be generalized as they depend on context and are disease/pest specific. herefore, we focus on major pests and diseases affecting coffee and cocoa globally, and that are affected by soil suppressiveness or soil management (Avelino et al., 2012)

In coffee:

- Root-knot nematodes Meloidogyne spp., other nematodes Pratylenchus coffeae
- Coffee leaf rust
- Coffee berry borer

In cacao:

- Ceratocystis wilt (Ceratocystis cacaofunesta/formerly C. fimbriata)
- Rosellinia root rot (Rosellinia necatrix /R. pepo)
- Stem cankers Phytophthora megakarya and Phytophthora palmivora -also causes black pod rot
- Pratylenchus coffeae is a plant-pathogenic nematode infecting several hosts including potato, banana, sweet potato, peanut and citrus.

Limit pesticide use: ***Established but incomplete***

- Reduce pesticide use and where needed use narrow-spectrum pesticides and biopesticides helps to protect soil community including non-target organisms such as biocontrol agents. However few field data are available on the effects of different (combinations of pesticides) on beneficial soil organisms.

Agroforestry: ***Established but incomplete***

- Incidence of black pod disease (Phytophthora spp.) did not differ between agroforestry and monoculture (Riedel et al., 2019).

Soil cover: ***Established but incomplete***

- Mulching, prevent spread of spores through rainsplash (Ratnadass et al., 2021)
- Considering pests and diseases when selecting cover crops and intercrops can reduce the incidence of pests and diseases. For example, nematodes are hard to eradicate; the best way is through green fallow with a non-host species like Crotalaria (Bessi & Massayuki Inomoto, 2022). On the other hand, potato, banana, sweet potato, peanut and citrus can be hosts for plant-pathogenic nematodes such as Pratylenchus coffeae and should be avoided when such nematodes are a problem in coffee.

Organic inputs: ***Established but incomplete***

- There is evidence to suggest that application of cocoa pod husk-based compost reduces black pod disease both by reducing Phytophthora spores and by raising the nutrient status of the cocoa plants to induce resistance (Doungous et al., 2018).
- Use of substrates to attract antagonistic fungi or predators of soil-born pests (Clocchiatti et al., 2021).

*Reference applies to cocoa; reference applies to coffee; reference applies to tropical tree crops; reference applies to other crops.

Biostimulants/beneficial microorganisms: ***Established but incomplete***

- Manipulation of the cacao root-associated microbiome to promote disease-suppressive taxa (e.g., biological control and suppressive soils) can complement breeding for rootstock resistance and microbiome-mediated resistance (Schmidt et al., 2022). Effects of improved soil health on pests and disease damage can also be indirect, through improved nutrient cycling and plant nutrition affecting plant defense (Mur et al., 2017).

8. Reduce cadmium availability and uptake (cocoa)

Inorganic and organic soil amendments: ***Inconclusive***

- So far very few field studies are available on the effectiveness of lime, gypsum, biochar, compost, among other organic and inorganic soil amendments in reducing the soil Cd availability and plant Cd accumulation in cocoa (Vanderschueren et al., 2021). There are important questions still regarding trade-offs and synergies of the proposed practices for (micro)nutrient availability and cocoa yields (Vanderschueren et al., 2021).
- Liming: Soil liming to lower cadmium (Cd) bioavailability is challenged in perennial cacao orchards by the low penetration of lime in soils, not reaching deeper roots (Argüello et al., 2022).

Optimized fertilization: ***Inconclusive***

- If cacao plants are deficient in Zn or Mn, fertilization with Zn or Mn could diminish Cd uptake, because these elements are taken up by the plant through the same transporter mechanisms. However, published studies in cocoa are scarce, especially field studies (Vanderschueren et al., 2021).

*Reference applies to cocoa; reference applies to coffee; reference applies to tropical tree crops; reference applies to other crops.

Annex 3.2. Existing indicator frameworks

The following existing indicator frameworks or tools could be of interest as inspiration for our project, some of them have been applied to coffee and/or cocoa or to other tropical perennial crops.

Framework name	Goal	Targeted users	Spatial scale	Crop systems	Geographical scope	Approach and indicators	Interpretation schemes	References and URL
Soil management assessment framework (SMAF)	• Assess inherent soil quality and susceptibility to change • Evaluate management practices • Educate about soil quality	• Land managers • advisors • general public	-	-	USA, but approach has been applied in other countries, e.g. Brazil	Scoring with respect to 4 soil functions, in 3 steps: indicator selection, indicator interpretation, and integration into an index	integration into an index	Andrews et al., 2004; Karlen et al., 2001; Wienhold et al.,2004; Wienhold et al., 2009 https://acsess.onlinelibrary.wiley.com/doi/abs/10.2136/sssaj2015.09.0328
CASH	• Target management practices to alleviate soil constraints • Monitor soil improvement or degradation resulting from management • Compare management practices to develop specific soil health management recommendations	Farmers	Field	-	USA, but indicators have been applied to coffee in Colombia https://doi.org/10.1016/j.geodrs.2018.e00176 https://doi.org/10.1016/j.soilbio.2022.108708	Cash tested a range of physical, biological and chemical indicators. to come up with a final list: • Available Water Capacity, Surface hardness, • Subsurface hardness, • Aggregate Stability, • Organic matter, • Soil protein, • soil respiration, • Active carbon, • pH, • plant nutrients. Add ons are: • root pathogen pressure, • Potentially mineralizable N • Salinity and sodicity • heavy metals	Interpretation is with scoring curves, calculating an overall score	Moebius-Clune, B.N., et al. 2016. Comprehensive Assessment of Soil Health – The Cornell Framework. https://www.css.cornell.edu/extension/soil-health/manual.pdf. Standard Operating Procedures is available at bit.ly/SoilHealthSOPs
ENVASSO, RECARE	Assess soil degradation Provide objective, reliable and comparable information at European level		Not specified	-	EU			(Huber et al., 2008; Kibblewhite et al., 2008b; Stolte et al., 2016) http://esdac.jrc.ec.europa.eu/projects/envasso http://www.recare-project.eu
LDSF	Land degradation assesment		Land-scape		Global south			Winowicki et al. 2022

