Regenerative agriculture for low-carbon and resilient coffee farms
A PRACTICAL GUIDEBOOK

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EXCELLENCE IN AGRONOMY
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Foreword

Knowledge and people's competencies are always the starting point for any improvement. They are what make change and impact sustainable.

Acknowledging that we need stronger content and references on the concept of regenerative agriculture, the Nestlé agriculture team worked with the Alliance of Bioversity International and CIAT as well as many other expert stakeholders to translate our regenerative ambition into tangible and pragmatic field actions that can deliver positive impact for farmers, the planet, and society in general.

We are delighted and proud to release the first version of a practical guidebook on regenerative agriculture for low-carbon and resilient coffee farms, which complements the Nestlé Regenerative Agriculture Framework, to guide the field work with coffee farmers around the world. Future versions of this living document will incorporate innovations from the best agricultural research institutions, including our own Nestlé Institute of Agriculture Science.

We encourage our teams and partners to read and put this document to practical use, with the aim of accelerating the journey to regenerative coffee growing.

Pascal Chapot
Group Head of Sustainable Agriculture Development – Nestlé

About this guidebook

For decades, global coffee consumption has grown, as tastes and offerings for consumers have increased around the world, and global demand for coffee will continue to grow in the years to come. At the same time, climate change presents coffee producers and other supply chain actors with major challenges. Its impacts are already reducing the area that is well suited for growing coffee, and this lends urgency to the adoption of farming strategies than can secure future coffee supplies and the livelihoods of coffee-producing families. Major efforts are also needed to lower the contribution of agri-food systems, including coffee, to climate change and other negative environmental impacts, such as land degradation and biodiversity loss.

Regenerative agriculture provides coffee producers with a means to transform their farms by restoring and conserving soil, water and biodiversity, thus building *resilience* in the face of climate change. This approach also creates opportunities to reduce greenhouse gas emissions and enhance carbon storage on farms, while increasing farm income through diversification. Regenerative agriculture offers the further advantage of flexibility, based on principles that apply to both small- and large-scale production across many diverse conditions. As a result, this approach can address multiple environmental and production challenges in ways that are socially and economically viable.

Designed for field agronomists and technicians in the global coffee sector, this guidebook aims to help identify the best regenerative practices and adapt them to different origins, farm types and agroecological conditions. Each region and farm type has its own requirements. For this reason, we highlight key principles and a wide array of practices that can be applied flexibly and combined to enhance the sustainability and resilience of coffee farms. In other words, this guidebook describes the "what" and "why" of regenerative agriculture but does not prescribe "how" it should be implemented. Instead, we offer tools that enable agricultural extensionists to support farmers in the transition to regenerative agriculture by selecting the practices that best match specific needs, objectives and available resources, and by adapting them to the local context.

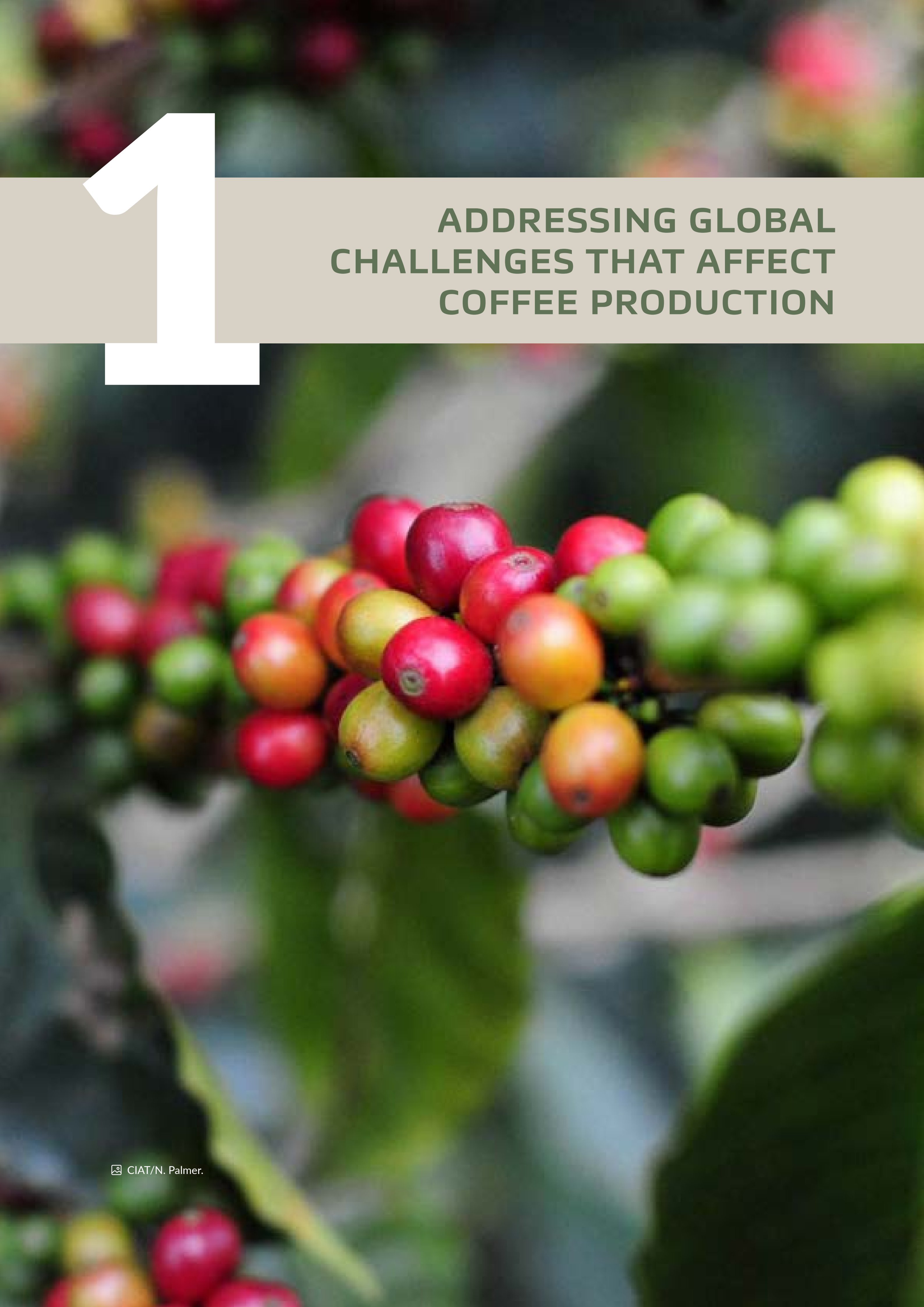
Chapters 1 and 2 of this guidebook lay out the concept, principles and benefits of regenerative agriculture. Chapter 3 describes 11 regenerative practices that are relevant to both Robusta and Arabica coffee cultivation in the world's major coffee-producing regions.

Finally, for ease of reading, a glossary of technical terms can be found on page 175. Please note these selected terms have been italicized throughout the text.

Content

Indonesia (Lampung - Southern Sumatra) | Nestlé

1 ADDRESSING GLOBAL CHALLENGES THAT AFFECT COFFEE PRODUCTION



CIAT/N. Palmer.

1.1. Agriculture: A driver of global change and a system under pressure

Agriculture, occupying almost 40% of the world's total land area, is a major driver of global change. While producing more and more food for a growing population in recent decades, mainstream farming has accomplished this without considering the true costs for the environment and society. One challenge is that modern food production relies heavily on the use of agrochemical inputs and other intensive farming practices that profoundly impact the structure and functioning of ecosystems, while contributing significantly to climate change. At present, nearly 23% of human-induced net greenhouse gas (GHG) emissions originate from agriculture and land-use change, and agricultural expansion and intensification threaten over 80% of species at risk of extinction [1,2].

Sustainable production of agricultural goods depends on favorable and stable climatic conditions as well as on *ecosystem services*, such as nutrient cycling, climate and water regulation, pollination as well as natural pest control). Major efforts are thus needed in the coming years to lower the contribution of agri-food systems to GHG emissions and other negative environmental impacts, such as land degradation and biodiversity loss, while improving the resilience of agricultural production systems to climate change. Societies and agri-food companies have started to acknowledge the urgent need for a real change in global agriculture to safeguard ecosystems, food security and human and animal well-being. In other words, we need a transition to agricultural systems that sustain and restore natural resources rather than degrade them [3]. Such a change requires major efforts from all the actors involved, including governments, the agri-food industry, farmers, other supply chain actors and consumers.

1.2. The case of coffee

Coffee is a case in point. This major agricultural commodity is cultivated on an estimated 12.5 million mostly smallholder farms in more than 20 countries [4]. As a shade-tolerant perennial crop that originated in the understory of tropical forests, coffee has characteristics that give it great potential to favor biodiversity conservation, land restoration and reduced net GHG emissions through carbon storage. Traditionally, coffee has been cultivated in biodiverse agroforestry systems (sometimes referred to as forest gardens), in which natural ecosystem processes sustain its productivity. Moreover, these systems are well suited to the fragile soils or steep slopes that characterize many coffee regions. Yet, in recent decades, the intensification of coffee production has led to the loss of shade trees and simplification of coffee farms and landscapes, leaving soils more prone to erosion and *soil fertility* loss [5]. While this has often resulted in higher coffee yields per hectare, the accompanying rise in agrochemical use has increased environmental impacts and production costs. Coffee's vulnerability to climatic stresses as well as pest and disease outbreaks further threatens future coffee supplies and the livelihoods of smallholder coffee farmers [5].

> **Adoption of practices that use natural resources sustainably rather than degrade them is essential for achieving and maintaining high coffee yields, while improving the ecological and socioeconomic performance of coffee farms. As a shade-tolerant perennial crop, coffee has much potential for land restoration and biodiversity conservation as well as for reducing GHG emissions through carbon storage.**

Coffee production intensity varies strongly between different production regions. At one end of the spectrum, lie the highly efficient coffee-producing regions of Vietnam and parts of Brazil. Those countries obtain average yields of 1.5–2.5 tons of green beans (GB) per hectare [6,7], using intensive farming methods with high amounts of external inputs, resulting in significant environmental risks. At the other end, are regions that produce, on average, 0.5–1.0 tons of GB per hectare, as is common in the majority of coffee-producing countries where smallholders predominate [8,9]. Given prevailing low coffee prices, high production costs, small farm sizes and low yields, coffee production is not economically viable for many of those farmers. An estimated 44% of coffee-farming families live at or below the poverty line [10]. As a consequence, they generally have very limited capacity to invest in adequate management practices and input use to sustain soil fertility and yields, and this worsens their socio-economic situation. In both high- and low-intensity coffee-production regions, it is essential for farmers to adopt practices that use natural resources sustainably, thus permitting them to achieve and maintain high coffee yields, optimize the use of agrochemical inputs, and improve the ecological and socioeconomic performance of coffee farms [3].

1.3. Coffee production and the need for climate change adaptation

Global coffee consumption will continue to grow in the coming decade [11], and other crops will increasingly compete with coffee for limited arable land. Moreover, climate change impacts are significantly reducing the area that is well suited for coffee. It is highly sensitive to those impacts, such as rising temperatures and changes in rainfall patterns, which affect productivity and bean quality [12]. One reason for the sensitivity of coffee farming to climate change is that current commercial varieties

CIAT/M. Pulleman.

have a narrow genetic base and therefore a narrow climatic range [13]. The fact that coffee is a perennial crop with a long lifespan further aggravates the vulnerability of coffee farms to climate change, meaning that coffee planted today will experience the prevailing climate over the next decade. To safeguard productivity and profitability, it is thus a key priority for coffee producers today to achieve climate change adaptation by using practices that make their production systems more resilient.

> **Climate change already affects coffee production and will continue to do so in the coming decades, threatening global coffee supply as well as the livelihoods of coffee farmers. Improving the resilience of coffee farming systems is thus vital for confronting the challenges ahead.**

Bunn *et al.* [12] projected that, in the absence of adequate adaptation measures, the area that is potentially suited for coffee production worldwide will decline substantially, with some areas more strongly affected than others. Both Arabica (*Coffea arabica*) and Robusta (*C. canephora*) can expect to lose large areas suited for production, despite important differences between the two species in plant characteristics and growth requirements (Box 1.1). Although Robusta is more heat tolerant, it also needs a climate with little intra-seasonal variability, and this limits it to low latitudes. Moreover, as the climate becomes not only hotter but also more variable, this may negatively affect Robusta coffee production. Overall, the analysis indicates up to 50% potential global losses in the area suitable for both species by 2050 [12]. The world's dominant production regions, Brazil and Vietnam, could experience potentially large reductions in the area suitable for coffee. In some parts of East Africa and Asia, climate change is projected to make some areas more suitable for coffee, partly compensating for losses in current production zones. However, much of these new areas is currently under forest [12]. The analysis highlights the urgent need to implement *climate change adaptation* measures. Without appropriate action, climate change can dramatically disrupt global coffee supplies, while driving production into new areas at higher altitudes and/or areas currently under forest, thus adding to the pressure on natural resources [5].

CCAFS SEA/L. Sebastian

Box 1.1. Characteristics of Robusta and Arabica coffee that may determine how climate change affects them

More than 100 species of coffee have been identified worldwide, but almost all coffee is made from beans of two species. Arabica (*Coffea arabica*) accounts for about 60% of global production and Robusta (*C. canephora*) for 40%. The two species show important differences in their tolerance to temperatures and susceptibility to major pests and diseases.

Characteristics	Arabica	Robusta
Chromosomes (2n)	44	22
Pollination	Self-fertile	Self-incompatible
Tree shape	Variable (tall and dwarf)	Tall
Root system	Deep	Shallow
Optimum mean annual temperature#	18–21°C	24–30°C
Optimum mean annual rainfall#	1,400–2,000 mm	2,000–3,000 mm
Pest and disease tolerance	Susceptible	Coffee leaf rust (CLR) (resistant), Coffee berry borer (CBB) (susceptible), nematodes (tolerant)
Heat tolerance	Sensitive	Tolerant
Tolerance to low temperatures	Tolerant	Sensitive
Postharvest process	Mostly wet	Mostly dry

Based on DaMatta *et al.* [18] and Campuzano-Duque *et al.* [19].

For both species, a short dry spell, corresponding to the quiescent growth phase, is important to stimulate flowering. Lack of a dry period with abundant rainfall throughout the year is often responsible for scattered harvest and low yields. A short dry period of less than 40 mm precipitation per month increases yield and promotes uniform flowering, but more than 3–4 dry months reduces yield and can limit coffee cultivation in lowland tropical regions.

The greatest climate-related threats to coffee cultivation in current production areas are rising temperatures and changes in rainfall patterns [14]. It has been shown that *vapour pressure deficit* during fruit development is a key indicator of coffee productivity, since it measures the plant's combined response to high temperatures and plant water stress [15]. Such interactions can strongly affect global coffee productivity under global warming. Climate change also affects the crop calendar together with the distribution and abundance of pests and diseases – e.g., coffee berry borer (CBB) and coffee leaf rust (CLR) [16] – as well as pollinators [17], with potentially important consequences for coffee yields, quality and production costs. Finally, extension of the wet season complicates sun-drying of coffee beans and reduces quality, unless farmers invest in improved drying facilities. All of these effects depend greatly on the context and involve significant uncertainty. Climate change adaptation should, therefore, focus on improving the resilience of coffee production systems. For this purpose, climate change and land degradation should not be considered separately but rather as mutually reinforcing pressures. Natural resource depletion (e.g., loss of soil quality and water provision in the landscape) aggravates the vulnerability of coffee farms to climate change and climate extremes [5].

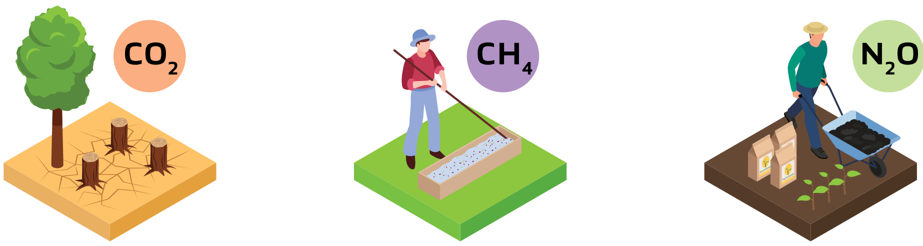
1.4. Greenhouse gas mitigation in coffee production

In addition to the urgent need for *climate change adaptation*, coffee producers and supply chain partners can also contribute to *mitigation* by reducing net GHG emissions from coffee production. This requires reductions in the emissions resulting from farm activities (i.e., reducing the *carbon footprint*) and *carbon removal* through *soil carbon sequestration* and reforestation, including *agroforestry*.

1.4.1. Reducing GHG emissions

GHG emissions from agriculture, as shown in Figure 1.1, include carbon dioxide (CO_2), mostly from deforestation and land-use conversion; nitrous oxide (N_2O), mainly from soils and the application of mineral and organic fertilizers; and methane (CH_4), which is produced under prolonged anaerobic conditions. Livestock digestive processes, especially in ruminants, and manure management are major sources of methane in agriculture [2]. Coffee production can result in significant methane emissions from organic waste and wastewater produced during postharvest wet processing as well as during anaerobic *compost* production (Figure 1.2).

Because GHGs differ in their ability to absorb energy (their "radiative efficiency") and in the length of time they stay in the atmosphere (also known as their "lifetime"), they have different *global warming potential* (Figure 1.1). Global warming potential is used to convert N_2O and CH_4 emissions into *CO_2 equivalents*, thus providing a common unit of measurement for adding up emission estimates of the three different gases to calculate the total carbon footprint of a farm or product (see Box 1.2).



Greenhouse gas	CARBON DIOXIDE	METHANE	NITROUS OXIDE
Emission source	Deforestation, fertilizer production, soil degradation, fuel use	Waste water management, (anaerobic) composting	Fertilizer application, decomposition of crop residues, organic waste processing (e.g., composting).
100 years global warming potential	1	27	273

Figure 1.1. GHGs emitted from agriculture, their most important sources relevant to coffee farming and their *global warming potential*.

Multiple studies [20–22] have estimated GHG emissions and carbon footprints in coffee production systems. The estimates vary considerably among and within farm types, even when the same methods and assumptions are used. This reflects variation in production intensity, postharvest processing methods and the coffee yields obtained. A clear example comes from a study by van Rikxoort et al. [21], who compared the carbon footprint of Arabica coffee production (expressed in kilograms of CO_2 equivalent per kilogram of dry parchment coffee or DPC) for different farm types across Central America. Variation in the carbon footprint of different farm types ranged from 3.7 to 9.4 kg CO_2-eq/kg of DPC, largely depending on management intensity and coffee yields. On average, across all coffee farming systems, the contribution of different on-farm activities to coffee's carbon footprint (Figure 1.2) decreased in the following order: emissions from fermentation and wastewater (57%); fertilizer production and application, including background soil emissions (35%); emissions from prunings and crop residues decomposing on the ground (7%); followed by other sources, such as fuel and electricity as well as pesticide production (<2%). The relative importance of individual activities in determining the carbon footprint of the entire production system also showed high variability among farms, even for the same type [21].

Despite the large variations in emissions estimates, the evidence clearly shows that net emissions on coffee farms are key for reducing the crop's carbon footprint. Moreover, the large variations found between farms employing different production and processing practices convincingly illustrate the possibility of significantly reducing the carbon footprint on coffee farms. This requires efforts to optimize coffee yields, while improving fertilizer-use efficiency as well as postharvest processing methods.

Taking gas samples in the field for the measurement of GHG emissions from soil | CIAT/M. Romero.