Framework name	Goal	Targeted users	Spatial scale	Crop systems	Geographical scope	Approach and indicators	Interpretation schemes	References and URL
Open Soil Index			Agricul-tural Field	Arable land, grassland	Netherlands	The OSI is an open-source modular framework in which soil properties, functions, indicators and scores, and management advice are linked hierarchically. Soil health is evaluated with respect to sustainable crop production but can be extended to other ecosystem functions. The OSI framework is highly influenced by SMAF.	The primary building block is 'soil functions'. Each function is quantified based on measurable indicators. The soil indicators are further aggregated into an integral assessment score reflecting the weighted distance to target. Finally, recommendations are given for farming practices that can be implemented toimprove soil health.	Ros et al 2022. https://doi.org/10.1021/acs.est.2c04516
Biofunc-tool	Soil quality index for assessing the impact of land management on soil quality (the capacity of the soil to function)	Not specified		Tree-based cropping systems, and other tropical land uses	Thailand	Biofunctool® uses a core set of ten indicators to monitor changes in three key soil functions: carbon transformation, nutrient cycling and structure maintenance. Information from all the indicators is integrated in a Soil Quality Index using multivariate analysis (PCA) weighting. Uses natural forest as a reference. Indicators included: soil aggregate stability, soil infiltration potential, Visual Evaluation of Soil Structure, NO_3^-, soil available nitrogen, surface cast density, lamina baits, POXC and basal soil respiration.		Thoumazeau et al 2019, 2020
n.a.	Define a MDS of soil quality indicators to classify and compare soil quality in agroforestry cacao systems	Not specified	Plot, farm	Agroforestry systems (Cocoa, Quesungual)	Nicaragua, Costa Rica	Framework based on indicator sets of baseline soil physical and chemical indicators, along with macrofauna groups. A minimum set of four well-accepted abiotic soil quality indicators (bulk density, sum of bases, pH and carbon) was able to separate cacao AFS plots and forests into five distinct clusters along a low-to-high 'soil quality' gradient.		(Rousseau et al., 2012 + 2013)
Soil quality index (SQI) for cacao cropping systems	Establish a soil quality index for the Bahia region in Brazil	Not specified	Field, farm	Cocoa	Brazil	Available water function (AWF), root growth function (RGF), mineral nutrition of plants function (MNF) and environmental safety function (ESF) for potentially toxic elements were included in the additive model of SQI for cacao cropping systems 21 soil quality indicators were assessed at depth of 15 cm: available water-holding capacity, clay content, soil bulk density, total soil porosity, soil organic matter, C/N ratio, pH, Al^{3+} saturation, cation exchange capacity, extractable P, K, Ca, Mg, Si, Fe, Zn, Cu, Mn, Ba, Cd, Pb.	The quality indicators were standardized for scores ranging from 0 to 1, according to the function of Wymore (Citation1993)	(Araujo et al., 2018) https://doi.org/10.1080/03650340.2018.1467005 Fernandes et al. (2013)Evaluation of soil quality in areas of cocoa cabruca, forest and multicropping in Southern Bahia, Brazil. Agrotrópica. 25:137–148. [in Portuguese].

Annex 3.3. Overview of related research projects

The following ongoing projects focus on closing some of the knowledge gaps on soil health in coffee and cocoa and aim at developing and testing indicator frameworks for assessment and monitoring.

Project name	Period	Implementing institutes	Relevant knowledge or data/method gaps being addressed	Crop (Arabica, Robusta, Cocoa)	Countries	URL	Contact
Clima-LoCa	2020-2024	Alliance of Bioversity-CIAT, WUR and others		Cocoa	Colombia, Ecuador, Peru	www.climaloca.org	Mirjam Pulleman
Excellence in Agronomy	2022-2030	One CGIAR, IITA, Alliance of Bioversity-CIAT, WUR		Cocoa (and coffee?)	Ghana		Mirjam Pulleman, Leonard
Agroecological Regenerative Cocoa (ARC)	2021-2024	Alliance of Bioversity-CIAT, ICRAF, TNC, etc		Cocoa	Perú, Ecuador, Colombia		Mirjam Pulleman, Yovita Ivanova
Regenerative Coffee farming		Alliance of Bioversity-CIAT		Coffee	Kenya, Uganda,		Eric Rahn
Soil4Africa	?	ISRIC, WUR, IITA and others	Soils4Africa will put in place by 2024 an Open-data Soil Information System (SIS). SIS is a tool to target interventions that improve soil quality and provides insight in the impact of these interventions. Developing detailed procedures for laboratory work and analyse the collected soil samples at one reference laboratory located in Africa; and developing the technical infrastructure for the soil information system and making the results available as open data.	-	Africa	https://www.soils4africa-h2020.eu/	
BENCHMARKS	2023-2027	Wageningen University and partners	Indicator frameworks and interpretation schemes,	-			Mirjam Pulleman, Rachel Creamer
CA4SH Coalition of Action for Soil Health			"CA4SH advocates for the implementation of robust soil health monitoring frameworks to track interventions over time. Recommends Measurements for Scaling Soil Health Assessment https://soilhealthinstitute.org/our-work/initiatives/measurements/			www.coalitionforsoilhealth.org	

Annex 3.4 Long list of potential soil health indicators relevant to coffee and cocoa

Table 2. Table listing *potential* soil health indicators relevant to each of the criteria. The complete table with information about the verifiers and data collection methods and notes about existing applications and certification programs can be found here.

Indicator type	Indicator (longlist)	Field or Lab method	Nutrient cycling	Carbon storage/ cycling	Water regulation (including soil erosion)	Pest control	Soil bio-diversity	Cd mitigation	Preselected (research phase)	Potential for assessment at scale
Biological	Active fungal and bacterial abundances	Lab	1	1	0	0	1	0	Yes	No
	AMF fungi colonization (microscopy)	Lab	1	0	1	0	0	0	No	No
	Earthworm density	Field	1	1	1	0	1	0	Yes	Yes
	Enzyme activities	Lab	1	1	0	0	0	0	Yes	No
	Functional fauna activity	Field	1	0	0	0	1	0	No	No
	Functional genes	Lab	1	0	0	0	0	0	No	No
	Litter decomposition	Field or lab	1	1	0	0	0	0	Yes	No
	Microbial biomass	Lab	1	1	0	1	0	0	Yes	No
	Microbial catabolic level physiological profiles	Lab	0	1	0	0	1	0	No	No
	Fungal taxonomic diversity (DNA)	Lab	0	1	0	1	1	0	No	No
	Bacterial taxonomic diversity (DNA)	Lab	0	1	0	1	1	0	No	No
	Nematode communities and maturity index	Lab	1	0	0	1	1	0	Yes	No
	Potential carbon mineralization	Lab	1	1	0	0	0	0	Yes	Yes
	Potential carbon respiration/ microbial biomass	Lab	1	1	0	0	0	0	No	No
	Potential N mineralization	Lab	1	0	0	0	0	0	Yes	No
	Soil fauna community (abundances and richness)	Field	1	0	0	0	1	0	No	No
	Soil suppressiveness (assay)	Lab	0	0	0	1	0	0	No	No
	SPAD analysis (plant)	Field	1	0	0	0	0	0	Yes	Yes
	Visual assessment (excre-ments, pores, spores, etc)	Field or lab	0	0	0	0	1	0	No	No
Chemical	Exchangeable Al, Al saturation, Available/exchangeable macro and micronutrients, CEC, base saturation, soil pH	Lab	1	0	0	0	0	1	Yes	Yes
	Electrical conductivity (when relevant)	Field or lab	0	0	1	0	0	0	Yes	Yes
	d13C	Lab	0	1	0	0	0	0	No	No
	Foliar nutrient contents	Lab	1	0	0	0	0	0	Yes	No
	Inorganic N (NO3, NH4)	Field or lab	1	0	0	0	0	0	No	No
	POXC	Lab	0	1	0	0	0	0	No	No
	Total SOC content, or SOM	Lab	1	1	1	0	0	0	Yes	Yes
	Total soil N and C:N ratio	Lab	1	0	0	0	0	0	Yes	No
	Water extractable organic carbon	Lab	0	1	0	0	0	0	No	No
	Soil Cd (static, when relevant)	Lab	0	0	0	0	0	1	Yes	Yes
	Leaf Cd and Leaf Cd:soil Cd	Lab	0	0	0	0	0	1	Yes	Yes
	Bean Cd and bean Cd:soil Cd	Lab	0	0	0	0	0	1	No	No
	Extractable Cd	Lab	0	0	0	0	0	1	No	No

Indicator type	Indicator (longlist)	Field or Lab method	Nutrient cycling	Carbon storage/ cycling	Water regulation (including soil erosion)	Pest control	Soil bio-diversity	Cd mitigation	Preselected (research phase)	Potential for assessment at scale
Physical	Min. soil depth (static, when relevant)	Field	1	1	1	0	0	0	Yes	Yes
	Texture (clay, silt, sand) (static)	Lab	0	1	1	0	0	0	Yes	Yes
	Mineralogy (Al, Fe) (static)	Lab	0	1	1	0	0	0	Yes	No
	Aggregate stability	Lab	0	1	1	0	0	0	Yes	Yes
	Slaking / dispersion test	Field or lab	0	0	1	0	0	0	Yes	Yes
	Available water content	Lab	0	0	1	0	0	0	Yes	No
	Bulk density, soil porosity	Lab	0	1	1	0	0	0	Yes	No
	Infiltration	Field	0	0	1	0	0	0	No	No
	Soil hardness	Field	1	0	1	0	0	0	Yes	Yes
	Soil cover	Field	0	0	1	0	0	0	Yes	Yes
Physico-Chemical	POM-C and MAOM-C	Lab	0	1	0	0	0	0	Yes	No
	SOC/clay	Lab	0	1	0	0	0	0	Yes	Yes
Physical-Biological	Carbon and nutrient stocks in litter layer	Lab	1	1	0	0	0	0	Yes	No
	Visual soil assessment (VESS)	Field	0	1	1	0	1	0	Yes	Yes