Coffee producers and supply chain partners can contribute to climate change mitigation by reducing net GHG emissions. Coffee farms have much potential to reduce the carbon footprint associated with production. These farms can also contribute to significant carbon removal through carbon sequestration.

Box 1.2. What is a carbon footprint, and how is it calculated?

Carbon footprint is an indicator that measures the impact that a certain production system or product has on global warming. It is calculated as the total amount of the greenhouse gases CO_2, CH_4 and N_2O, expressed in terms of *CO_2 equivalents* that are emitted due to the production or supply of this product. Carbon footprint provides a useful way to compare the opportunities for emissions reduction of different production systems and practices. Since it is expressed in CO_2 equivalents, one can include and compare the contributions of different GHGs, while considering the differences in their *global warming potential* (Figure 1.1).

Depending on the goal, farmers may focus on reducing the climate impact of their operations (total emissions expressed as tons per hectare of CO_2 equivalent (t CO_2-eq/ha) or produce a low-carbon product (total emissions expressed as kilograms of CO_2 equivalents per kilogram of product: kg CO_2-eq/kg product). Just reducing the emissions per unit of product may or may not decrease total farm emissions, as farmers may choose to grow more product. The opposite is also true. A farm may have relatively low emissions, but due to even lower productivity, it may have a high footprint per unit of product.

The carbon footprint of coffee production is calculated by estimating all the GHG emissions produced through the different activities involved in crop production and on-farm processing of the beans (Figure 1.2). This calculation usually considers all on-farm emissions, including those from purchased inputs, such as fertilizer and electricity. Various tools are available, such as the Cool Farm Tool (https://coolfarm.org/), for estimating the carbon footprint of specific production systems. Such tools can stimulate thinking about possible improvements in management by showing which activities or sources are emissions hotspots and by helping to develop action plans accordingly. For this purpose, farm records are important, since the accuracy of the calculations depends on the quality and detail of the data used.

Carbon footprint analyses focus on emissions and do not capture the potential positive contributions of coffee production systems to climate change mitigation through *carbon removal* via reforestation or *soil carbon sequestration*.

1.4.2. Carbon removal

Depending on land use and management practices, farming systems can contribute to carbon removal by capturing CO_2 from the atmosphere and storing it in tree biomass through reforestation or in the soil as *soil organic matter* (Figure 1.2). Since coffee is a woody perennial, coffee production systems have great potential for carbon removal, especially when the crop is grown with shade trees or cover crops.

The amount of carbon that coffee production systems store can vary widely, since they range from full-sun systems to complex agroforests. For example, a study in Costa Rica [23] reported above- and belowground carbon stocks of C. 14 t C/ha in an unshaded coffee monoculture versus 32 t/ha in a coffee system with shade trees of the genus *Inga*. In the study mentioned earlier, van Rikxoort et al. [21] estimated that the amount of carbon stored in vegetation ranged from 11 t/ha in unshaded monocultures to 43 t/ha in traditional polycultures. The authors acknowledged that adding soil carbon to the calculations would likely result in even more pronounced differences due to the higher litter inputs in polycultures. However, they did not consider soil carbon stocks in their model calculations, because conclusive studies needed to reliably predict differences in soil carbon storage among coffee systems are lacking [21].

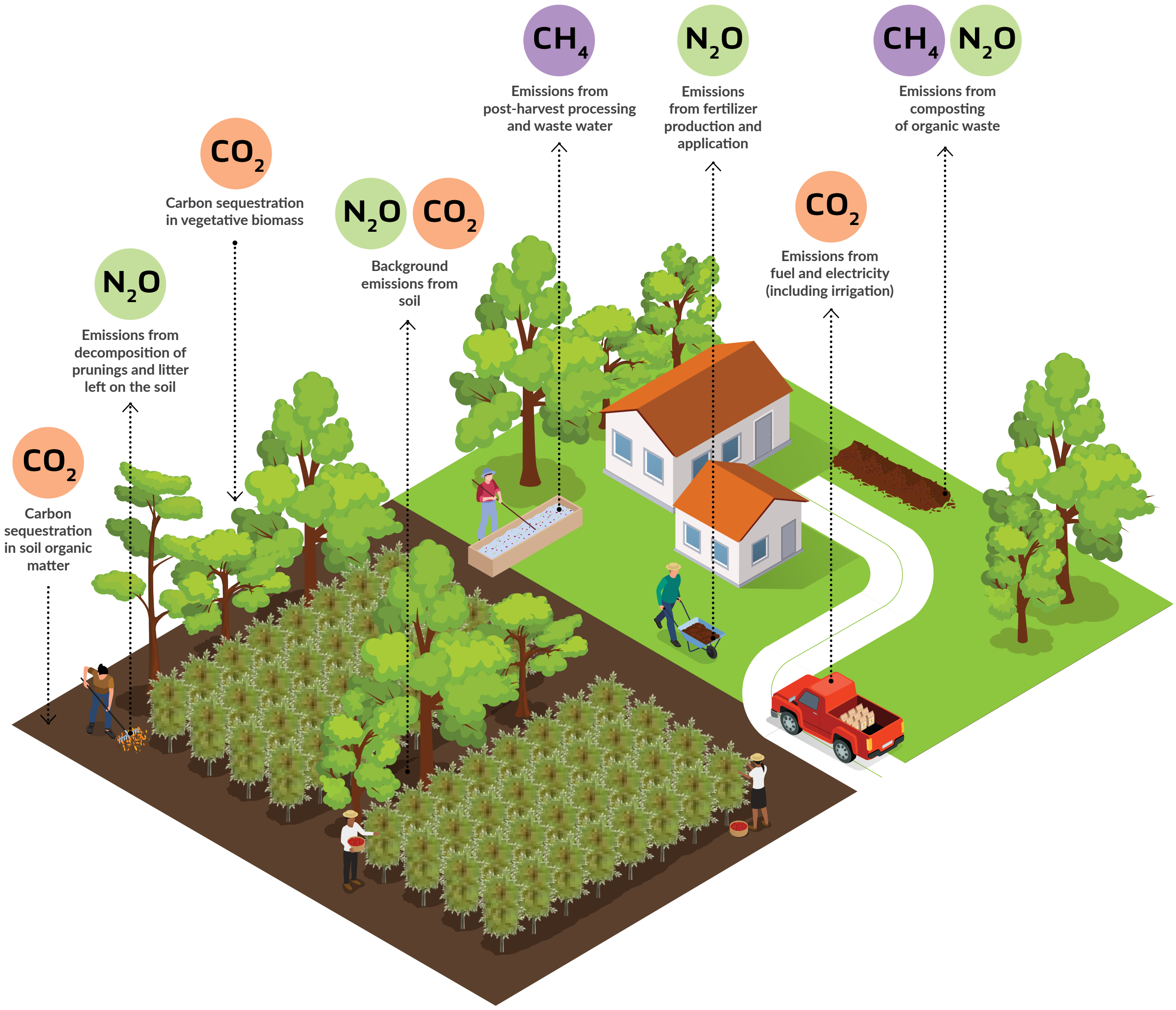


Figure 1.2. The main sources of GHG emissions and carbon sinks related to coffee production and on-farm processing. This representation of a farm is simplified, considering only the coffee crop and no livestock integration. We considered the period from production of dried coffee parchment until the coffee is transported to the mill as the boundary of the coffee system.

To achieve climate-friendly coffee production, it is necessary to optimize both dimensions of climate mitigation – carbon footprint and carbon removal [21]. The type of coffee production system (e.g., the use of shade trees) is clearly relevant to its overall climate impact, and so are individual production and postharvest processing practices. Since carbon footprints are generally considered per unit of product, coffee yields are a key component affecting carbon footprint calculations. By implication, systems that have high carbon stocks do not automatically result in a low-carbon footprint. For instance, traditional coffee agroforestry systems with high amounts of carbon stored in tree biomass can have very high carbon footprints if fertilizer is applied inefficiently and yields remain low due to other limiting factors, such as excessive shade, aged coffee plants, or lack of weed management or pruning [21]. It is therefore key to achieve emissions reduction and removal in coffee production without adversely affecting yield, especially in low-yielding coffee systems.

1.5. Looking ahead: Regenerative coffee farming as part of the solution

Safeguarding sustainable coffee supplies and the livelihoods of coffee producers urgently requires a global transition towards production practices that optimize coffee yields and enhance the resilience of coffee farms by restoring and conserving natural resources, such as biodiversity, water and soil. Such a transformation must go hand in hand with adequate climate change adaptation and mitigation. Adding to the urgency are changes in consumer demand and the regulatory requirements of coffee-importing countries, regarding pesticide reductions, zero deforestation or biodiversity reporting [24,25]. Much increased efforts are needed to address these challenges for coffee producers, industry, and other partners along the supply chain.

> **Regenerative agriculture provides coffee farmers across diverse agroecological and socioeconomic conditions with the tools they need to transform their farms and build resilience in the face of climate change by restoring and conserving soil, water and biodiversity. Regenerative agriculture can also permit agri-food companies to mitigate GHG emissions in their supply chains.**

The good news is that coffee offers a good opportunity to combine the objectives of improved production with natural resource conservation and carbon sequestration [26]. By adopting the principles of regenerative agriculture (see Chapter 2), farmers can transform their production systems and practices in ways that improve productivity and/or profitability, while building resilience to climate change and market volatility as well as mitigating GHG emissions. Regenerative agriculture offers a flexible approach that can be tailored to specific farming contexts and is thus well suited to the diverse agroecologies and socioeconomic realities of small- and large-scale coffee farmers. The approach can thus address multiple environmental and production challenges in ways that are socially and economically viable. Critical for success are a sound understanding of the diverse realities of coffee farmers and effective strategies to support farmers, especially smallholders, in making the required changes [27,28].

As part of Nestlé's climate pledge and road to net-zero emissions as well as the Nescafé plan and Nespresso strategy towards 2030, the company considers regenerative agriculture to be a key component of its effort to reduce carbon emissions and offset residual emissions. The company expects to reduce emissions through carbon sequestration on coffee farms, while supporting coffee growers in transforming their farms to increase productivity, profitability, and environmental sustainability of the land (Box 1.3).

Box 1.3. Nestlé's commitments to deploy regenerative agriculture at scale: What are the ambitions, and how will they be achieved?

As one of the largest global food processors, Nestlé recognizes the urgency of addressing multiple sustainability challenges in its supply chains. In line with the **Nestlé Net Zero Roadmap** (http://bit.ly/3kXmENc), the company aims to achieve net zero GHG emissions by 2050, including all direct and indirect emissions. It will reduce emissions as much as possible and remove carbon through nature-based solutions within the supply chain, thereby generating benefits for communities, while protecting natural ecosystems. To this end, the company has embarked on a long-term effort to transform the way it sources ingredients used in its products. The **Nestlé Agriculture Framework** (https://bit.ly/3yK0Urr), released in September 2022, describes Nestlé's corporate vision for agriculture as a central building block for a regenerative food system.

NESTLÉ GOALS

Net Zero by 2050

- **20%** emissions reduction by 2025
- **50%** emissions reduction by 2030
- **Net zero** emissions by 2050 at the latest

Advancing regenerative food system at scale

- **20%** of its key ingredients will be sourced through regenerative agriculture by 2025
- **50%** of its key ingredients will be sourced through regenerative agriculture by 2030

What about coffee?

Nestlé is the world's largest coffee buyer. Its coffee brands Nescafé and Nespresso play a key role in achieving the company's commitments to reach "net zero" and transition to regenerative agriculture.

Nescafé Plan 2030 (https://bit.ly/47xI0UI) outlines how Nescafé will make coffee farming more sustainable, address climate change and improve farmers' livelihoods by helping them transition to regenerative agriculture. Nescafé provides farmers with training, technical assistance and high-yielding coffee plantlets. Nescafé is also working with coffee farmers to test and assess the effectiveness of regenerative agriculture practices and promote learning.

Regenerative agriculture is also at the heart of the **Nespresso strategy** (https://bit.ly/3ZqlvfL) towards 2030. It lays out how Nespresso, in partnership with the Rainforest Alliance, will scale up regenerative agriculture to restore soils and biodiversity and thus enhance the resilience of ecosystems and farmers' livelihoods, while mitigating climate change. Nespresso agronomists work closely with farming communities in AAA countries worldwide, supporting farmers in their journey. Nespresso goals, aligned with Nestlé goals, aim to accelerate positive impacts.

NESPRESSO GOALS

- Source **95%** regenerative coffee by 2030
- Accelerate towards **Net zero** by 2035, at the earliest

1.6. References

1. Benton T; Bieg C; Harwatt H; Pudasaini R; Wellesley L. 2021. *Food System Impacts on Biodiversity Loss: Three levers for food system transformation in support of nature*. Chatman House. 75 p. https://bit.ly/43k4Fl7

2. IPCC. 2019. *Climate Change and Land: An IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems.* https://www.ipcc.ch/srccl/

3. Nestlé. 2022. The Nestlé Agriculture Framework. https://bit.ly/3zKFevv (Accessed on January 30, 2023).

4. Enveritas. 2019. How many coffee farms are there in the world? https://bit.ly/3KMXLhk (Accessed on 30 January 2023).

5. Harvey CA; Pritts AA; Zwetsloot MJ; Jansen K; Pulleman M; Armbrecht I; Avelino J; Barrera JF; Bunn C; Hoyos J; Isaza C; Munoz-Ucros J; Pérez-Alemán C; Rahn E; Robiglio V; Somarriba E; Valencia V. 2021. Transformation of coffee-growing landscapes across Latin America. A review. *Agronomy for Sustainable Development*. 41. https://doi.org/10.1007/s13593-021-00712-0

6. Conab. 2023. *Acompanhamento Da Safra Brasileira: Café Safra 2023 n.1 - Primeiro Levantamento.*

7. ICO. 2019. Country Coffee Profile Vietnam. In: International Coffee Council 124th Session. https://bit.ly/41g95rl (Accessed on 30 January 2023).

8. Waller JM; Bigger M; Hillocks RJ. 2007. World coffee production. In: *Coffee Pests, Diseases and Their Management*. CABI. https://doi.org/10.1079/9781845931292.0017

9. Bacsi Z; Fekete-Farkas M; Ma'ruf MI. 2022. Coffee Yield Stability as a Factor of Food Security. *Foods*. 11. https://doi.org/10.3390/foods11193036

10. Bozzola M; Charles S; Ferretti T; Gerakari E; Manson H; Rosser N; von der Goltz P. 2021. *The Coffee Guide*. International Trade Centre. Geneva, Switzerland. https://intracen.org/media/file/5718

11. CDI. 2023. *Coffee Market Size, Share & Trends Estimation Report By Product Type (Fresh Coffee, Coffee Pods & Capsules), By Category (Conventional, Organic), By Distribution Channel (Store-Based, Non-Store-Based), By Region, and Segment Forecasts, 2023–2030.* https://bit.ly/41dENFL (Accessed on 1 February 2023).

12. Bunn C; Läderach P; Ovalle Rivera O; Kirschke D. 2015. A bitter cup: climate change profile of global production of Arabica and Robusta coffee. *Climatic Change*. 129. https://doi.org/10.1007/s10584-014-1306-x

13. Damatta F; Rodríguez N. 2007. Sustainable production of coffee in agroforestry systems in the Neotropics: an agronomic and ecophysiological approach. *Agronomía Colombiana*. 25. http://www.scielo.org.co/pdf/agc/v25n1/v25n1a13.pdf

14. Pham Y; Reardon-Smith K; Mushtaq S; Cockfield G. 2019. The impact of climate change and variability on coffee production: a systematic review. *Climatic Change.* 156. https://doi.org/10.1007/s10584-019-02538-y

15. Kath J; Craparo A; Fong Y; Byrareddy V; Davis AP; King R; Nguyen-Huy T; van Asten PJA; Marcussen T; Mushtaq S; Stone R; Power S. 2022. Vapour pressure deficit determines critical thresholds for global coffee production under climate change. *Nature Food.* https://doi.org/10.1038/s43016-022-00614-8

16. Ziska L; Bradley B; Wallace R; Bargeron C; LaForest J; Choudhury R; Garrett K; Vega F. 2018. Climate Change, Carbon Dioxide, and Pest Biology, Managing the Future: Coffee as a Case Study. *Agronomy*. 8. https://doi.org/10.3390/agronomy8080152

17. Imbach P; Fung E; Hannah L; Navarro-Racines C; Roubik D; Ricketts T; Harvey C; Donatti C; Läderach P; Locatelli B; Roehrdanz P. 2017. Coupling of pollination services and coffee suitability under climate change. *Proceedings of the National Academy of Sciences (PNAS).* 114. https://doi.org/10.1073/pnas.1617940114

18. Damatta FM; Ronchi CP; Maestri M; Barros RS. 2007. Ecophysiology of Coffee Growth and Production. *Brazilian Journal of Plant Physiology.* 19. https://doi.org/10.1590/S1677-04202007000400014

19. Campuzano-Duque LF; Herrera JC; Ged C; Blair MW. 2021. Bases for the Establishment of Robusta Coffee (*Coffea canephora*) as a New Crop for Colombia. *Agronomy*. 11. https://doi.org/10.3390/agronomy11122550

20. Noponen MRA; Edwards-Jones G; Haggar JP; Soto G; Attarzadeh N; Healey JR. 2012. Greenhouse gas emissions in coffee grown with differing input levels under conventional and organic management. *Agriculture, Ecosystems & Environment*. 151. https://doi.org/10.1016/j.agee.2012.01.019

21. van Rikxoort H; Schroth G; Läderach P; Rodríguez-Sánchez B. 2014. Carbon footprints and carbon stocks reveal climate-friendly coffee production. *Agronomy for Sustainable Development*. 34. https://doi.org/10.1007/s13593-014-0223-8

22. Ortiz-Gonzalo D; de Neergaard A; Vaast P; Suárez-Villanueva V; Oelofse M, Rosenstock TS. 2018. Multi-scale measurements show limited soil greenhouse gas emissions in Kenyan smallholder coffee-dairy systems. *Science of The Total Environment*. 626. https://doi.org/10.1016/j.scitotenv.2017.12.247

23. Hergoualc'h K; Blanchart E; Skiba U; Hénault C; Harmand JM. 2012. Changes in carbon stock and greenhouse gas balance in a coffee (*Coffea arabica*) monoculture versus an agroforestry system with *Inga densiflora*, in Costa Rica. *Agriculture, Ecosystems & Environment*. 148. https://doi.org/10.1016/j.agee.2011.11.018

24. zu Ermgassen SOSE; Howard M; Bennun L; Addison P; Bull J; Loveridge R; Pollard E; Starkey M. 2022. Are corporate biodiversity commitments consistent with delivering 'nature-positive' outcomes? A review of 'nature-positive' definitions, company progress and challenges. *Journal of Cleaner Production.* 379. https://doi.org/10.1016/j.jclepro.2022.134798