Annex 4.1. State of the art detail for biodiversity

Land conversion
Different local studies have found that cocoa and coffee established on forest land causes declines in forest and restricted range species (Bobo *et al*., 2006; Oke and Chokor, 2009; Valencia *et al*., 2014; Buechley *et al* 2015; Mbolo *et al*., 2016), and in species that support ecosystem functioning such as dung beetles and termites (Eggleton *et al*., 2002; Perfecto *et al*., 2003; Davis and Philips, 2005). Nevertheless, there is also evidence that, depending on management, cocoa and coffee farms can support significant levels of species diversity (e.g., Bhagwat *et al* 2008), including high proportions of forest species (Philpott *et al*., 2008; Holbech, 2009, Waltert *et al*., 2005; Buechley *et al* 2015) and species that support ecosystem functioning (Perfecto *et al*., 2003; Tadu *et al*., 2014).

The range of relationships found across the literature suggests that there is a large range of possible biodiversity outcomes across cocoa and coffee growing areas depending on environmental factors, land use history, landscape context and management.

System design and management
Agroforestry is a broad practice where one or more shade-tolerant crops are cultivated in combination with trees (Somarriba, 1992).Cocoa and coffee production systems exist on a gradient of vegetation structure and shade management: from traditional (also called 'rustic') agroforestry systems with cocoa or coffee planted under thinned primary or older secondary forest, to planted shade systems, ranging from a combination of multiple species of planted trees with some remnant forest trees to a combination of planted shade trees, cocoa or coffee and other tree crops, to monocultural systems where one or few species of shade trees dominate (genera), to full-sun coffee or cocoa with no shade. Another type of agroforestry system is when associated trees are planted as border trees rather than combined within the coffee or cocoa plot. These categories are however not consistently defined, and all studies may use different criteria, which are often not quantified (e.g., how many trees and species). A more quantified definition proposes a combination of relative basal area of associated trees to cocoa/coffee and number of species, where cut-off points can be agreed for different definitions (see van Noordwijk 2021), but this is not consistently used across literature.

By increasing vegetation structure and species diversity within agricultural (eco)systems, agroforestry practices support greater biodiversity compared to open land systems (Maney *et al*., 2022 and references therein). In addition, it is also seen as an important practice to support climate change adaptation, both for productivity (e.g., microclimate regulation) and production system resilience, diversification of incomes etc. (Tscharntke *et al*., 2011; Vaast and Somarriba, 2014; Norgrove and Beck, 2016; Abdulai *et al*, 2018; Niether *et al*., 2020).

Studies on the effect of different types of agroforestry systems on biodiversity find that coffee and cocoa systems with a diverse shaded canopy support more biodiversity (Mbolo *et al*., 2016; Buechley *et al* 2015; Zewdie *et al*., 2022; Jha *et al* 2014), and ecosystem services such as pollination and pest and disease control (Tscharntke *et al*., 2011; Andres *et al*., 2018, Rice and Greenberg, 2000; Kellerman *et al*., 2008; Vergara and Badano, 2009; Martinez-Salinas *et al*., 2016).

Land use history also affects biodiversity outcomes. Forest-derived agroforestry systems host greater diversity of certain species than agroforestry systems that were established on open land (Perfecto *et al*., 2003; Sambuichi *et al*., 2012; Nijmeijer *et al*., 2019, Martin *et al*., 2020), but open land derived systems provide opportunity to improve biodiversity and ecosystem services outcomes, whilst forest derived systems are more likely to lose biodiversity over time under current trends (Ruf *et al*., 2011).

In a meta-analysis of 74 studies from across Africa, Latin America and Asia to assess the impact of the conversion of natural forest into coffee and cocoa agroforestry and the subsequent intensification of these systems on biodiversity and ecosystem services, DeBeenhouwer *et al*., (2013) found *that forest species richness and total species richness were significantly lower in the more intensively managed than in the more natural land use categories* DeBeenhouwer *et al*., (2013). The decline in total species richness was greater when transitioning from traditional agroforests to plantations dominated by coffee or cocoa with just a few associated trees (true monocultures were not included) than when transitioning from forest to agroforests. Maney *et al*., (2022) reached similar conclusions in a study modelling the effects of land-use change in different types of cocoa production systems on whole-community biodiversity intactness (BII, representing the diversity of a system relative to primary forest) based on original field data from 36 studies (1295 sites) from across the world.

In their review, Marsden *et al*., (2020) find that *"effects on fauna abundance and diversity are mainly positive when agroforestry is compared to cropland, and neutral or negative when compared to forests. Few publications actually measure soil fauna functions, or characterize their* *interactions and evolution in time and space depending on system design and management"*.

In studies on the impacts of cocoa and coffee management on biodiversity, management intensity is often used as a metric, both in qualitative and quantitative terms (e.g., Bisseleua and Vidal, 2008; Zewdie *et al*., 2022). It is generally based on (a combination of) shade levels and diversity, cocoa/coffee density and/or levels of chemical inputs use, with shade levels the most frequently used as a proxy for management intensity (Norgrove and Beck, 2016). Plant features or functional traits beyond tree heights and canopy size (e.g., phenology, rooting systems) are not often considered.