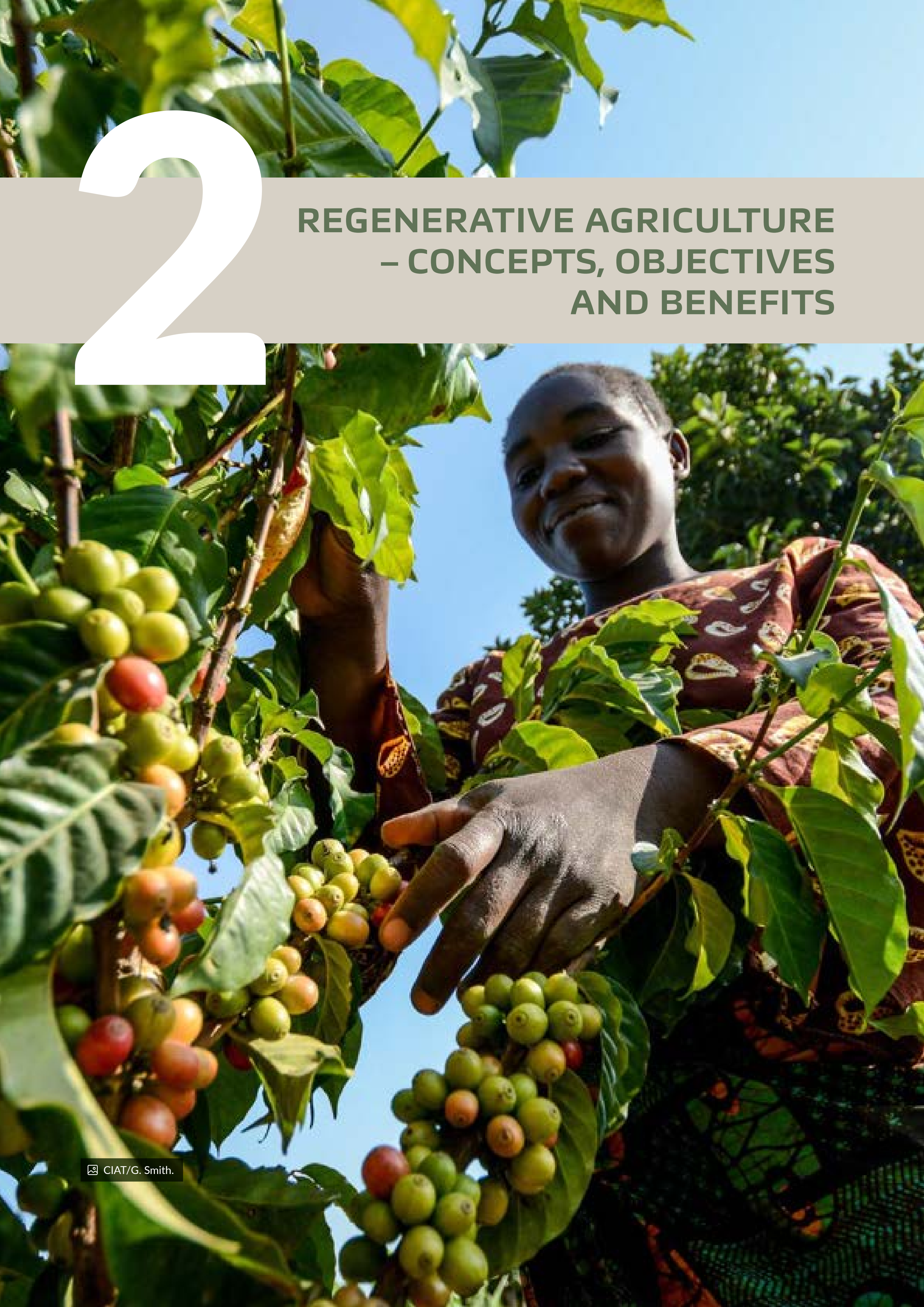
25. Matthews A. 2022. Implications of the European Green Deal for agri-food trade with developing countries. In: 96th Annual Conference of the Agricultural Economics Society. AgEcon Search. https://ageconsearch.umn.edu/record/321162/

26. Birkenberg A; Birner R. 2018. The world's first carbon neutral coffee: Lessons on certification and innovation from a pioneer case in Costa Rica. *Journal of Cleaner Production.* 189. https://doi.org/10.1016/j.jclepro.2018.03.226

27. Le QV; Cowal S; Jovanovic G; Le DT. 2021. A Study of Regenerative Farming Practices and Sustainable Coffee of Ethnic Minorities Farmers in the Central Highlands of Vietnam. *Frontiers in Sustainable Food Systems.* 5. https://doi.org/10.3389/fsufs.2021.712733

28. Nuñez-Solis M del M; Rosin C; Ratna N. 2020. Coffee micro-mills in Costa Rica: A non-cooperative path to regenerative agriculture? In: Duncan J; Carolan M; Wiskerke JSC, eds. *Routledge Handbook of Sustainable and Regenerative Food Systems.* Routledge. https://doi.org/10.4324/9780429466823

2 REGENERATIVE AGRICULTURE – CONCEPTS, OBJECTIVES AND BENEFITS



CIAT/G. Smith.

2.1. What is regenerative agriculture?

Regenerative agriculture is a holistic approach to sustainable farming that focuses on restoring natural resources on farms and in the surrounding landscapes.

> **By adopting regenerative practices that restore soil health and protect biodiversity in and around their farms, coffee producers can contribute positively to nature. Nature's contributions to people, in turn, can benefit coffee producers.**

Regenerative agriculture is not new; the concept dates to the early 1980s [1]. However, more recently, it has gained much attention because farmers, consumers, governments and agrifood companies are increasingly aware that a change in the way we produce our food, including coffee, is needed. There is no universally accepted definition of regenerative agriculture. Yet, there seems to be general agreement that regenerative agriculture is not just about 'doing less harm', or being merely 'sustainable', but makes positive contributions by 'restoring' natural ecological functions [2]. The different descriptions in use emphasize the importance of restoring soil health, reversing biodiversity loss and strengthening ecosystem services. Many also highlight that enhancing the social and financial well-being of farm families is a central objective [3]. Regenerative agriculture shows important overlap with other sustainable farming models or concepts (see Box 2.1), although different organizations may show varying interpretations of what regenerative agriculture precisely entails in practical terms.

This guidebook describes Regenerative Agriculture as **a farming approach that emphasizes protecting and restoring natural resources (primarily soil, but also water and biodiversity) to deliver multiple benefits to farmers, environment and society.** By strengthening *soil health* and *ecosystem services*, regenerative agriculture helps make agroecosystems more productive and resilient, while also improving farmers' livelihoods. A focus on regenerative agriculture further creates important opportunities to mitigate greenhouse gas (GHG) emissions.

Box 2.1. How does regenerative agriculture relate to other integrated farming approaches?

Regenerative agriculture, while incorporating many aspects of good agricultural practices [1], also shares ideas and principles with other farming approaches considered to be sustainable alternatives, such as *conservation agriculture*, *climate-smart agriculture*, agroecology and *ecological intensification*. These approaches may consider different scales (fields, farms or food systems) and may prioritize environmental, economic and/or social outcomes differently. Yet, they have the common goal of reversing negative impacts associated with conventional agriculture, such as environmental degradation, intensive use of external inputs and lack of resilience to such pressures as climate change. Like regenerative agriculture, these other approaches also recognize the importance of *soil health* and natural processes for efficient use of external inputs, thus improving agricultural production systems and farmers' livelihoods, while enhancing their resilience. Regenerative agriculture brings together these various approaches, aiming not only to protect natural resources but to actively enhance them [4].

Another approach – organic agriculture – is defined as "a production system that sustains the health of soils, ecosystems, and people. It relies on ecological processes, biodiversity and cycles adapted to local conditions, rather than the use of inputs with adverse effects" [5]. While sharing similar objectives to those of regenerative agriculture, there are also fundamental differences between the two approaches. Unlike regenerative agriculture, organic farming prescribes strict standards and regulations – for example, on the use of synthetic fertilizers and pesticides, eliminating the use of synthetic inputs. Regenerative agriculture, in contrast, does not exclude the use of chemical inputs altogether (especially in case of synthetic fertilizers), but rather optimizes their use to reach multiple objectives, such as increasing productivity and limiting negative environmental impacts. Organic farming is thus not the long-term ambition of regenerative agriculture but rather offers one possible interpretation towards regenerative farming (sometimes referred to as "regenerative organic") [1].

The characteristics described below are key to the concept of regenerative agriculture and its implementation:

1. Regenerative agriculture is **outcome focused.** The approach does not prescribe specific practices but rather seeks to achieve specific goals linked to multiple aspects of sustainability (environmental, economic and social).
2. Regenerative agriculture is **flexible.** Guided by general agronomic and ecological principles and broadly defined practices, the approach can be adapted to small- and large-scale production as well as to different agroecological conditions. This is illustrated in Chapter 3.
3. Regenerative agriculture is based on **scientifically sound and context-relevant** evidence.
4. Adoption involves a **transition** or "journey". Regenerative agriculture is knowledge intensive and requires a process of learning and adaptation. Different regenerative practices can be combined or applied incrementally to achieve multiple benefits. To foster such innovations, collaboration among farmers, supply chain partners and researchers is important.

Nestlé.

2.2. The pillars and objectives of regenerative coffee farming

Regenerative agriculture focuses on three main pillars: **soil, biodiversity** and **water**. The pillars represent key natural resources in farmland that are essential for improving and maintaining the productivity and environmental quality of farmland. The restoration and sustainable management of these resources require actions on individual farms and collectively across landscapes. In addition to the three pillars, farmers and their families are central to regenerative agriculture. Farmers depend on coffee for their livelihoods. They also make the decisions about production practices and are responsible for their implementation, while taking into account the specific circumstances of their farms and the available assets, such as labor, knowledge and inputs.

Regenerative agriculture emphasizes the diversification of production systems, where possible, complemented by landscape actions. In line with agroecological principles, increasing the diversity and complexity of coffee production systems helps to strengthen the natural processes that underpin ecosystem services. Examples are climate regulation through agroforestry, or improved pollination through the integration of flowering crops and wild plants. Greater crop species diversity and vegetation complexity also make production systems more resilient to environmental shocks as well as to pests and diseases, and less dependent on external inputs. Where applicable, the integration of livestock can help improve nutrient cycles and optimize returns on land and biomass. In addition, diversification offers opportunities to increase farmers' incomes and reduce their vulnerability to volatile markets, low coffee prices and other external shocks. Finally, landscape actions aimed at conserving and restoring biodiversity, protecting waterways, and creating ecological corridors and buffer zones can strengthen the impact of regenerative practices implemented by individual farmers in their coffee fields.

This combination of diversification and landscape actions to restore natural resources characterizes the holistic model of regenerative agriculture [4]. This model applies to different types of production systems, including coffee, as is shown schematically in Figure 2.1.

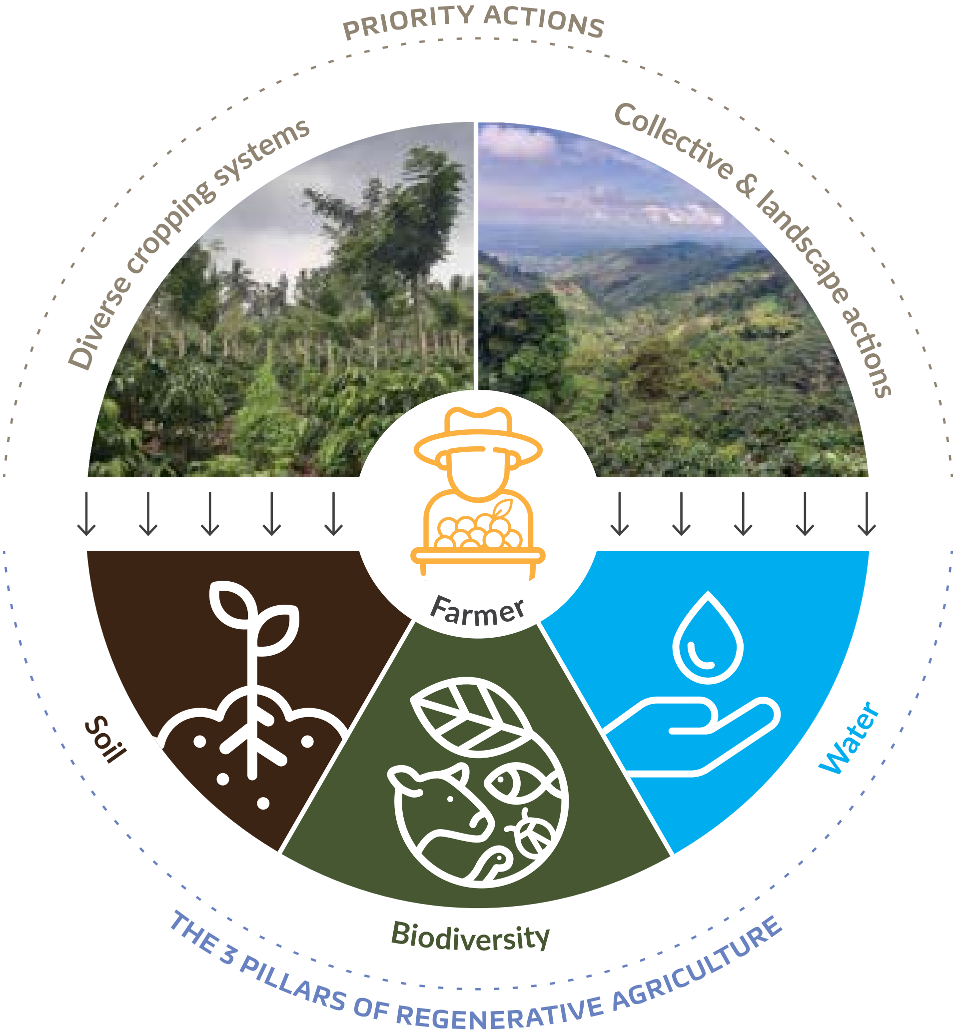


Figure 2.1. The holistic model of regenerative agriculture as applied to coffee production. The model consists of three pillars and two priority actions at the farm and landscape levels. Farmers play a central role, making decisions about farm management. Modified from the Nestlé Agriculture Framework [4].

2.2.1. Pillar 1 – Soil

Soils are a fundamental resource supporting the very basis of our food system. They have been formed through the interaction of parent material, relief, climate and organisms over long periods in the geological time scale. This process of soil formation has resulted in a wide variety of soil types (each with its characteristic properties), even within the same landscape. Over shorter time periods, land use and management strongly affect soils, including their chemical, physical and biological properties. Unsustainable soil management, including for agriculture, has led to widespread soil and land degradation, affecting an estimated 3.2 billion people [6]. Major soil threats include soil erosion, the decline of soil organic matter and soil fertility, the loss of soil biodiversity, soil acidification and soil compaction.

Soil health

Soil health refers to the capacity of soil to perform its *ecological functions*, i.e. sustaining plant productivity and biodiversity, acting as a habitat for soil biota, regulating water, cycling and provision of nutrients, buffering pollutants, and regulation of pest and disease populations [7]. The capacity to perform those functions depends on a series of chemical, physical and biological soil properties, such as pH, soil organic matter content, *soil structure* and aggregation and the activities of soil biota, amongst others (Box 2.2). By storing soil organic carbon and supporting biomass production, healthy soils also contribute to GHG gas mitigation [8]. Improved soil nutrient cycling is important to support good coffee yields while using mineral fertilizers efficiently. Healthy soils also enhance the climate resilience of production systems through improved water infiltration, moisture retention, rooting conditions and disease suppressiveness [9].

> **Regenerative agriculture emphasizes the improvement of soil health. By enhancing soil biodiversity and natural soil processes, healthy soils help to use mineral fertilizers more efficiently, foster pest and disease control, improve water retention and store soil carbon. Healthy soils provide the basis for climate-resilient coffee production, while also creating opportunities for carbon footprint reduction and carbon removal.**

Objectives for soil health improvement

Regenerative agriculture improves soil health (and stimulates soil life) by achieving the following objectives (Figure 2.7):

- Controlling soil erosion and runoff
- Minimizing soil tillage and compaction
- Maintaining permanent soil cover
- Recycling of organic matter
- Optimizing nutrient management
- Limiting pesticide use

Controlling soil erosion and runoff is a key objective for coffee farms, especially since much coffee is produced on steep slopes and in places where intense rain showers can lead to gradual erosion of the topsoil or landslides that cause the loss of the complete soil profile during one event. Eroded soils have a lower capacity to retain water and provide nutrients to crops. Soil erosion and runoff may also lead to the contamination of water bodies, flooding and damage to infrastructure. Runoff water and sediments may carry fertilizers and pesticides that have been applied on coffee farms, representing both an economic cost for farmers and an environmental cost for society. Soil conservation measures are therefore central to regenerative coffee farming (see Chapter 3.4.4).

Minimizing soil tillage and compaction is essential for reducing negative impacts on soil physical and biological processes. Although soil tillage can help to control weeds and improve water infiltration in the short term, it also leaves the soil bare, causes disintegration of soil aggregates, and harms soil structure and soil life. The use of heavy machinery causes soil compaction with detrimental effects on soil aeration, drainage and root development. Although regular tillage and the use of heavy machinery are not common in coffee production, there are exceptions, as in Brazil. When soils are already severely compacted, deep tillage is sometimes applied before coffee establishment to allow for better root growth. This technique should be combined with the planting of deep-rooting crops (e.g., grasses) to stimulate natural, lasting and cost-effective soil improvement [[10]].

Erosion of topsoil in Colombian coffee fields | CIAT/N. Palmer.

Maintaining a permanent soil cover through mulching or the use of cover crops (also called "living mulch") has many benefits for soil health. These practices protect soil from the impacts of water and wind as well as extreme temperatures, reduce weed growth and provide the soil with organic matter and nutrients. Perennial crops like coffee provide good opportunities for cover crops or mulching, especially after renovation/rehabilitation or in mechanized systems, when soil protection is a priority and enough light is available to grow an additional crop between the coffee rows (see Chapter 3.4.4).

Recycling organic matter is very important for maintaining or restoring soil organic matter content. Soil organic matter is a critical component of soil health, through its positive effect on various chemical, physical and biological soil properties and processes (Box 2.2). Those include nutrient retention and cycling, water retention and purification, buffering of soil acidity, soil structure formation and disease suppression, among others. Organic matter is also the main source of energy for soil biota. Agricultural systems are prone to soil carbon loss through natural decomposition and to nutrient loss through leaching, GHG emissions and the export of harvested products. Lost carbon and nutrients should be replenished through the recycling of crop residues and local waste streams.

Optimizing nutrient management is key for sustaining coffee productivity and quality, while minimizing loss of nutrients to the environment. Fertilizers, in mineral and/or organic form, are an essential part of coffee production. Optimizing their use involves balanced fertilizer applications – based on the 4R principle (right rate, right source, right placement, and right timing) as well as soil testing – together with measures to prevent or correct soil acidification. Optimizing nutrient management also requires strengthening of the soil's nutrient cycling capacity through the management of organic resources (in the form of living plants, including legume species that can fix atmospheric nitrogen, dead plant material, animal manure or other organic residues). Chapter 3.4.7 discusses these recommendations in more detail.

Limiting pesticide use. Insecticides, fungicides and herbicides can have detrimental effects on the soil and surrounding environment. Some pesticides persist in the soil for a long time, harming beneficial soil organisms (e.g., bacteria, fungi and soil fauna like earthworms). In turn, this reduces the capacity of the soil to decompose organic matter, cycle nutrients, and maintain or restore soil structure. In addition, excessive pesticide use may lead to the development of resistant pest, disease or weed populations, thus creating a vicious cycle of dependence on chemical inputs. Alternative approaches based on integrated pest management and integrated weed management can help reduce farmers' dependence on pesticides and herbicides, while preventing yield losses. Chapters 3.4.5 and 3.4.6 discuss these practices in more detail.

Box 2.2. Soil organic matter, a key component of soil health

Soil organic matter is composed of plant material and soil biota at various stages of decomposition. Most soil organic matter (SOM) that is present in the soil is already in an advanced stage of decomposition and bound to mineral soil particles, especially clay. This is what is considered stable SOM. A smaller proportion of SOM is relatively young, depending on recent inputs such as leaf litter, crop residues, animal manure, roots and root exudates.

Since carbon is the main component of soil organic matter, the terms soil organic matter (SOM) and soil organic carbon (SOC) are often used interchangeably. Practices that promote the accumulation of SOM include *cover cropping*, mulching, and the addition of manure or *compost*. SOM plays a key role in the different chemical, physical and biological soil properties and processes that determine soil health.

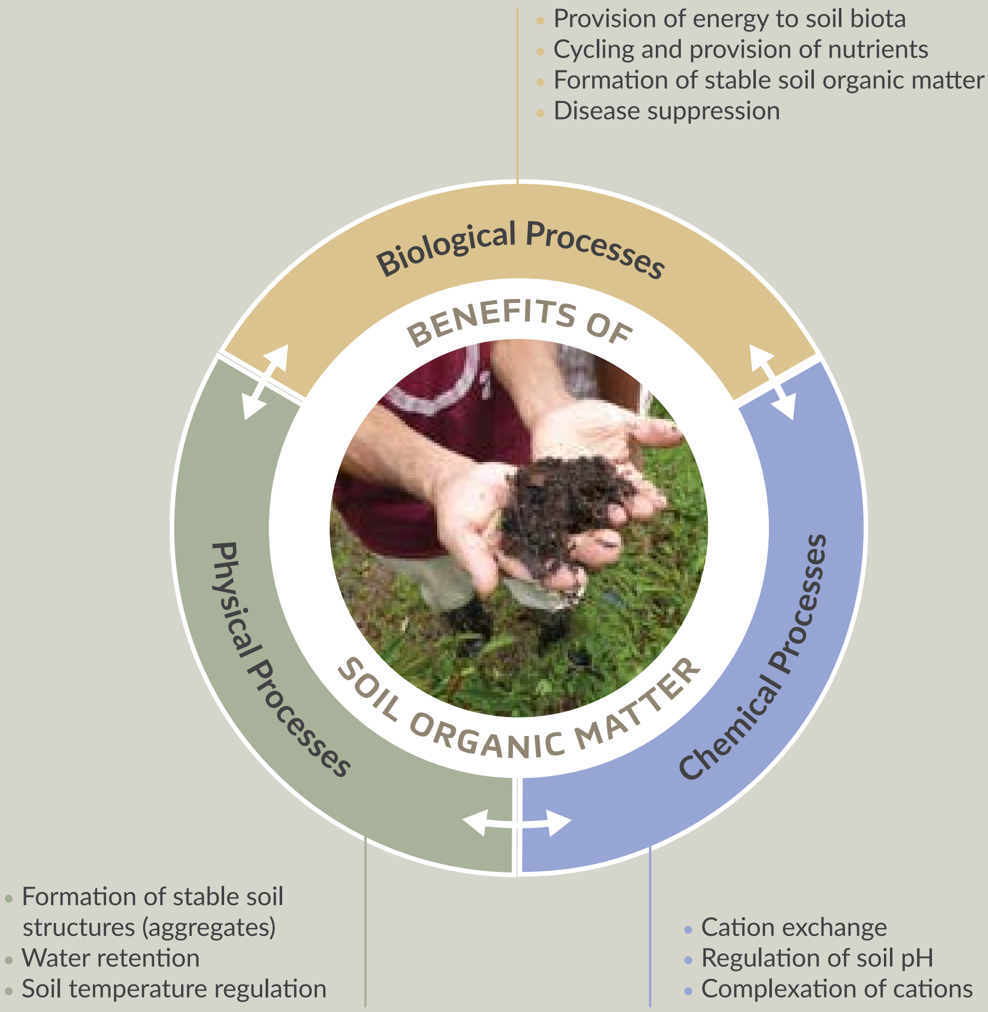


Figure 2.2. The benefits of soil organic matter through its effect on biological, chemical and physical processes.

Biological soil processes – SOM is the main source of energy and nutrients for soil organisms. Soil fauna (e.g., earthworms) play an important role in the initial breakdown of complex and large pieces of organic matter, making it more accessible to smaller organisms. But bacteria and fungi are considered to be the key drivers of organic matter decomposition and nutrient mineralization. SOM serves as an important reservoir of plant residues, which are released into the soil solution upon decomposition and can be taken up by plant roots. Excess nutrients can be lost to the environment as leachates or GHGs. Microorganisms are also directly responsible for the formation of soil organic matter, which is further stabilized through protection in soil aggregates and binding with clay particles. SOM is thus both a food source for, and a product of, soil organisms [11]. Higher SOM contents support biotic interactions that contribute to disease suppressiveness, although the practical significance of this benefit depends on the specific context and disease [12].

Chemical soil processes – Due to its large, exposed surface area, SOM plays an important role in the binding and exchange of cations, thus improving the soil's *cation exchange capacity* and retaining nutrients that could otherwise be leached out. SOM also contributes importantly to buffering of soil acidity, mitigation of aluminum toxicity and retention of contaminants [11].

Physical soil processes – Plant roots, fungal hyphae and the activity of macrofauna (e.g., earthworms) cause the binding of organic matter and soil particles (clay, silt and sand) into aggregates that can be further stabilized through microbial processes. Such stable macroaggregates contribute to a favorable *soil structure* with good aeration, allowing for rapid water infiltration. This is important to reduce the soil's vulnerability to soil erosion, while also improving growth conditions for plant roots and associated access to water and nutrients. SOM also improves the soil's water retention capacity.

Increasing SOM in agricultural soils is important both for sequestering atmospheric CO_2 and essential to restoring soil health. The practical challenge is to identify soil management practices that promote carbon sequestration, while also improving crop productivity and farm profitability [11,12]. In this regard, increasing the amount of SOM in soils is known to be important for soil productive capacity and efficient use of inputs. Further research is needed to determine which types and characteristics of organic inputs are most important for promoting *soil carbon sequestration*, improving soil structure and suppressing diseases [11].

The importance of soil biodiversity, and the effects of agricultural practices

Soil biodiversity refers to the variety and abundance of organisms that spend all or part of their life cycle underground, including viruses, bacteria, fungi, protozoa, nematodes, collembolans, mites, earthworms, soil-dwelling insects, and vertebrates such as moles and voles, among others. Soil is by far the most biologically diverse part of the Earth.

Soil biota plays a central role in mediating the different soil processes and functions that underpin soil health. The huge diversity of soil organisms present in soils interact with one another and with plants and animals, forming a complex food web. At the base of the food web are those that feed directly on dead or living plant material, including root exudates, while at the top are the predators that feed on smaller organisms. Predators, in turn, provide a food source for above-ground biodiversity, such as birds and mammals (Figure 2.3).

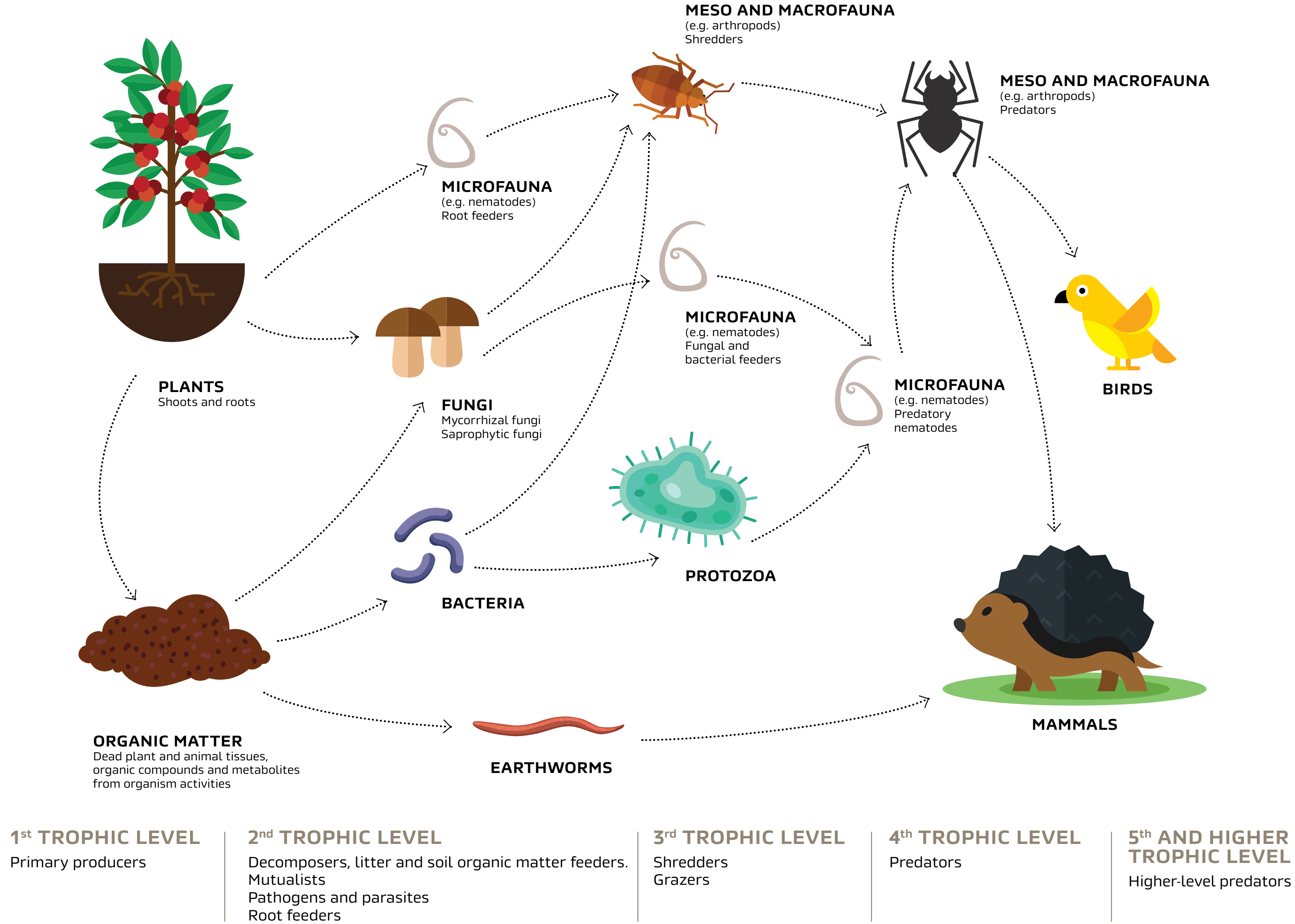


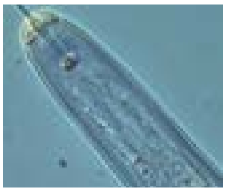
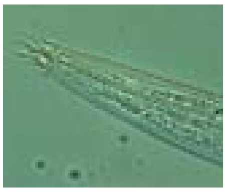
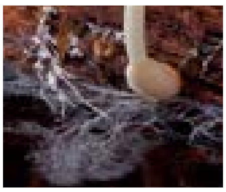
Figure 2.3. The soil food web. Modified from the Global Soil Biodiversity Atlas [13].

Earthworms | Nestlé.

Soil organisms can be classified according to their species, position in the soil food web and body size. Identifying species is difficult, because certain groups are hugely diverse and a vast number of soil organisms have not yet been identified. As different groups of soil biota perform different roles in soils we sometimes classify them according to their dominant function in soil (See Table 2.1). Agricultural activities have different effects on soil organisms and their activities, thus affecting soil functions. Conventional agricultural management practices – including intensive soil tillage, pesticide use and lack of organic inputs – tend to have strong negative effects on organisms at higher trophic levels in the food web, and on soil fauna with larger body sizes. This, in turn, may have cascading effects on those organisms at the lower trophic levels. Such changes in soil food webs, as well as the loss of so-called keystone species (which are species that are particularly sensitive to disturbance and play a unique role in specialized soil processes) can drastically affect nutrient cycling or water regulation [13]. Examples of keystone species are Rhizobium strains that fix nitrogen in association with specific plant species, fungal species that decompose particular organic compounds and *soil ecosystem engineers*, such as earthworms and termites which play a major role in soil structure formation (Table 2.1).

Yet, regenerative agricultural practices can help reestablish diverse soil communities and their activities [20–22]. The most effective way to promote and protect soil biodiversity is by providing organic inputs and covering the soil surface with mulch and cover crops, while also reducing pesticide use and mechanical soil disturbance (e.g., tillage). This creates ideal conditions for the native soil community to thrive. For an extensive, illustrated overview of different soil organisms, their occurrence, and functions in different agroecosystems, we refer to the Global Soil Biodiversity Atlas [13].

Table 2.1. Different groups of soil biota, their functional roles in soils, and how they are affected by agricultural practices. Based on, and with pictures from Orgiazzi et al. 2016 [13]. The organisms shown in the pictures are underlined.

MAIN FUNCTIONAL GROUPS		SOIL PROCESSES	DESCRIPTION
	**Soil engineers** Examples: earthworms, termites, ants	Soil structure formation and mixing of crop residues into the mineral soil	Soil engineers make burrows and incorporate plant litter and crop residues into the soil. They create pores, channels and solid aggregate structures that provide a habitat for other, smaller organisms. This group is important for water infiltration and storage as well as for soil aeration. They also stimulate nutrient cycling.
	**Litter transformers** Examples: Sowbugs, millipedes	Litter decomposition and fragmentation	This group consists of invertebrates that feed on leaf litter. They comprise a large number of arthropods of different body sizes that fragment and digest plant residues. They are numerous and diverse in tropical forests and can be important in coffee, especially in agroforests with a thick layer of leaves and pruning residues covering the soil surface.
	**Plant feeders** Examples: Plant-parasitic nematodes, other herbivores	Herbivory	This group includes soil organisms that feed on living roots or above-ground plant parts along with important agricultural pest species.
 	**Predators** Examples: Predatory ants, centipedes, predatory mites	Biological control	Predators comprise soil invertebrates that are larger (macrofauna) or smaller (mesofauna) than 2 mm in body size and feed on other soil fauna. They are important for biological regulation (e.g., of pest species).
	**Fungal and bacterial feeders** Examples: Bacterial-feeding nematodes, fungal feeding nematodes, protozoa	Nutrient cycling	Fungal and bacterial feeders comprise a wide diversity of invertebrates ranging from <0.2 mm to 2 mm in body size. They feed on microorganisms, thus regulating their activities and indirectly stimulating nutrient cycling. They may be the only soil animals left in severely degraded soils.
 	**Micro-organisms** Examples: Bacteria, fungi, archae	Organic matter decomposition and carbon stabilization as well as nutrient transformation and biocontrol	Soil microbial communities are extremely abundant and hugely diverse. Decomposer microorganisms include fungi, bacteria and archae. They are the main group responsible for organic matter decomposition and soil organic matter formation. This group also includes important nutrient transformers, such as nitrifiers, denitrifiers, etc., as well as microbes that form symbiotic associations with plants, helping them to obtain nutrients, such as mycorrhizal fungi and N-fixing bacteria. Fungi and bacteria can be important biocontrol agents, suppressing plant pathogens. An example are species from the genus *Trichoderma*, which have been used for biocontrol of plant fungal diseases.

Apis dorsata pollinating coffee, India | Smitha Krishnan.

2.2.2. Pillar 2 – Biodiversity

Biodiversity is the variety of living organisms present across different ecosystems, including marine, aquatic and terrestrial ecosystems. Different levels of biodiversity can be considered: biological variation across ecosystems, both natural and agricultural, (ii) variation across species, and (iii) genetic variation within species (e.g., different cultivars within one crop species) (Figure 2.4). *Functional biodiversity* refers to (groups of) species that support the delivery of certain ecosystem services, including those that support the production of agricultural goods (Figure 2.5); it also has important cultural and intrinsic value.

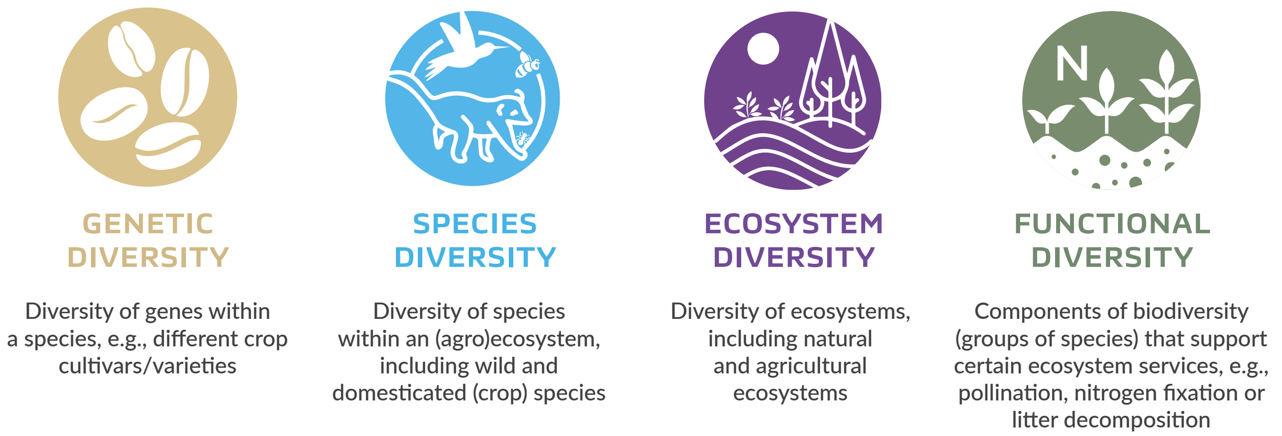


Figure 2.4. Different levels and components of biodiversity.

Biodiversity and coffee production

The enhancement and sustainable use of biodiversity are key aims of regenerative farming. They are especially relevant to coffee, since it is produced in tropical forest areas that encompass some of the world's biodiversity hotspots [14]. Coffee can affect biodiversity positively or negatively, depending on how it is cultivated. One of the primary effects of coffee production on biodiversity results from the conversion of natural forests into coffee plantations, leading to habitat loss and fragmentation. Moreover, in many regions, coffee farming has followed a historic trend toward simplified production systems, with a tendency to adopt full-sun monoculture and intensify the use of agrochemicals [15]. Many pesticides and some herbicides also harm non-target organisms, such as beneficial insects that support natural pest control and pollination, or soil health [16–18].

> **Coffee farming can have both positive and negative effects on biodiversity, depending on how it is practiced. Enhancing both wild and agricultural biodiversity is an important objective of regenerative agriculture because of its significant impact on ecosystem services. This, in turn, can benefit coffee production and reduce reliance on agrochemicals.**

On the other hand, shaded coffee can provide a habitat for plants, birds and insects and other wildlife [19,20]. In addition, coffee farmers can manage pests and diseases through natural pest control methods or integrated pest management (see Chapter 3.4.6), complemented by actions at landscape level (see Chapter 3.4.11) to reduce the use of harmful chemicals. For example, it has been demonstrated that retaining forest patches on and around coffee farms is important for biological control of coffee berry borer beetle in Costa Rica [21]. Such approaches represent a win-win solution for biodiversity and coffee farmers, particularly considering the substantial reduction in economic losses due to pests. Some coffee farmers establish selected plant species, including cover crops, within or around coffee plots to provide a habitat and food resources for beneficial insects [22]. The presence of a wide range of nectar- and pollen-producing plants on the farm together with the presence of forest patches close to coffee plots can also attract a greater number and variety of pollinators, particularly native bee species, helping to increase coffee yields, fruit set and berry weight [23].

Objectives for biodiversity enhancement

Regenerative agriculture seeks to sustainably enhance and harness the benefits of biodiversity by contributing to these objectives (Figure 2.7):

- Fostering the diversification of cropping systems
- Limiting the use of pesticides and herbicides

- Providing habitats for wild plants, animals and other organisms, both within coffee farms and in the surrounding landscape
- Strengthening functional biodiversity (e.g., biological pest control and pollination).