Crop management
Evidence on the relationship between biodiversity outcomes and specific crop management practices in coffee and cocoa is scarce. Reviewing the potentially relevant evidence from other crops comprehensively is beyond the scope of this work. A few elements are touched upon below.

Organic matter management:
According to a review by Barrios *et al* (2013), agroforestry systems, across crops, increase the abundance of soil organisms compared to simpler systems. Overall, when organic matter is added, earthworm densities are expected to increase due to higher food availability. This has been found in studies on cocoa and coffee as well. For example, there is evidence that organic matter additions (e.g., compost, pruning residues), in combination with organic management in cocoa systems favours soil microbial community diversity (Lori *et al*., 2022).

Pesticide, fungicides, herbicides
Pesticides can affect soil macro and microbiota and their functions (for further references see Labordiere *et al*., 2020). Most studies in cocoa and coffee compare with untreated natural vegetation. A few also consider differences between untreated and treated cocoa or coffee systems. They find that both pesticides and fungicides affect soil faunal communities (e.g. Norgrove *et al*., 2009).

Chemical fertiliser use:
Studies in different agricultural systems have found that Nitrogen fertilizers may affect bacterial and fungal communities in soils, as well as nematodes (both beneficial and not) and earthworms but most of these studies have taken place in the Northern hemisphere, including in China.

Adding trees/cover crops:
In a study in Malaysia, Vanhove *et al*., (2016) found that applying even a simple agroforestry system (tree and banana shade) had positive effects on yield in degraded (previously intensively fertilised) cocoa plantations and that this was likely linked *"with the creation of an environment that improves cocoa crop physiology and reduces pressure of pests and diseases, rather than with the improvement of soil quality as a consequence of intercropping with trees"*.

Biodiversity vs ecosystem services
Understanding of the relationship between agricultural management practices and biodiversity-mediated ecosystem services is poor. Findings are often contradictory or dependent on site-specific biophysical characteristics and land-use history. Evidence for some aspects is given below.

Carbon storage
In most cocoa and coffee growing areas, the above ground biomass of existing cocoa agroforestry increases with tree species diversity, as shown by Jacobi *et al*., (2014) for Bolivia, Schroth *et al*., (2015) for Brazil, Somarriba *et al*., (2013) for Central America, and Abou Rajab *et al*., (2016) and Sari *et al*., (2020) for Indonesia. Carbon storage in agroforestry systems is significantly higher than in monocultures (De Beenhouwer *et al*., 2016, Nijmeijer *et al*., 2019; Schneidewind *et al*., 2019; Schroth *et al*., 2016).

Micro-climate regulation and disease
Shading in agroforestry systems can help provide a cooler and more sheltered microclimate (Niether *et al*., 2018), though there is also a perception that the humid and low light environment created by high shade levels facilitates fungal disease such as black pod rot (Clough *et al*., 2009). On the other hand, some fungal diseases, such as witches' broom, may be diminished in traditional cocoa agroforestry systems compared to monocultures (Andres *et al*., 2018; Rice and Greenberg, 2000). Agroforestry systems may help mitigate the effects of swollen shoot disease: Andres *et al*., (2018) studied the effects of shade on cocoa swollen shoot symptom severity, capsid damage and cocoa yield on a gradient of shading in Ghana and found that around 50% shade is optimal to balance symptom severity with reduced cocoa yield (Andres *et al*., 2018). To stop the spread of the mealybug vectors, strips of non-host crops are likely the most effective (Domfeh *et al*., 2016). Shade, distributed across the plot, is also considered an effective management strategy to control cocoa mirids, though supporting ecological knowledge is lacking (Babin *et al*., 2010; Gidoin *et al*., 2014).

Across the literature, the incidence of different diseases and pests in cocoa and coffee production systems varies in relation to shade canopy cover and management intensity, but most suggest that intermediate levels of shade from trees with economic and socio-environmental values, with intermediate levels of pest infestation, may lead to the most optimal outcomes for (system) yields, incomes and overall sustainability, especially in smallholder systems (Tscharntke *et al*., 2011; Rice and Greenberg, 2000; Zewdie *et al*., 2020; Djuideu *et al*., 2020).

Pollination, natural pest control

Overall, greater biodiversity in shaded agroforests leads to an increase in functionally important taxonomic groups, including insectivorous bats and birds, seed dispersing birds, pollinators and different groups providing pest control services (Tscharntke *et al*., 2008 and references therein; Forbes and Northfield, 2017).

In general pollinator abundance and diversity in agricultural landscapes are understood to be influenced by habitat availability, both with cropland as well as surrounding natural habitats. Cocoa is entirely pollination dependent, whilst in coffee pollination enhances yields (by 50-90% for Arabica and Robusta respectively) and supports higher bean quality (Rickets, 2004; Klein *et al*., 2007; Veddeler *et al*., 2008).

In cocoa, the most widely acknowledged pollinators are ceratopogonid midges, though other species have also been found to visit cocoa flowers, including in the apparent absence of ceratopogonids (Toledo-Hernández *et al*., 2021). Ceratopogonids are relatively short ranged, and favourable habitat within plantations, such as intercropping with plantain or bananas and returning cocoa husks to the plantation affects pollinator abundance and cocoa pod set (e.g. Frimpong *et al*., 2011; Cordoba *et al*., 2013; Forbes and Northfield, 2017). In Indonesia, Toledo-Hernández *et al*. (2021), found that the presence of forest and agroforests around cocoa farms, higher canopy cover and on-farm pollinator habitat drove pollinator diversity and were associated with higher flower visitation rates. The effects of surrounding habitats depend on species ranges (Claus *et al*., 2018).