Through production system diversification and landscape actions, regenerative agriculture seeks to increase plant (including crop) diversity and provide habitats for wildlife, thus harnessing the ecosystem services they provide (Figure 2.5). Greater crop species diversity can help build the ecological resilience of farming systems to pest and disease outbreaks. Increasing biodiversity in coffee farms, both above and belowground, and in the surrounding landscape thus contributes to the conservation of wild species, while also creating benefits for coffee production and farmers. Crop diversification also enhances farmers' economic resilience by providing different income sources and mitigating the risks associated with coffee production and marketing that arise from climatic events and price fluctuations.

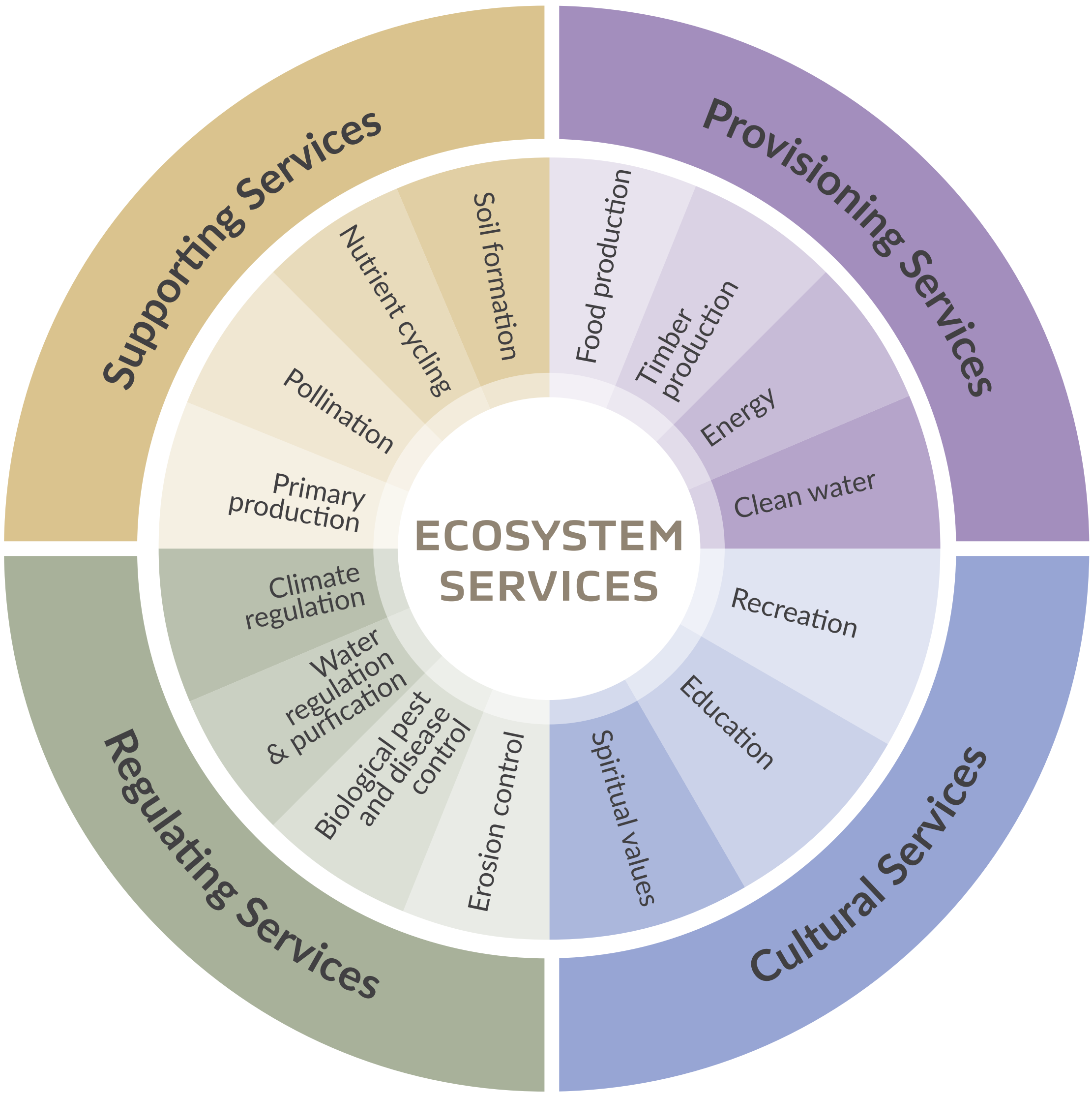


Figure 2.5. Examples of *ecosystem services* that biodiverse farmland can provide, according to the four different categories: supporting, regulating, provisioning and cultural services.

2.2.3. Pillar 3 – Water

The availability, quality and management of water resources is critical for people to have secure access to clean water for domestic, agricultural and industrial uses. Excessive water extraction – when more water is extracted from a *watershed* than is naturally replenished every year – and pollution from agricultural or industrial activities threaten the water security of watershed inhabitants. Leaching of fertilizers, pesticides and contaminants can lead to pollution and eutrophication of ground and surface water, and harm aquatic ecosystems. Climate change, deforestation and land-use change can all reduce water availability and quality by inducing more frequent and intense droughts and floods, which reduce yields, and damage crops and infrastructure.

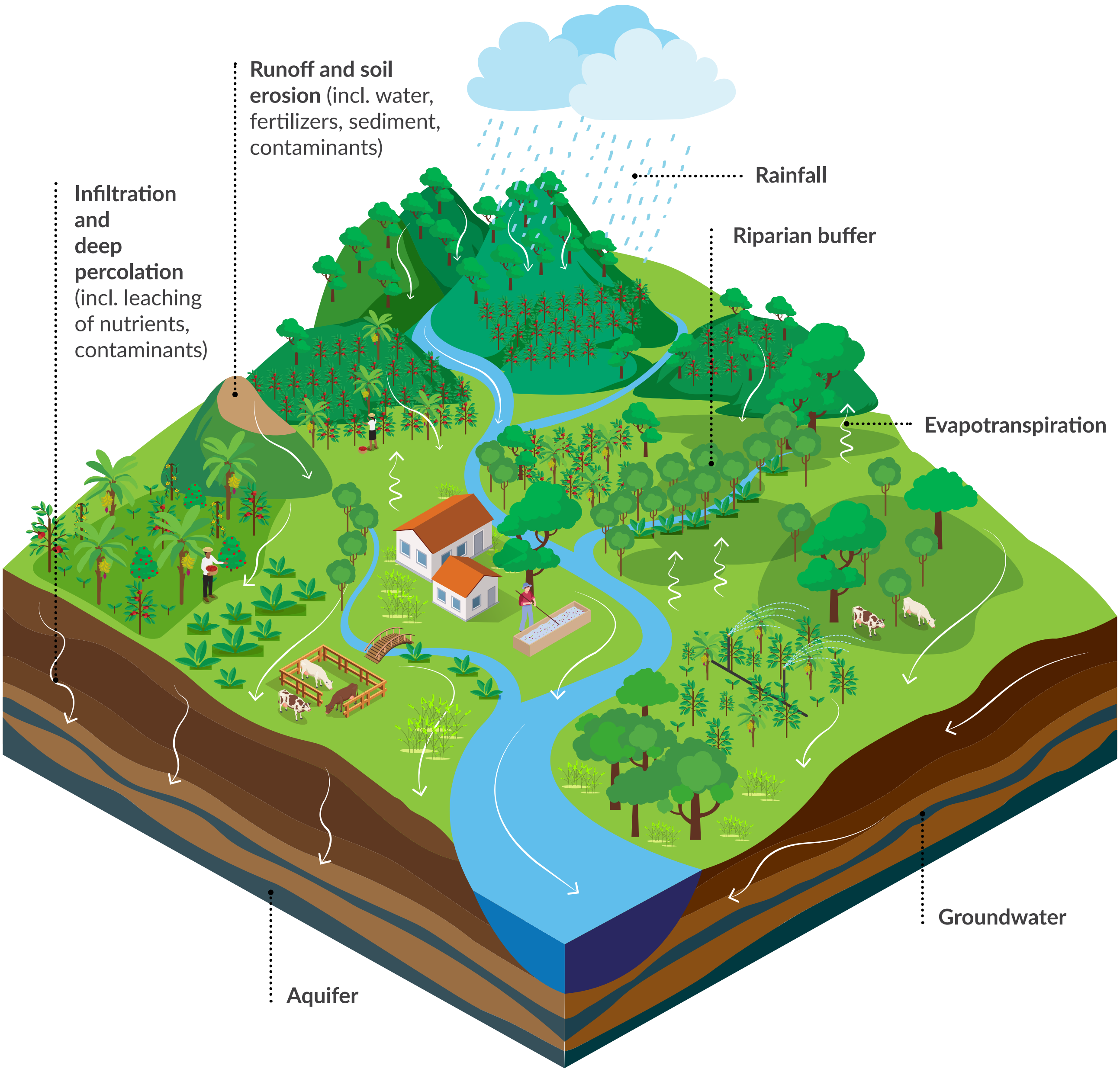


Figure 2.6. *Watershed* processes and the effects of coffee farming on water security and quality.

Effects of coffee farming on water resources

Coffee is a water-intensive crop and thus highly dependent on a consistent supply of water. Besides meeting household needs, coffee farmers may use large amounts of water for irrigation and wet processing. In addition to the quantity, the quality of the water, in terms of acidity, salinity and contaminants, can impact crop production. The flavor profile of the final product is also very sensitive to the quality of the water used during wet-processing, including flavors and odors.

Most coffee production is rainfed, and areas with low overall annual rainfall are not suitable for the crop. Nevertheless, there are important exceptions in regions with seasonally dry or monsoon climate. In parts of Brazil, India and Vietnam, irrigation is used to support coffee development during the prolonged dry season and/or to trigger flowering [[24]]. In Vietnam, irrigation water is drawn mainly from aquifers through wells [[24]], while in Brazil, coffee is mostly irrigated with water from rivers and reservoirs [[25]]. Coffee farmers often use more irrigation water than is recommended or required [[24]]. Excessive use of groundwater or water from reservoirs can have devastating effects on watersheds and surrounding communities, while ultimately jeopardizing the production of coffee and other crops. However, water is a key resource for rainfed coffee farmers as well protecting watershed functions through improved infiltration and storage in the soil is important for building resilience to drought for all coffee farmers. It also helps prevent flooding, surface runoff and contamination of water resources with sediments, fertilizers, pesticides and other pollutants.

An important risk to water security is high water consumption during coffee wet processing and disposal of the resulting wastewater. When organic waste is washed into watercourses, decomposing microorganisms deplete oxygen in the water, posing a threat to aquatic wildlife. It is therefore essential to reduce the volume of water used in postharvest processing as well as to treat and recycle wastewater appropriately.

Objectives for water conservation and quality

Using regenerative practices, coffee farmers can improve water management on their farms by various means (Figure 2.7):

- Controlling erosion and runoff, while enhancing soil water infiltration and retention
- Avoiding contamination of water sources with harmful pesticides and fertilizers
- Making efficient use of irrigation water
- Reducing water use for wet processing
- Treating and recycling wastewater from coffee processing

Regenerative practices targeting water conservation are often closely linked to soil management as healthy soils contribute to improved water infiltration and storage, thus limiting runoff. Healthy soils can also help to reduce dependence on agrochemical inputs with benefits for water quality. Chapter 3 describes a range of regenerative practices that can improve water management in both rainfed and irrigated coffee.

Finally, farmers should be aware of potential impacts of water management beyond the farm boundaries, in terms of water quality and volumes, including groundwater recharge [26]. Considering this broader perspective, collective action may be needed to safeguard water security, supported by policies and regulations, monitoring and assessment and engagement with communities and other actors in the watershed.

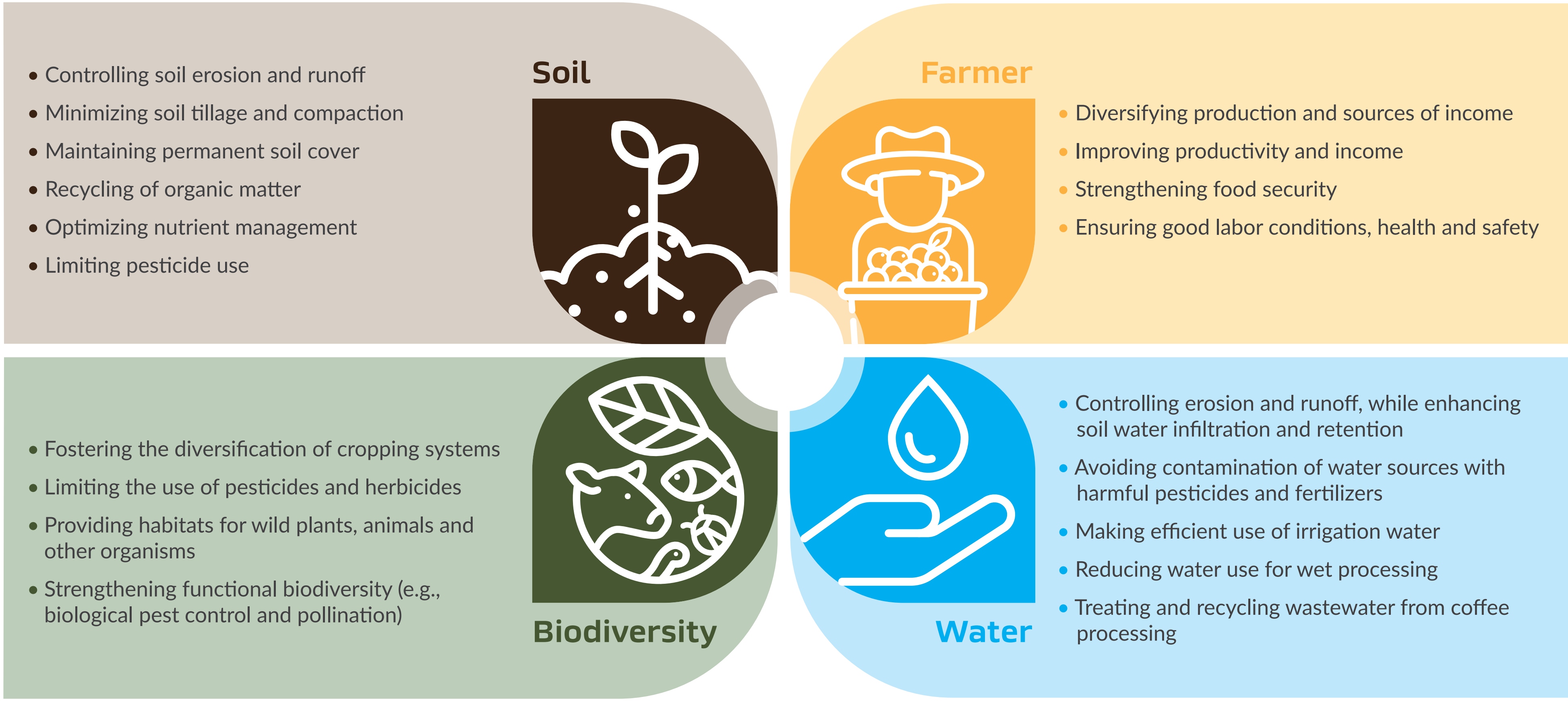


Figure 2.7. Objectives of regenerative agriculture for the three pillars, and in terms of benefits for coffee farmers.


Coffee and banana farmer in Rwanda | CIAT/N. Palmer.

2.3. Benefits for farmers

In the transition to regenerative agriculture, farmers occupy center stage and play a decisive role (Figure 2.1). Success depends on the management decisions they take, and on their willingness and capacity to adopt regenerative practices as well as on the benefits they obtain. An important goal of regenerative agriculture is, therefore, to enhance the resilience of farmers' livelihoods by improving their income, labor conditions and food security, while making farmers less vulnerable to economic and environmental shocks. These include the impacts of market fluctuations (volatility of farmgate prices for coffee and other agricultural products), high costs of agricultural inputs, disease and pest outbreaks, and climate change. Regenerative farming gives high priority to diversifying production systems, with the aims of increasing and diversifying income sources as well as food supplies for household consumption.

Regenerative agriculture seeks to improve coffee farmers' livelihoods by achieving these objectives (Figure 2.7):

- Improving productivity and income
- Strengthening food security

- Ensuring good labor conditions, health and safety
- Diversifying production and sources of income.

The benefits of regenerative agriculture are not automatic. Careful design and alignment are key, depending on the three pillars described above as well as on farmers' objectives, priorities and specific circumstances, both in terms of agroecological conditions and available assets, such as labor, capital and inputs. This is why it is important to view the adoption of regenerative agriculture as a transition or journey, which requires new knowledge and investments, while also entailing risks. Farmers, especially resource-poor smallholders, need support to reap the benefits of regenerative farming. Ideally, they can adopt different regenerative practices stepwise, combining or applying them incrementally, while making adjustments, as needed, to gain multiple benefits. Improvement is also needed in farmers' access to training, finance and services.

2.4. Impact areas

Since regenerative agriculture focuses on outcomes rather than prescribed practices, it is important to have clarity about the goals and to evaluate progress and impact on this basis. The goals for regenerative agriculture are linked to multiple aspects of sustainability (environmental, economic and social). They emphasize positive impacts on three pillars (soil health, biodiversity and water) described in this chapter, and related objectives in terms of farmers' livelihoods, coffee productivity and the mitigation of greenhouse gas emissions. Different regenerative practices can thus be selected, combined and adapted to context, with the ultimate aim to positively impact the following six key impact areas relevant to coffee farming globally (Figure 2.8).

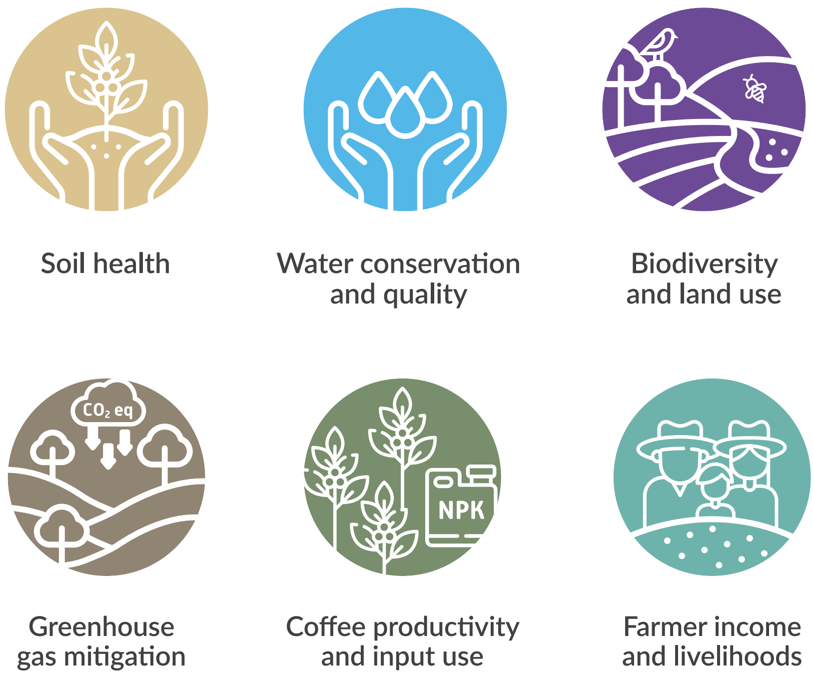


Figure 2.8. Impact areas for regenerative coffee farming.

1. **Soil health.** Regenerative coffee farming emphasizes the enhancement of soil health through soil erosion control and through the improvement of chemical, physical and biological soil properties and related soil functions.

2. **Water conservation.** Regenerative coffee farming seeks to secure water availability and quality by using water resources efficiently and responsibly, while improving the water retention and regulation function of soils, both on farms and in watersheds.

3. **Biodiversity and land use.** Regenerative coffee farming aims to enhance and sustainably use biodiversity in farmland, focusing on wild and agricultural species as well as land use and habitat quality on farms and in the surrounding landscape.

4. **Greenhouse gas mitigation.** An important goal for regenerative coffee farming is to reduce GHG emissions associated with coffee production (thus lowering the carbon footprint of coffee production) as well as stimulating carbon removal through sequestration of atmospheric CO_2 in tree biomass and in soil.

5. **Coffee productivity and input use.** Regenerative coffee farming aims to secure coffee production in the face of climate change, without further expansion of coffee lands (through *sustainable intensification*). At the same time fertilizers should be used more efficiently and the use of harmful pesticides should be minimized.

6. **Farmer income and livelihoods.** A key goal for regenerative agriculture is to help generating higher farm incomes and strengthening food security for smallholders, while improving labor conditions. Of particular interest are the benefits of product and income diversification for household resilience in the face of climate change impacts and market volatility.

2.5. References

1. Giller KE; Hijbeek R; Andersson JA; Sumberg J. 2021. Regenerative Agriculture: An agronomic perspective. *Outlook on Agriculture* 50. https://doi.org/10.1177/0030727021998063

2. Cusworth G; Garnett, T. 2023. What is regenerative agriculture? TABLE Explainer. TABLE, University of Oxford, Swedish University of Agricultural Sciences and Wageningen University and Research. https://doi.org/10.56661/2d7b8d1c

3. Schreefel L; Schulte RPO; Boer IJM de; Schrijver AP; Zanten HHE van. 2020. Regenerative agriculture – the soil is the base. *Global Food Security* 26. https://doi.org/10.1016/j.gfs.2020.100404

4. Nestlé. 2022. The Nestlé Agriculture Framework. Available at: https://bit.ly/3oyHJi7 (Accessed on 30 January 2023).

5. IFOAM. Definition of Organic Agriculture. Available at: https://bit.ly/43Px0zZ (Accessed on 10 March 2023).

6. IPBES. 2018. Summary for policymakers of the assessment report on land degradation and restoration of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. Bonn.

7. Doran JW; Zeiss MR. 2000. Soil health and sustainability: managing the biotic component of soil quality. *Applied Soil Ecology* 15. https://doi.org/10.1016/S0929-1393(00)00067-6

8. Lehmann J; Bossio DA; Kögel-Knabner I; Rillig MC. 2020. The concept and future prospects of soil health. *Nature Reviews Earth & Environment* 1. https://doi.org/10.1038/s43017-020-0080-8

9. Bongiorno G; Postma J; Bünemann EK; Brussaard L; Goede RGM de; Mäder P; et al. 2019. Soil suppressiveness to *Pythium ultimum* in ten European long-term field experiments and its relation with soil parameters. *Soil Biology and Biochemistry* 133. https://doi.org/10.1016/j.soilbio.2019.03.012

10. Silva RF da; Severiano E da C; Oliveira GC de; Barbosa SM; Peixoto DS; Tassinari D; et al. 2021. Changes in soil profile hydraulic properties and porosity as affected by deep tillage soil preparation and Brachiaria grass intercropping in a recent coffee plantation on a naturally dense Inceptisol. *Soil and Tillage Research* 213. https://doi.org/10.1016/j.still.2021.105127

11. Hoffland E; Kuyper TW; Comans RNJ; Creamer RE. 2020. Eco-functionality of organic matter in soils. *Plant and Soil* 455. https://doi.org/10.1007/s11104-020-04651-9

12. Bonanomi G; Lorito M; Vinale F; Woo SL. 2018. Organic Amendments, Beneficial Microbes, and Soil Microbiota: Toward a Unified Framework for Disease Suppression. *Annual Review of Phytopathology* 56. https://doi.org/10.1146/annurev-phyto-080615-100046

13. Orgiazzi A; Bardgett RD; Barrios E; Behan-Pelletier V; Briones MJI; Chotte J-L; et al. (Eds.). 2016. *Global Soil Biodiversity Atlas*. European Commission Publications Office of the European Union, Luxembourg. http://dx.doi.org/10.2788/799182

14. Harvey CA; Pritts AA; Zwetsloot MJ; Jansen K; Pulleman MM; Armbrecht I; et al. 2021. Transformation of coffee-growing landscapes across Latin America. A review. *Agronomy for Sustainable Development* 41. https://doi.org/10.1007/s13593-021-00712-0

15. Jha S; Bacon CM; Philpott SM; Méndez VE; Läderach P; Rice RA. 2014. Shade coffee: update on a disappearing refuge for biodiversity. *BioScience* 64. https://doi.org/10.1093/biosci/biu038

16. Gaupp-Berghausen M; Hofer M; Rewald B; Zaller JG. 2015. Glyphosate-based herbicides reduce the activity and reproduction of earthworms and lead to increased soil nutrient concentrations. *Scientific Reports* 5. https://doi.org/10.1038/srep12886

17. Miglani R; Bisht SS. 2019. World of earthworms with pesticides and insecticides. *Interdisciplinary Toxicology* 12. https://doi.org/10.2478/intox-2019-0008

18. Serrão JE; Plata-Rueda A; Martínez LC; Zanuncio JC. 2022. Side-effects of pesticides on non-target insects in agriculture: a mini-review. *The Science of Nature* 109. https://doi.org/10.1007/s00114-022-01788-8

19. Perfecto I. 2015. *Coffee Agroecology*. Routledge, 2015.

20. Philpott S; Arendt W; Armbrecht I; BIchier P; Diestch T; Gordon C; et al. 2008. Biodiversity loss in Latin American coffee landscapes: review of the evidence on ants, birds, and trees. *Conservation Biology* 22. https://doi.org/10.1111/j.1523-1739.2008.01029.x

21. Karp DS; Mendenhall CD; Sandí RF; Chaumont N; Ehrlich PR; Hadly EA; et al. 2013. Forest bolsters bird abundance, pest control and coffee yield. *Ecology Letters* 16. https://doi.org/10.1111/ele.12173

22. Ferla JJ; Araújo GJ de; Venzon M; Nascimento PHMG; Kalile MO; Pancieri SD; et al. 2023. Intercropped plants provide a reservoir of predatory mites in coffee crop. *Agriculture* 13. https://doi.org/10.3390/agriculture13020285

23. Imbach P; Fung E; Hannah L; Navarro-Racines CE; Roubik DW; Ricketts TH; et al. 2017. Coupling of pollination services and coffee suitability under climate change. *Proceedings of the National Academy of Sciences* 114. https://doi.org/10.1073/pnas.1617940114

24. Amarasinghe UA; Hoanh CT; D'haeze D; Hung TQ. 2015. Toward sustainable coffee production in Vietnam: More coffee with less water. *Agricultural Systems* 136. https://doi.org/10.1016/j.agsy.2015.02.008

25. Venancio LP; Filgueiras R; Mantovani EC; Amaral CH do; Cunha FF da; Santos Silva FC dos; et al. 2020. Impact of drought associated with high temperatures on *Coffea canephora* plantations: a case study in Espírito Santo State, Brazil. *Scientific Reports* 10. https://doi.org/10.1038/s41598-020-76713-y

26. Gómez-Delgado F; Roupsard O; Maire G le; Taugourdeau S; Pérez A; Oijen M van; et al. 2011. Modelling the hydrological behaviour of a coffee agroforestry basin in Costa Rica. *Hydrology and Earth System Sciences* 15. https://doi.org/10.5194/hess-15-369-2011

3 REGENERATIVE COFFEE FARMING IN PRACTICE

Indonesia (Lampung – Southern Sumatra) | Nestlé

3.1. From principles to practices

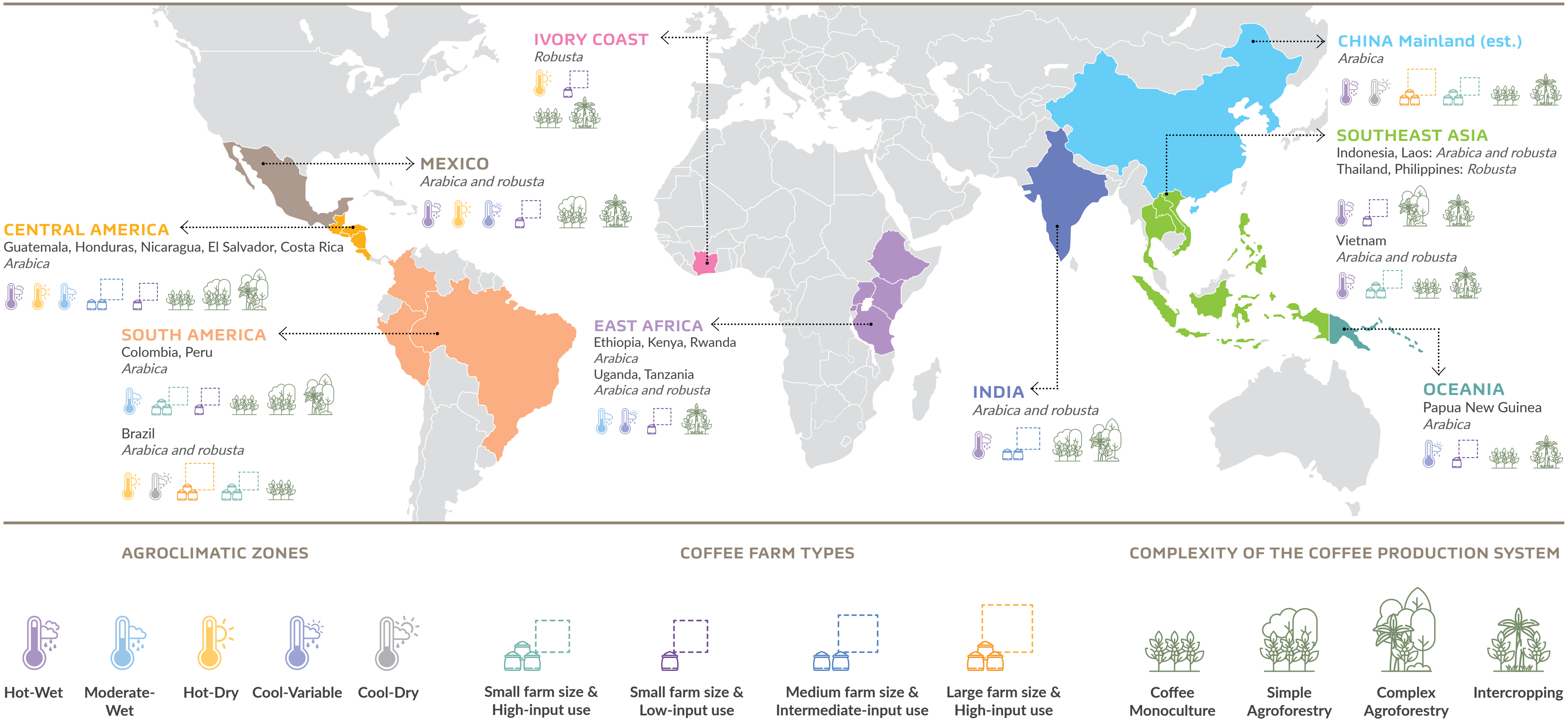
A key question for farmers and other actors in the coffee sector is how regenerative agriculture can be put into practice. In this chapter, we present 11 regenerative agricultural practices that can contribute to achieving one or more objectives of regenerative farming. Those practices are broadly defined, building on the pillars and principles of regenerative agriculture described in Chapter 2. They apply to coffee production systems worldwide, both Arabica and Robusta. Yet, when promoting and implementing regenerative practices, it is crucial to bear in mind that coffee-growing conditions, farm sizes and intensity of coffee production vary greatly both across and within regions (Figure 3.1). Proper adaptation to the context is essential for achieving the desired impacts.

For each of the 11 practices, we describe the most important benefits and provide practical guidance on their implementation, considering different contexts and farm characteristics. We also discuss possible limitations or challenges to adoption and ways to overcome the challenges. For each practice, references for further reading and useful tools are provided.

Regenerative agriculture involves not just a set of isolated interventions but an integrated, holistic approach to farmland management. Because coffee producers have different objectives, means and priorities, they can follow different pathways on their journey to regenerative farming, adopting, adapting and combining the practices that are most relevant to their situation and offer the greatest benefits in terms of improved farm sustainability.

3.2. Coffee farming contexts

We can broadly classify different coffee farming contexts on the basis of (i) *agroecological zones* (including the dominant coffee species), (ii) farm size and management intensity and (iii) complexity of the coffee production system. In practice, these classification criteria are often closely interrelated, as described below.



Hot-wet: characterized by high maximum temperature in the warmest month, high annual precipitation, a short dry season | **Moderate-wet:** characterized by lacking temperature seasonality, lowest mean values for daily and annual temperature range, high annual precipitation and a short dry season | **Hot-dry:** characterized by high maximum temperatures and no cold month. Annual total precipitation is low and a long dry season | **Cool-variable:** characterized by the highest annual temperature range. Precipitation is moderate | **Cool-dry:** characterized by the lowest minimum temperature of the coldest month, but also the lowest annual precipitation with a long dry season.

Figure 3.1. Worldwide distribution of broadly defined coffee-farming contexts and main farm types in the top 25 coffee-producing countries.

Contexts and farm types were classified according to (i) *agroecological zones* and dominant coffee species, (ii) farm size and management intensity, and (iii) complexity of the coffee production system. Based on Bunn et al. [1] and IDH [2,3].

3.2.1. Agroecological zones

Generally, coffee is best planted in areas where annual precipitation ranges from 1,500 to 3,500 millimeters, with a maximum of three dry months. Arabica coffee is suited to cooler areas at altitudes over 1,000 meters above sea level, whereas Robusta is grown in hotter (and often more humid) areas at lower altitudes. In Central and South America and along the Great Rift Valley in Eastern Africa, many Arabica coffee systems are found on relatively fertile, including volcanic, soils in mountainous areas. Frequently situated on steep slopes, these systems face high risk of erosion and landslides. Robusta is mostly cultivated in flatter areas on older soils that are deeply weathered or have a high sand content, with low capacity to retain water and nutrients. Robusta is often grown with little or no shade to maximize production. Yet, a recent study has shown that shade trees can positively impact growth and yields of Robusta, depending on the type of clone used and the age of the coffee trees [4].

Even for the same coffee species, agroecological conditions differ substantially across regions, and this has important implications for production practices, such as shade management, irrigation and mechanization. For example, in hotter areas with higher solar radiation, Arabica coffee growers frequently integrate shade trees to create improved microclimate conditions for coffee growth and bean quality. Unlike in other parts of the world, much of Brazil's coffee farming (Robusta and Arabica) is mechanized and involves somewhat unique practices, such as high planting densities and wider inter-row spacing to make way for machinery. Irrigation is important in the two biggest coffee-producing countries – Brazil and Vietnam – where the crop is grown in areas characterized by a prolonged dry season. Here, irrigation is used to ensure good production and to induce homogeneous flowering, which facilitates harvesting.

Finally, climate change increasingly affects where and how coffee is produced. For Arabica coffee, this most commonly entails shifting coffee production to higher altitudes and latitudes, a trend that might induce deforestation and threaten the soil and water retention functions of watersheds [5]. To secure future production and earn stable incomes, coffee producers need to develop strategies for adapting their farms to climate change [6,7], as discussed in Chapter 1. For this purpose, policymakers, agronomists and coffee farmers need access to information on how current and projected climatic conditions might affect coffee production systems across regions, and what adaptation strategies could be considered, including changes in farming practices. Examples of such decision support tools can be found at www.aclimatar.org (in Spanish) and https://climatesmartcoffee.cgiar.org/ (in English).

3.2.2. Farm type

Access to land and other resources (such as education, finance, inputs, hired labor, mechanization and technical assistance) varies widely between coffee farmers. Worldwide, 95% of coffee farms are smaller than 5 hectares and rely mainly on family labor. Moreover, these smallholder farms are generally shrinking in size, as farms are subdivided from one generation to the next. While medium to large family-owned farms and agri-business estates account for only 5% of coffee farms globally, they supply about 40% of total coffee production [8]. Large-scale farms tend to focus on maximizing production by using high amounts of external inputs. Smallholder farmers might have other priorities, such as income diversification, food security and lower production costs or risks. Farm type thus weighs heavily in shaping farmers' objectives and the availability of resources they can invest as they move into regenerative farming.

In Figure 3.2, we distinguish between four broad coffee farm types, based on farm size and level of intensification (defined as the use of external inputs and mechanization for coffee production): (1) small, intensively managed farms with high external input use; (2) small, extensively managed farms with low external input use; (3) medium-sized to large farms with intermediate use of inputs but low mechanization; and (4) very large, intensively managed farms with high external input use. Mechanization is common in Brazil for large farms, and also for small farms located in areas with relatively flat topography. As regenerative practices can be applied in both organic and conventional coffee production, we have not further subdivided farm types on this basis.

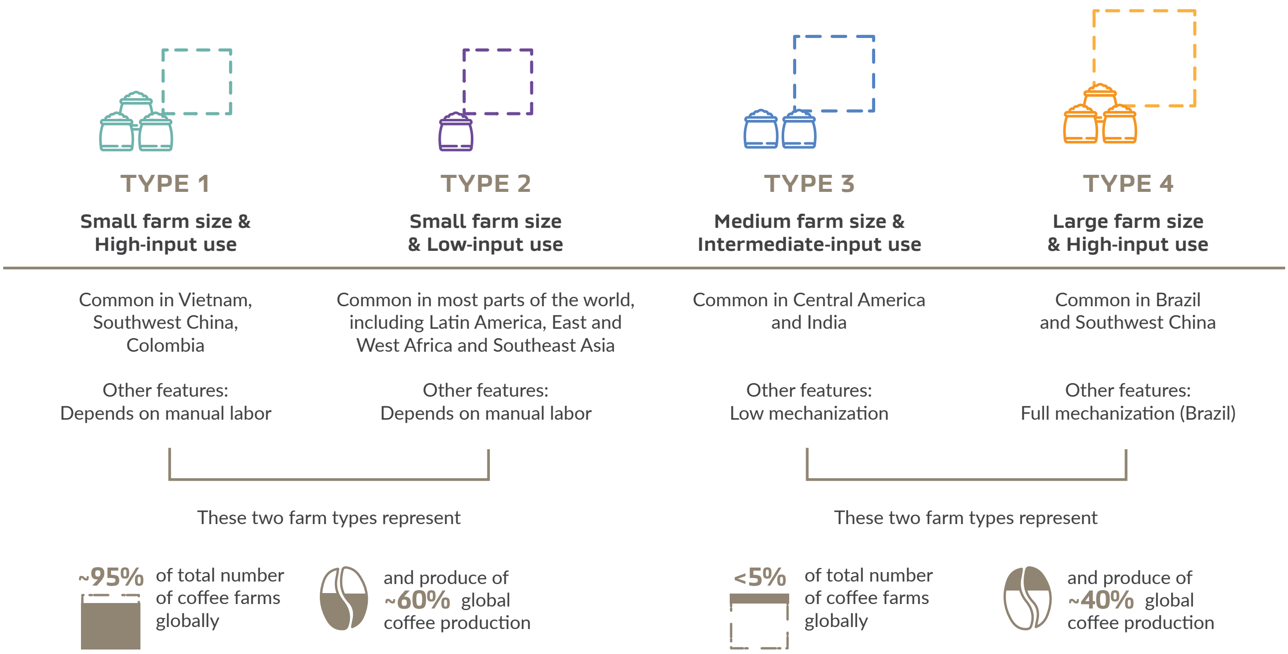


Figure 3.2. Broad coffee farm types and their contribution to global coffee production.