In coffee, the main pollinators are different species of bees. Distance to natural habitats has been found to influence pollinator richness and abundance, in particular wild honeybees, in different studies (e.g., Rickets, 2004; Klein, 2009; González-Chaves *et al*., 2020). Although a systematic literature review, combined with ex-post assessment of surrounding habitat for study sites, by Moreaux *et al*. (2022) found such an effect only if the surrounding habitat was dense tropical forest, and not more sparse natural vegetation. Moreaux *et al*. (2022) did find strong empirical support for the role of animal pollinators in enhancing fruit set in coffee.

Better habitat for pollinators is generally also better habitat for pest predators. There are also likely synergies between pollination and natural pest control services, as tested and found by Martínez-Salinas *et al*., (2022). However, there may be trade-offs as well, e.g., where predatory species deter or attack pollinators (e.g. certain ant species see Rodríguez-Gironés *et al*., 2013).

In numerous studies though, better habitats around and inside cocoa and coffee plantations, have been associated with increased density and diversity of predatory species (e.g., birds, bats, skinks, spiders, ants), and with reduced pest damage and increased yields (e.g., Bael *et al*., 2007); Wielgloss *et al*., 2014; Milligan *et al*., 2016; Forbes and Northfield, 2017; Aristizábal and Metzger, 2019). Moreover, in different studies, the exclusion of birds and bats has been shown to increase the abundance of herbivore pests and decrease yield (by 31% according to Maas *et al*., 2013), outweighing the competition and shade costs in high shade systems (Ferreira *et al*., 2023).

Nutrient cycling, soil fertility

Due to the more forest like conditions, nutrient cycling in diverse agroforestry systems may be comparable to that in natural systems (Nijmeijer *et al*., 2019). Yet, studies on soil fertility effects of shade trees show varying results. There are however indications that shade tree litter fall is not sufficient but the organic matter from shade tree pruning is needed to significantly affect soil fertility (e.g., Tscharntke, 2011; Blaser *et al*., 2017; Andres *et al*., 2018 and references in these papers). The functional traits of shade tree species are also likely to impact soil fertility benefits (see e.g., Sauvadet *et al* 2020).

Soil organisms support a wide range of ecosystem services to both natural and agricultural ecosystems (Wall, 2004), including nutrient cycling. Soil organisms are strongly impacted by above ground management practices (Wardle *et al*., 2004). From a global meta-analysis, van Groenigen *et al*., (2014), conclude: on average earthworm presence in agroecosystems leads to a 25% increase in crop yield and a 23% increase in aboveground biomass. The magnitude of these effects depends on presence of crop residue, earthworm density and type and rate of fertilization. The positive effects of earthworms become larger when more residue is returned to the soil, but disappear when soil nitrogen availability is high. This suggests that earthworms stimulate plant growth predominantly through releasing nitrogen locked away in residue and soil organic matter. Our results therefore imply that earthworms are of crucial importance to decrease the yield gap of farmers who can’t -or won’t- use nitrogen fertilizer.

Biodiversity versus yield objectives

In cocoa and coffee, most research related to biodiversity-yield interactions has focussed on the effects of vegetation structure and management intensity (e.g., Perfecto *et al*., 2005).

High shading can affect cocoa productivity, though see Clough *et al*., (2011) and Steffan-Dewenter *et al*., (2007) or several examples of less strong negative relationships between different biodiversity components and productivity in cocoa systems. Most studies find that shade is unlikely to compromise annual productivity at levels up to around 30- 40% (Steffan-Dewenter *et al*., 2007; Blaser *et al*., 2018), or even 60% (Zuidema *et al*, 2005). Also, higher shade tree canopies have been found to perform better due to lower competition for light (Blaser *et al*., 2021).

There is little evidence on the impact of different elements of biodiversity (e.g., woody and herbaceous species) on coffee and cocoa yields (though see Zewdie *et al*., 2022). Perfecto *et al*., (2005): *data currently available do not allow us to say with confidence what levels of shade or what qualitative vegetative structure are the best for maintaining biodiversity in coffee plantations without significantly sacrificing yield. A recent study comparing ants, butterflies, and birds in the same plots along a coffee intensification gradient (forest, traditional polyculture, commercial polyculture, and shaded monoculture; (Perfecto et al., 2003), showed that while there is a general decline in associated species richness, the pattern of species loss is different for the three taxa.*

In a global meta-analysis (52 papers) Niether *et al*., (2020), found that cocoa yields in agroforestry systems were 25% lower than in monocultures. However, the systems being compared in different studies are often not comparable in terms of management. E.g., when intensive monocultures are compared with more extensively managed smallholder agroforestry systems. There is little evidence on the difference in cocoa productivity between a monoculture and an agroforestry system in the same location, both managed using best agricultural practices (appropriate for each system). System productivity (cocoa and associated trees products) is greater in agroforestry systems than monocultures though as they can provide additional crops besides cocoa and coffee (Blaser *et al*., 2018; Waldron *et al*., 2012; Niether *et al*., 2020). Agroforestry systems, also potentially provide a higher return on labour relative to more intensive, monoculture strategies (Armengot *et al*., 2016).