Based on Browning and Moayyad [8] and Enviritas [9].

3.2.3. Coffee production system complexity

Complexity refers to the variety of crops, tree species and animals in a farming system, and the extent to which these components are integrated within a field or on a given farm. At the field level, we can characterize the complexity of a coffee production system according to the diversity of plant species and the vegetation structure (Figure 3.3). Simple agroforestry systems contain few shade tree species, and these trees can form a single canopy layer. Complex agroforestry systems typically contain multiple vegetation layers composed of various shade tree species along with cash and food crops besides coffee. For the most part, complex agroforests are maintained by small-scale coffee producers. Those systems support biodiversity conservation and ecosystem services, while providing a diversity of cash crops besides coffee (such as spices) as well as food crops, firewood and timber; they might also include domestic animals.

Recent decades have seen a strong global trend towards intensification and simplification of coffee production systems. As a result, in most coffee-growing countries, the area of full-sun or low-shade coffee has increased at the expense of traditional agroforestry systems. However, currently there is renewed interest in the diversification of coffee production systems using shade trees, and public and private sector investment as well as government policies have encouraged this trend. In India, for example, national law requires coffee systems to be shaded [10]. Similarly, the Pu'er government in Yunnan, China, embarked on a campaign in 2012 to foster a large-scale transition to shaded coffee cultivation [11].

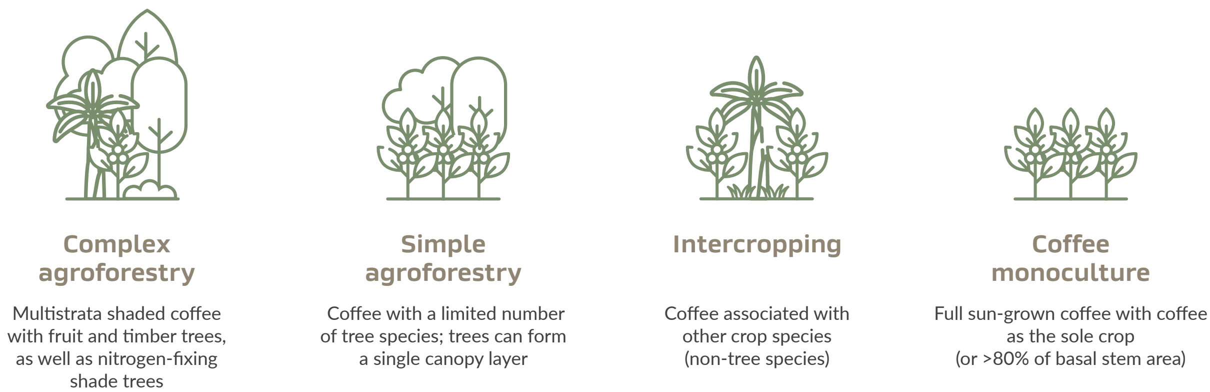


Figure 3.3. Classification of coffee production systems, based on the diversity of plant species within the coffee plot and the vegetation structure.

Coffee monoculture in Colombia | CIAT/M. Pulleman

3.3. Trajectories for regenerative coffee farming

The biggest coffee producers, in particular Brazil and Vietnam, have reported significant production growth [12]. This has been achieved mainly by intensifying coffee cultivation and in some cases by expanding it into new areas. Such intensification, while leading to high coffee yields, has also been linked with negative impacts on natural resources, including *soil degradation*, biodiversity loss, water pollution, loss of tree cover and deforestation [5,12]. On the other hand, the productivity of smaller origins tends to stagnate or even decline. Here, yield improvement per unit of land remains a key priority to improve farmer income and reduce pressure on land that is currently under forest or can be used to produce other crops. This shows that, as farmers transition to regenerative coffee production, they depart from different situations and might have different objectives or priorities. As a result, their regenerative journeys follow different pathways [13], as shown in Figure 3.4.

Farmers might perceive a *trade-off* between productivity and environmental sustainability or farm resilience, but this is not necessarily the case. For instance, small farms with low use of external inputs and consequent low *productivity* often face declining soil fertility through nutrient mining and poor soil health. With this in mind, farmers might adopt regenerative practices that allow them to close yield and income gaps without significant loss of ecosystem services (farm 1 in Figure 3.4 represents this trajectory). Practices that promote soil water retention, efficient water use, or natural pest control, can enhance farm resilience in the face of climate change while also reducing the carbon footprint from post-harvest processing (farm 2 in Figure 3.4). By optimizing water and nutrient management, regenerative practices can also reduce production costs and improve farm revenues. The latter is especially important for coffee farms where high use of agrochemicals and overirrigation are linked to negative impacts on the environment, vulnerability to climate change and high production costs (as with farm 3 in Figure 3.4).

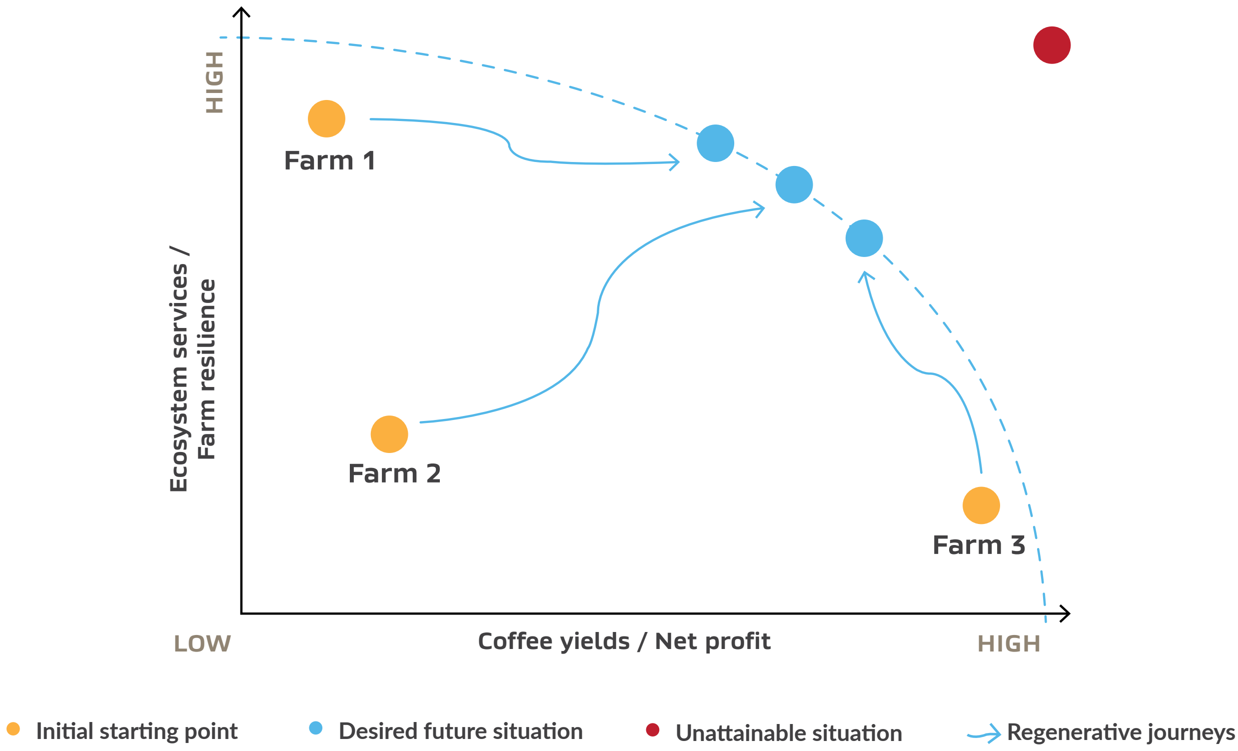


Figure 3.4. Possible trajectories for coffee farms that seek to improve the balance between two objectives: productivity and sustainability. The blue dotted curve shows the so-called "productivity-sustainability frontier". The red dot represents a situation that growers cannot attain, because maximizing coffee yields or profit (shown on the horizontal axis) is not consistent with maximizing *ecosystem services* and *resilience* (shown on the vertical axis). However, depending on the starting point, farms might still have room for improvement for either one, or both, objectives without necessarily incurring a *trade-off*, until they reach the frontier.

The main message is that both small-scale farms using low amounts of external inputs as well as intensively managed coffee farms can benefit from a better balance between productivity and profitability, on the one hand, and environmental sustainability and resilience, on the other. Synergies as well as *trade-offs* between economic, social and environmental goals might occur when transitioning to regenerative farming, and require a careful balance to ensure a viable outcome in a given context. Regardless of the starting point, clear objectives as well as careful selection, adaptation and implementation of regenerative practices are key to a successful journey.

3.4. Regenerative agricultural practices

Table 3.1 presents an overview of 11 regenerative practices applicable to coffee production and primary processing at the source of origin. Each of the 11 practices can positively influence one or more of the impact areas defined in Chapter 2, albeit to differing degrees. Below we describe the practices one by one, including potential benefits, considerations for practical implementation, challenges for adoption and ways to overcome these. As part of the journey towards regenerative coffee farming, different practices can be combined or added in a stepwise manner.

Table 3.1. The 11 regenerative agricultural practices for coffee farming described in this chapter.

The symbols indicate the degree to which each of those practices can benefit the six impact areas. The symbols refer to: no benefit (—); small benefit (●); moderate benefit (● ●); or strong benefit (● ● ●).

PRACTICES	IMPACT AREAS					
	Soil health	Water conservation and quality	Biodiversity and land use	Greenhouse gas mitigation	Coffee productivity and input use	Farmer income and livelihoods
1 Renovation/rehabilitation and use of improved varieties	●	—	—	● ● ●	● ● ●	● ● ●
2 Agroforestry	● ● ●	● ●	● ● ●	● ● ●	●	● ●
3 Intercropping	● ●	●	●	●	● ●	● ● ●
4 Soil conservation practices and cover cropping	● ● ●	● ●	● ●	● ●	● ●	● ●
5 Integrated weed management	● ● ●	● ●	● ●	—	● ● ●	● ● ●
6 Integrated pest management	● ● ●	● ●	● ●	—	● ● ●	● ●
7 Integrated nutrient management	● ●	● ●	● ●	● ● ●	● ● ●	● ●
8 Efficient water use	—	● ● ●	—	●	● ●	● ●
9 Wastewater management	—	● ● ●	●	● ● ●	—	●
10 Waste valorization and production of organic inputs	● ●	●	—	● ●	● ●	● ●
11 Landscape actions	● ●	● ● ●	● ● ●	● ●	●	● ●

Coffee renovation in a coffee-banana system with mulching, Rwanda | CIAT/N. Palmer

3.4.1. Renovation/rehabilitation and the use of improved varieties

Overview of the practice

Rehabilitation and renovation are strategies to rejuvenate plantations that suffer from aging and to replace diseased or poorly managed coffee trees with improved *coffee varieties*. Such varieties must be well suited to the prevailing agroecological conditions and farm objectives, and capable of producing higher yields and/or better qualities.

'Renovation/rehabilitation and the use of improved varieties' is listed as the first of 11 regenerative practices for coffee farming, because healthy and productive trees, well adapted to the local agroecological conditions and farming systems, are a basic prerequisite for obtaining a good response to the adoption of any such practice.

Renovation involves uprooting old trees and filling gaps with new plantings to replace the current *coffee variety* as well as the rootstock. This practice also makes it possible to increase planting densities or change to a different system design.

Rehabilitation involves pruning and stumping of the coffee trees, while maintaining the current root stock. Stumping can be combined with grafting of selected scions on the regenerated suckers to replace the current genotype with new materials possessing the desired characteristics.

Low and declining coffee productivity due to aging tree stock, poor tree management, pests and diseases, and climate change poses a major problem for coffee farmers worldwide, especially smallholders. Renovation/rehabilitation is vitally important for addressing these problems. This practice could benefit at least 50% of the world's 7 million hectares of smallholder coffee land [14].

What are the most important benefits?

Healthy, well-adapted coffee trees, planted at adequate densities, give higher yields and permit more efficient use of resources (including agricultural inputs, labor and land), while also reducing the carbon footprint of coffee products [15]. These benefits depend also on the adoption of good agronomic practices. The use of improved varieties that are resistant to pests and diseases will further reduce the need for pesticides and labor-intensive phytosanitary practices. Maintaining stable, high yields over time might reduce pressure on remaining forest or encourage the restoration of biodiversity [14]. Particularly important with prolonged dry seasons is the use of drought-tolerant varieties (Figure 3.5). Renovation/rehabilitation thus complements other regenerative agricultural practices, contributing indirectly to improved livelihood resilience, climate change adaptation and natural resource management.

IMPACT AREAS	TEN POTENTIAL BENEFITS
Soil health	1 Adequate planting densities are important for soil cover and erosion control (but initially R/R reduces soil cover so care should be taken to prevent soil erosion)
Water conservation and quality	2 By using well-adapted and resistant/tolerant varieties, this practice can reduce nutrient and pesticide use, with positive impact on water quality 3 Well-adapted varieties allow for a more efficient use of irrigation water
Biodiversity and land use	4 By increasing productivity, the practice allows for a more efficient use of available land and can reduce pressure on remaining forest 5 Reduced use of pesticides favors non-target organisms and ecosystem services (e.g., pollination)
Greenhouse gas mitigation	6 The practice increases productivity and fertilizer-use efficiencies, resulting in a lower carbon footprint
Coffee productivity and input use	7 The practice promotes higher and more stable coffee yields and quality 8 Use of resistant and tolerant varieties reduces the need for pesticides
Farm income and livelihoods	9 The practice leads to improved and more stable income from coffee cultivation 10 When reducing pesticide use, the practice reduces health risks for farm workers

Figure 3.5. Ten potential benefits of renovation/rehabilitation (R/R) and the use of improved varieties.

Where should renovation/rehabilitation be implemented?

Renovation should be implemented in plantations where aging, diseased or poorly managed coffee trees have low or declining yields. Planning for renovation, and to some extent rehabilitation, provides a perfect opportunity to implement other regenerative practices that require restructuring of the production system. These practices include system diversification using well-suited intercropping and agroforestry designs as well as soil conservation practices and other measures to improve soil health (e.g., integration of erosion barriers, planting of cover crops and application of organic amendments in planting holes).

Rehabilitation should be done regularly (on average, every 5–8 years of production) and prioritized over renovation, where possible, to lower investments in planting materials and labor. Moreover, yields recuperate more quickly after rehabilitation (typically in 1–2 years) than after renovation (more than 3–4 years). Rehabilitation is also less risky, since it preserves the old root systems. New seedlings, in contrast, are more susceptible to drought and diseases [14]. In some situations, renovation is the only option – for example, when the tree density is low, the tree stock is in poor condition and unproductive, severe disease outbreaks damage the roots or stems of the trees, or when the trees are very old (more than 20 years of production). Changing climatic conditions could also require replanting with more drought-tolerant and disease-resistant varieties.

Box 3.1. When to prioritize renovation or rehabilitation

Renovation should be prioritized under the following conditions:

- Farms with old (more than 20 years) or deteriorated coffee trees that give yields below a locally relevant threshold.
- Farms with severe pest and disease problems (such as coffee leaf rust and plant parasitic nematodes), for which tolerant or resistant (rootstock and scion) varieties are available.
- Farms with high tree mortality.
- Farms with inadequate planting schemes (e.g., poor densities and shading).

Otherwise, **rehabilitation** can be adopted:

- Every 5–8 years of production or when yields start to drop or in case of severe die-back to keep the tree stock rejuvenated.
- Farms with poorly managed coffee trees that have too many stems per tree or unbalanced distribution of productive branches.
- Farms where limited investment capacity makes renovation less feasible.
- Farms with old but healthy rootstock.

As a general rule, rehabilitation or renovation needs to be done more frequently in hot climates (e.g., low altitude, Robusta coffee) and in full-sun plantations, compared to cool climates (e.g., high altitude, Arabica) and under shaded conditions.

What should be considered in implementing renovation/rehabilitation?

Rehabilitation

This offers the possibility of restoring the productivity of deteriorated coffee trees without uprooting rootstock. Excessive or unproductive branches and/or stems are removed to regenerate the crown of the coffee tree, using different techniques:

- **Pruning**
  Regular pruning is essential to ensure optimal yields. Very old coffee trees or coffee trees with more than four stems per tree (or less in the case of non-intensively managed plantations) tend to produce less, because nutrients are allocated to vegetative growth rather than to coffee cherries. Proper pruning of the suckers stimulates the allocation of nutrients to flowers and fruits. Moreover, pruning helps eliminate unproductive and/or infested branches, thus reducing the spread of diseases. Rehabilitation pruning, aimed at rejuvenating coffee plants, can be done using multiple techniques, including topping, "esqueletamento," "decote" and "agobio." These methods vary in the type of branches that are eliminated (orthotropic versus plagiotropic) and the height of the cut. For further information, see Netsere A et al. [16].

- **Stumping**
  Stumping (cutting the main stems) is a more drastic method, used when coffee productivity has declined below a specific threshold, generally between the fourth and fifth harvest [17]. When coffee trees have very few productive branches, stumping can restore coffee productivity. Stumping can also be used to make space for associated crops (intercrops or planting of new trees).

- **Grafting**
  Rehabilitation techniques can be combined with grafting (see more below under Renovation).

Renovation

This makes it possible to change the planting scheme and replace coffee varieties. It can be implemented through different propagation methods. Ideally, renovation should include the use of improved varieties (if available), which offer advantages from coffee genetic diversity and breeding to help maintain productive coffee trees with the required cup quality (see Figure 3.6, and Box 3.2 for further background). The following renovation techniques can be used:

- **New plantlets**
  When implementing renovation, it is vital to select high-quality seeds and/or plantlets, purchasing certified material from trusted suppliers. In the case of Arabica, which is over 90% *self-pollinating*, it is common to propagate by seeds selected from homogeneous plantations. In the case of Robusta, the use of planting material from seeds results in highly heterogeneous characteristics due to uncontrolled pollination. Establishing homogeneous Robusta plantations requires the use of vegetative methods for clonal propagation with rooted cuttings and grafting. The best-performing


Vietnam | Nestlé.

trees on the farm or established mother gardens with selected material can be used for this purpose. To ensure adequate pollination of Robusta, practitioners should employ multiple clonal lines within one plantation. At least four clonal lines are recommended to achieve synchronous flowering [18]. Arabica *F1 hybrids* are also propagated vegetatively, although this can be costly [19].

- **Grafting**
  Grafted plants use rootstocks from one coffee variety or species (usually seedlings resistant to drought, soil pests or diseases) and a *scion* from another that has better productivity, quality or agronomic characteristics. Grafting is preferable to the use of cuttings. The latter can result in poor development of the radicular root system, limiting production of the aerial biomass and reducing drought tolerance [20]. Grafting on rootstock from the same coffee species (intra-specific) or another coffee species (inter-specific) can be employed to enhance drought tolerance and resistance to *root-knot nematodes*, without affecting cup quality [21]. For example, grafting of Robusta plants on Excelsa rootstock is a common practice in Vietnam. Compatibility and adaptation to field conditions can vary according to the rootstock material. For instance, Robusta rootstocks may not be suited at high altitudes because of their poor adaptation to low temperatures.

Other important considerations

- To minimize risks and yield losses from renovation/rehabilitation, it is recommended to plan stumping or replanting over several years (e.g., 10 to 20% of the acreage per year).
- Further, practitioners should consider the best time of year to implement the practice, according to *plant phenology* and climatic conditions. The best time is after harvest to reduce the impact on production. Moreover, depending on the region's climate, rehabilitation is best performed during a period of lower ambient humidity and rainfall to avoid fungal disease incidence on cutting wounds.