Yields on most smallholder cocoa and coffee farms, including those with no or low shade levels, are so far below potential than increasing tree cover in these systems even a little is highly likely to support win-win situations of increased (system-level) productivity and decreased risks to farmers whilst improving biodiversity outcomes. Especially in combination with better crop management (Armengot *et al*., 2016; Abdulai *et al*, 2018; Blaser *et al*., 2018; van Noordwijk *et al*., 2021). This is the case for most West African cocoa farmers, smallholder coffee farmers in East Africa, to some extent also in Central America and Colombia, Peru, Indonesia.

Therefore the general assumption that agroforestry systems are inherently less productive than monocultures, and may therefor require more land to meet production goals, should probably be revisited, especially in resource-poor smallholder contexts.

Annex 4.2. Existing indicator frameworks for biodiversity

Biodiversity indicators are used to represent components of the environment that are relevant to decision-making - the state of biodiversity (e.g., a species or ecosystem), or the pressures (e.g., a threat) on biodiversity (IUCN, 2018). They need to be responsive to change in management, be easy and resource efficient to measure and interpret.

Indicators can be a single measure (e.g., number of species, tree density) or an aggregate measure (e.g., aggregating all possible species for which there is data, or combining habitat condition and extent, agroforestry as practice could also be considered an aggregate indicator because it combines different sub-practices).

Biodiversity indicators can be broken down into compositional, structural, and functional diversity indicators. Compositional and structural biodiversity are more easily assessed than functional biodiversity (ecosystem processes, species interactions etc.) and the focus of most biodiversity indicators.

Biodiversity indicators for business
Efforts to develop biodiversity indicators for business (or finance institutions) tend to focus on supporting initial risk screening or providing general information on the impact of a particular commodity in a certain area (e.g., International Finance Corporation's GMAP, EU's Biodiversity Impact Metric) or the potential contribution to better biodiversity outcomes (e.g., Species Threat Abatement and Restoration (STAR) metric). These use existing globally available data, which is often low resolution and only provide a coarse overview on biodiversity impact. The metrics are generally not commodity specific and unable to assess what might be the impact of changes in specific management practices within a particular category of land use (e.g., increasing associated tree diversity or canopy structure, organic matter management, inputs use in perennial (agroforestry systems).

Most assessments of land use impacts on biodiversity used by or developed for business use some measure of species richness as an indicator for the state of biodiversity. This is also the case for life cycle analysis (LCA) approaches (Souza *et al*., 2015). These calculate potential biodiversity impacts often as a percentage loss (or gain) in species richness: a response ratio of *species richness in the land area used/species richness in a reference land use* expected from the conversion of land to a certain level of land use intensity, generally from a pristine reference state. The biodiversity impacts of specific practices on the ground is rarely quantified (De Souza *et al* 2015; core initiative, 2018).

"LCA does not assess the changing state of biodiversity or ecosystems, but rather the relative environmental impact of anthropogenic production systems" (Souza *et al* 2015).

Other metrics are needed to detect on-the-ground impacts (CISL, 2020).

Indicators for on-the-ground impacts
In site-based studies on the impacts of cocoa and coffee management practices on biodiversity, management intensity is often used as a metric, and characterised in either qualitative and quantitative terms (e.g., Bisseleua and Vidal, 2008; Zewdie *et al*., 2022). It is generally based on (a combination of) shade levels and diversity, cocoa/coffee density and/or levels of chemical inputs use, with shade levels the most frequently used as a proxy for management intensity (Norgrove and Beck, 2016).

These studies assume that land use or management intensity adequately represents impacts across (most) taxonomic groups. However, for example, a global meta-analysis by Gibsonet *et al*., (2011 cited in Souza *et al*., 2015) found that different taxonomic groups had different sensitivities to land-use change: mammals were less sensitive to disturbances than birds, who were especially sensitive to change from forest to agriculture. Birds are in fact often used as an indicator species for this reason. Based on a study in Indonesia, Kessler *et al*., (2011), conclude that increasing the number of taxa assessed produces the best overall biodiversity indication and that the most cost-efficient approach to inventories may be to select multiple taxa with the lowest survey costs. Whether this is really the most cost-effective approach may depend on local contexts and methods used though.

Practice-based indicators should be based on knowledge on results or at least a strong theoretical impact pathway towards desired biodiversity change. This is especially a challenge with aggregate indicators where practices are categorised into more or less favourable habitats with associated inferred (through modelling or even expert knowledge) species diversity response rates.

Aggregate indicators, through modelling studies, assess the relationship between categories of crop specific methods of cultivation and species diversity across locations and taxa. Impacts on biodiversity can then be based on an assessment of whether a farm or area has transitioned to practices with better values for biodiversity. However, such an approach requires agreement on a typology of practices and these still need to be monitored.

Advanced technology for biodiversity monitoring
Stephenson (2020) reviews four technological monitoring solutions: satellite-based remote sensing, cameras (traps and drones), acoustic recording devices and environmental DNA (eDNA). They offer promising avenues. For many of these tools data availability (high resolution RS imagery), capacity to use and process collected data and costs of implementation still remain a challenge.

Citizen science is another approach meeting increasing interest, especially with the spread of mobile technology across the world. It can be cost effective when large areas need to be covered and if the methods require limited training and equipment.

Existing biodiversity indicators/ frameworks
We sought out existing indicators or indicator frameworks for biodiversity in cocoa and/or coffee and present the results in this table. The main ones are listed below.

Rainforest Alliance scorecard
The overall indicator framework for the Rainforest Alliance Standard includes the following bodiversity related indicators:

- Area in conservation management area or set aside
- Measures taken to protect and restore forests and other natural ecosystems in the surrounding landscape
- Change in forests and natural ecosystems in the surrounding landscape
- % of total farm area under natural vegetation cover
- % shade cover averaged over the portion of the farm or group of farms growing shade-tolerant crops
- Average number of native tree species per hectare growing shade-tolerant crops- Quantity and diversity of on-farm vegetation
- Presence, abundance, or survivorship of species in key taxa around certified farms
- Quantity and diversity of on-farm vegetation

Rainforest Alliance has a scorecard for regenerative agriculture, with three levels of performance. For biodiversity, all levels require an agroforestry system, but with different levels of associated tree diversity and natural habitat on farm. Indicators are tree species diversity and density and % natural vegetation on farm (including riparian).

Rainforest Alliance. (2021, 02 8). Guidance M: Natural Ecosystems and Vegetation. Retrieved 01 20, 2023, from Rainforest Alliance: https://www.rainforest-alliance.org/resource-item/guidance-m-natural-ecosystems-and-vegetation/

Rainforest Alliance. (2021, 02 18). Indicator and Monitoring Framework. Retrieved 01 17, 2023, from Rainforest Alliance: https://www.rainforest-alliance.org/resource-item/indicator-and-monitoring-framework/

Rainforest Alliance. (2022, 08 29). QGIS Guidance on Converting and Managing Geospatial Files. Retrieved 01 20, 2023, from Rainforest Alliance: https://www.rainforest-alliance.org/resource-item/converting-geospatial-files-guidance/

Rainforest Alliance. (2022, 04 15). Regenerative Coffee Scorecard. Retrieved 01 13, 2023, from Rainforest Alliance: https://www.rainforest-alliance.org/resource-item/regenerative-coffee-scorecard/

Landscale sustainability assessment framework
https://www.landscale.org/wp-content/uploads/2022/10/v1_framework_EN.pdf Not suited for farm level assessments but for landscapes, so potential if interest is to monitor a sourcing area.

FAT perennial crops scorecard, Nestle (Nespresso)
Relevant topics include questions on:

- Mulch or grow cover crops application (% land, cover over time)
- Application of chemical insecticides and/or fungicides, use of IPM
- Application of chemical herbicides , use of integrated weed management
- Percentage of farmland with biodiversity infrastructures
- Keeping of beehives
- Percentage of agriculture land dedicated to agroforestry
- Percentage of shade cover on coffee and cocoa
- Number of different shade tree species (excl. commercial tree species)
- Percentage of permanent crop land (coffee, cocoa, etc.) intercropped with multiple commercial crops (and number of these crops)

World Cocoa Foundation (WCF) Cocoa Measurement and Progress (CocoaMAP) initiative (2012-2013)
This looks like an elaborate tool with protocols that have been tested in the field. According to the available information: *"CocoaMAP FIT was designed as a relatively inexpensive method of collecting high-quality data to be used in CocoaMAP. [...] CocoaMAP FIT can be easily used by non-specialists, including coca farmers […]."* Assessment protocols are included in a Farm Inventory Tool Kit. The Tool Kit could however not be found online, nor any evidence that the tool was applied and by whom, besides the testing phase reported on. Focus is on characteristics of on-farm and in-plot woody vegetation as indicators for biodiversity.

The biodiversity indicators of the CocoaMAP initiative:

- Shade Trees: Number of Shade Trees Per Hectare of Cocoa Land (# of trees >12 meters in height per hectare of cocoa land)
- Shade Cover: Percentage Shade Cover in Cocoa Fields (% of area in cocoa covered by foliage during the dry season)
- Canopy Structure: Number of Strata (Layers) in the Shade Canopy in Cocoa Fields
- Species Diversity: Average Number of Tree Species Per Hectare of Cocoa Land (# of tree and shrub species per hectare of cocoa land)
- On-Farm Forest: Average Area of Cocoa Farms in Forest or Native Vegetation (Hectares of land on cocoa farms still covered in forest, native vegetation or late secondary regeneration)

World Cocoa Foundation. (2012, 12). CocoaMAP FIT for Biodiversity and Sustainability. Retrieved 01 23, 2023, from International Finance Corporation- World Bank Group: https://www.ifc.org/wps/wcm/connect/regprojects_ext_content/ifc_external_corporate_site/bacp/library/bacp_wcf_successstory2

The Cool Farm Tool
The biodiversity module of the Cool Farm Tool is currently not available for Moist Tropical Regions. Indicator scores are based on answers to detailed questions about practices such as numbers of crops, the practices on inputs, cover crops, wildlife friendly measures taken, management of natural habitat etc.

Solidaridad
Solidaridad indicates that they collect biodiversity information through a systematic monitoring programme but indicators and methods are not publicly available (https://www.solidaridadnetwork.org/news/enhancing-biodiversity-conservation-in-agriculture-landscapes/ (2018)). An Internal biodiversity monitoring systems (IBMS) is reportedly implemented in Guatemala in oil palm. *"Digital tools are used for data collection and analysis on mass data management platforms".* https://www.solidaridadnetwork.org/news/engaging-producers-with-digital-tools/ (2020).

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