- Farmers should attempt to regulate shade and thus provide optimal conditions for the growth of young seedlings and also guarantee grafting success, since grafts are sensitive to high temperatures and direct sunlight.

- During rehabilitation, and especially during renovation, there is limited soil cover, which increases evaporation and vulnerability to soil erosion. The maintenance of a good soil cover (e.g., through mulching, cover cropping or intercropping) is recommended on slopes. See Chapters 3.4.3 and 3.4.5 for further descriptions.

- New planting material for renovation should come from reputable, controlled or certified sources that can guarantee its genetic composition and sanitation. Preferably, materials should be certified and, when sourced from nurseries, require assurance that plantlets are not contaminated with nematodes or other pathogens, have been adequately fertilized, have undergone hardening and are grown in good quality substrate. Moreover, the seedling's origins should be registered, ensuring the traceability of all transactions, so that agronomists can trace back any issue with plant performance that may occur in the field.

Figure 3.6. Criteria for the selection of suitable coffee varieties for planting in a particular farm.

A first factor is the availability of improved varieties in the region. Some countries currently restrict the production of Robusta coffee [5]. A second factor in selecting varieties is their resistance or tolerance to biotic stresses (e.g., pests) and their adaptation to the prevailing agroecological (e.g., drought or nutrient deficiencies) and management conditions (shade management, cultural practices, and fertilizer use). Producers must also consider cup quality as well as other market demands (e.g., organic). Occasionally, markets pay a premium for specific (e.g., traditional) coffee varieties.

Box 3.2. The importance of genetic diversity in coffee varieties

Coffea arabica (Arabica) and *C. canephora* (Robusta) are different coffee species. Arabica has twice as many chromosomes as Robusta, making the former a tetraploid plant. Robusta cannot *self-pollinate* and has a diverse gene pool. Arabica, in contrast, can self-pollinate, which makes it much easier to breed for better sensorial and agronomic characteristics but also limits the species' gene pool. As a result, highly appreciated, traditional Arabica cultivars, such as Bourbon and Typica, have little genetic variability, making them highly susceptible to pests, diseases and climate change.

Breeding programs have introduced greater genetic variability in *C. arabica* through crossing with Timor Hybrid (TH). The latter is a cross between *C. arabica* and *C. canephora*, which happened naturally in Timor during 1917 and has enabled researchers to incorporate resistance genes from Robusta into Arabica. Composite varieties like *Castillo®* possess greater genetic diversity, since they are a mixture of multiple pure-bred lines, selected after several generations of recombination. This method of selection guarantees the best resistance to new disease strains. Crossings with TH possess multiple resistance genes to coffee leaf rust and coffee berry disease. The genetic characteristics of these varieties are stable, meaning that plants from the seeds will always be the same as the parent plants.

Another recent technological advancement in coffee genetic improvement involves the production of *F1 hybrids* through cross-pollination with wild cultivars. Because of hybrid vigor, these materials offer greater productivity, and they are also better adapted to adverse environmental conditions as well as pests and diseases [22]. In the past, coffee breeding has focused mainly on disease resistance and high yield in full-sun systems. Recent research has shown that F1 hybrids have potential for adaptation to changing climatic conditions and also for better performance under shaded conditions (few breeding programs have focused on shade tolerance as an important selection criterion). One exception is the F1 varieties developed by the European Breedcafs program together with the French Agricultural Research Centre for International Development (CIRAD) in Central America, which does take this trait into consideration [23]. With shade-tolerant coffee varieties, shade trees can be grown at higher densities, thus helping conserve a microclimate and biodiversity and sequester carbon. This development has important implications for the transition to regenerative agriculture in coffee cultivation. Plants grown from the seeds of F1 hybrids will never be the same as the parent plants, so hybrid seed must be purchased from a certified provider and must be clonally propagated.

What challenges does adoption of the practice pose, and how can these be overcome?

The main limitations to implementation of renovation and rehabilitation are the high upfront investments in planting materials and labour, especially in the case of renovation. A further disadvantage is that the practice leads to an initial, short-term loss of yield and income.

Additionally, managing plant development and successful grafting require time, for example, for monitoring seedlings, shoots and weeding. Some techniques, such as pruning and grafting, require specialized skills and are labor intensive.

In the medium term, regular renovation and rehabilitation can greatly improve productivity and generally result in positive cumulative cashflow for the farmer [14]. As lack of finance is the major barrier to investment in this practice, it can best be implemented gradually, replanting or rehabilitating 10–20%

of the farm each year. However, such phasing is irrelevant for farmers with small areas under coffee, i.e., less than 0.5 hectare [14]. Resource-poor farmers might be reluctant to implement renovation and rehabilitation because of the risks involved in changing varieties and establishing new seedlings. Limited access to quality planting material and its cost can pose further challenges. Financial and technical support from national governments, the private sector or development partners is therefore critically important, especially for smallholders.

Further reading and useful tools

Further reading and catalogues on coffee genetics and improved varieties:

- Coffee plants of the world https://sca.coffee/research/coffee-plants-of-the-world
- DaMatta FM; Ronchi CP; Maestri M; Barros RS. 2007. Ecophysiology of coffee growth and production. B*razilian Journal of Plant Physiology* 19. https://doi.org/10.1590/S1677-04202007000400014
- Ferreira T; Shuler J; Guimarães R; Farah A. 2019. In: Coffee: Production, Quality and Chemistry, ed. Farah A; Farah A.. The Royal Society of Chemistry. pp. 1-25. https://pubs.rsc.org/en/content/chapterhtml/2019/bk9781782620044-00001
- Global catalog of Arabica and Robusta coffee varieties from around the world (in English and Spanish) https://varieties.worldcoffeeresearch.org/

Toolbox for coffee variety selection:

- Coffee & Climate Toolbox https://toolbox.coffeeandclimate.org/tools/varietal-selection-drought/

Further reading on Renovation/Rehabilitation (in English, also available in Spanish and French):

- USAID R/R guidebook "Sustainable Coffee Challenges" https://agrilinks.org/sites/default/files/2017_rr_guidebook_c.pdf

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For further reading and visuals on grafting practices:

- GIZ coffee grafting guidebook https://www.giz.de/en/downloads_els/giz2021-en-coffee-crafting-made-easy.pdf

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Coffee agroforestry, India | Nestlé.

3.4.2. Agroforestry

Overview of the practice

Agroforestry is a production system that combines trees with crops, livestock or both, on the same land. Trees are commonly used on farms in other ways as well, including woodlots, fruit trees planted next to a homestead, riparian buffer strips and patches of natural forest. Some authors consider these and other uses of trees on farms to be part of a wider "landscape" concept of agroforestry [25]. Here, *agroforestry* refers to the practice of growing trees and coffee plants (and sometimes other crops) within the same plot, thereby creating multiple vegetation layers, somewhat similar to the structure of a natural forest. Trees can have multiple functions in the system, such as shade provision, microclimate regulation, nutrient cycling and production of additional products for consumption or commercialization.

There are many forms of coffee agroforestry, which differ in complexity (Figure 3.3), depending on the farmers' objectives and preferences. Complexity refers to the structure of the agroforest, i.e., the number of vegetation layers and shade density, as well as its diversity in terms of tree species and functions. Coffee agroforestry systems can thus range from simple agroforestry with a limited number of tree species and canopy layers to the most complex multi-layer agroforests, which host a great diversity of species, perform various functions and provide the farmer with fruits, spices, medicine, fodder and timber [25].

Agroforestry systems can be implemented during coffee establishment or renovation, or within existing coffee plantations. Planting designs vary; trees are either interspersed with coffee, or planted in strips or around coffee plots in the form of live fences, hedgerows or windbreaks. Coffee agroforests can also be established with coffee plants grown in naturally regenerated vegetation after a fallow period.

Under no circumstances, should coffee be planted after deforestation or thinning of natural forests. Deforestation is a major driver of biodiversity loss and land degradation, and greatly increases the carbon footprint of coffee production. This practice is in conflict with the principles of regenerative agriculture.

What are the most important benefits?

The benefits of agroforestry can be as diverse as the agroforest itself (Figure 3.7). Shade trees in coffee plantations help improve the microclimate in the understory, buffering (extreme) temperature fluctuations, regulating humidity and mitigating water stress. The trees also protect coffee plants from frost and strong winds, which cause water stress in plants [26]. Moderate levels of shade, carefully adapted to the local climatic conditions and intensity of solar radiation, can enhance plant health and productive capacity. In addition, by reducing the exposure of coffee trees to abiotic stresses, shade trees lower plant exhaustion and die-back (drying of the apical buds), thus extending the economic lifespan of coffee trees. This, in turn, makes it possible for plantations to be rehabilitated and renovated less frequently, reducing the associated long-term production costs.

IMPACT AREAS		TEN POTENTIAL BENEFITS
Soil health	1	Agroforestry better protects the soil against water and wind erosion
	2	The practice enhances soil life and nutrient cycling
Water conservation and quality	3	Water regulation and retention are improved
Biodiversity and land use	4	Agroforests host diverse tree species and provide habitats for wild species of plants and animals, especially complex agroforests
Greenhouse gas mitigation	5	Carbon is captured in woody biomass (and potentially as soil carbon)
Coffee productivity and input use	6	Depending on the context and under well-regulated shade levels, more stable coffee yields may be obtained due to improved microclimate and nutrient cycling (especially for low-input systems)
	7	The economic lifespan of the coffee plants is increased
	8	Enhanced biological pest and weed control in agroforests reduces the need for chemical inputs
Farm income and livelihoods	9	Diversification of production through agroforestry provides opportunities for improved, income, household food security, and mitigation of risks and price fluctuations
	10	Agroforests provide shade for farm workers

Figure 3.7. Ten potential benefits of agroforestry.

In general, shaded coffee systems give more stable production over time and require less fertilizer than full-sun coffee [27]. Moreover, shading reduces the biennial bearing pattern of coffee (on and off cycles), especially Arabica. Shaded coffee further has a tendency to produce larger berries and to prolong the fruit's ripening period, permitting greater flexibility at harvest [27]. These advantages are also often cited as reasons for shade-grown coffee's better cup quality in terms of body and acidity.

Agroforestry systems are further associated with a wealth of environmental benefits, including reduced soil erosion, enhanced nutrient cycling and soil fertility as well as water retention. Extensive and deep tree root systems can redistribute water and nutrients from subsoil, improving their availability for coffee. These benefits are known as the *hydraulic lift* and *nutrient pump effects*. Agroforestry systems can host considerably more biodiversity than coffee monocultures, since tree canopies and tree litter provide habitats for insects, plants, birds, soil fauna and microbes. Associated improvements in biological pest and weed control, as well as in pollination and soil fertility, can reduce the need for external inputs and harmful pesticides, or lead to increased productivity in low-input systems. Especially the more complex agroforestry systems contribute importantly to biodiversity and ecosystem services beyond the production of agricultural goods.

Growing trees remove CO_2 from the atmosphere through photosynthesis and storage of carbon in their standing biomass. The contribution of agroforestry to carbon sequestration is strongly supported by scientific literature, with agroforestry systems storing ~30–50 Mg C/ha more in standing tree biomass than coffee monocultures [28, 29]. Even though soil organic matter represents the largest carbon pool in the system, the potential for agroforestry systems to contribute to *soil carbon sequestration* through additional soil carbon storage is less clear (Box 3.3).

Box 3.3. Agroforestry and soil carbon sequestration

The evidence on the potential for agroforestry to sequester carbon in soil through the buildup of soil organic carbon (SOC) is limited. Few studies are available, and these show that the effects of coffee agroforestry can range from a decrease to no effect or an increase in SOC stocks compared to monocultures [30–32]. Effects tend to be site specific. Furthermore, the studies did not find a clear relation between aboveground biomass and *soil carbon sequestration*. Possible reasons for this are:

- Tree species and planting densities used, as well as pruning management, strongly influence the amount and type of organic matter inputs generated.
- Climatic conditions, *soil texture* (e.g., clay content) and mineralogy, as well as nutrient availability, affect the capacity of the soil to transform carbon inputs into stable *soil organic matter*.
- In most tropical soils, especially under warm, humid conditions, organic matter degrades quickly, making it hard to raise soil carbon concentrations. Given the large amount of SOC already present in the soil, the amount added annually in the form of newly formed soil organic matter is relatively small, so it takes several years before a measurable increase can be detected.
- The effect of agroforestry on soil carbon sequestration depends strongly on initial soil conditions and past land use. Degraded soils with very low soil organic matter have a greater capacity to store additional carbon than soils that are already high in SOC.

Equally important, timber and non-woody forest products (such as fruits, spices, medicine and resins) that are produced in agroforestry systems can enhance socio-economic resilience by strengthening household food and income security throughout the year, especially when income from coffee is low. Trees can also support climbing cash crops, such as vanilla and black pepper, thus allowing for additional diversification through intercropping (see Chapter 3.4.3). Finally, farmers often mention better working conditions in the shade as an advantage of agroforestry.

Where should agroforestry be implemented?

Agroforestry can be adapted to the agroecological and socioeconomic conditions of most coffee farms. The practice is especially suited for those farms where climatic conditions limit coffee production or where climate change is expected to create such conditions. This is the case, for example, with coffee grown at lower elevations or in regions with high solar radiation, high temperatures and low ambient humidity, or strong winds.

Farms on degraded soils with poor fertility, low organic matter content and/or high acidity as well as on soils with limited capacity for water and nutrient retention (such as sandy soils) can also greatly benefit from agroforestry. The integration of shade trees in coffee plots on steep slopes can improve soil erosion control. In addition, agroforestry systems have significant potential to generate green corridors connecting natural forest patches, with associated benefits for biodiversity conservation, pollination and natural pest control. Such a landscape approach (see Chapter 3.4.11) is especially relevant around natural parks and protected reserves.

Complex agroforestry systems benefit smallholder farmers in particular, helping them compensate for limited access to fertilizers and other external inputs, while supporting natural weed suppression. Of particular interest under such conditions are legume tree species (such those from the genus *Inga*), which can fix atmospheric nitrogen and promote biological pest control [33], as well as trees providing diverse products for household use and local markets. Simpler agroforestry systems, with commercial timber species or high-value fruit trees or spices planted in alleys, may be more suitable for farms that use larger amounts of inputs (especially fertilizer) and are mechanized.

Box 3.4. Conditions under which agroforestry should receive priority

- Farms with unfavorable climatic conditions (high solar radiation and temperatures, heavy rains, strong winds, extended drought, and frost)
- Regions where coffee suitability will decrease in the coming years due to climate change
- Farms on hilly terrain that is prone to soil erosion and landslides, and on degraded soils with low fertility and poor water retention
- Smallholder farms with limited access to land and external inputs (e.g., fertilizers).
- Farms that provide low incomes and household food security
- Areas surrounding natural parks and protected reserves

Robusta with shade trees, Ecuadorian Amazon | CIAT/M. Pulleman.

Shade tree management has differing effects on Robusta and Arabica because of variations in the physiological and ecological characteristics, as well as the fertilizer response of these species. Arabica and Robusta also differ in sensitivity to pests and diseases. Compared to the number of studies on agroforestry in Arabica, relatively few studies have examined the management of Robusta agroforestry. Yet, shade trees can offer Robusta producers important socioeconomic and ecological value [4,34] . Clearly, more research is needed on Robusta agroforestry systems under different biotic and abiotic conditions.

What should be considered in implementing agroforestry?

In agroforestry systems, shade trees interact strongly with coffee plants when utilizing resources, including light, nutrients and water. Agroforestry also affects other aspects of production, such as pests and diseases, as well as soil health. Those interactions can have both positive and negative effects on coffee productivity and farm income. First, even though the potential productivity of coffee plants may be highest under full sun, actual yields obtained at the farm level are often limited by factors other than light availability, such as water stress, temperature extremes, pests and diseases, and nutrient availability. When agroforestry contributes to alleviating those limiting factors, it can improve coffee productivity. Second, even if coffee yields are reduced in agroforestry systems, the total economic and ecological benefits often outweigh those of monocropping, provided that the right tree species are selected and the shade density is managed carefully.

Optimal shade management in coffee requires an understanding of the effects of light availability on physiological processes in coffee plants, especially flowering. For Arabica, a minimum of 20% shade is generally recommended but not more than 45% to avoid negative effects on productivity [27,35]. For Robusta, the recommended shade levels range from 10% to 30% [36]. Shade requirements depend on location-specific factors, such as elevation, solar radiation, temperatures and precipitation, as well as on the slope and orientation (south, north, east or west) of a particular coffee field. Fertilization also determines optimal shade density, since coffee responds simultaneously to the amount of light and to nutrient availability [27].

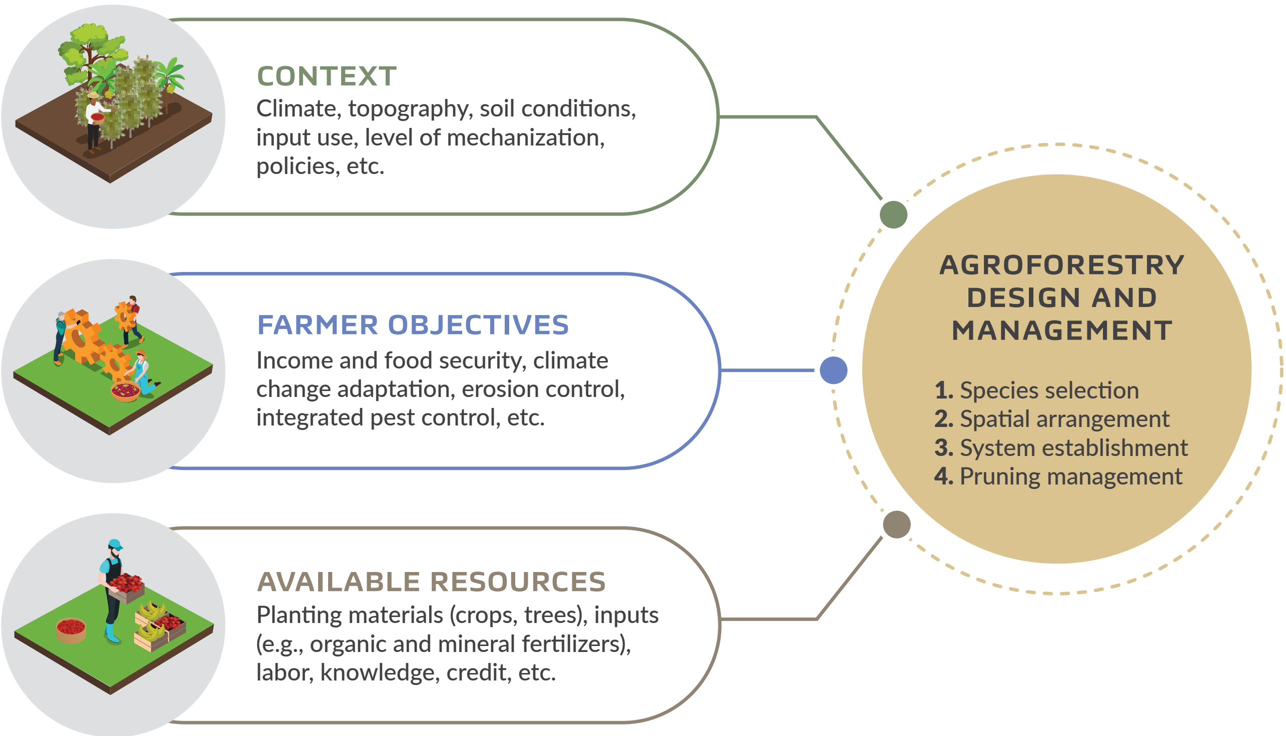


Figure 3.8. Schematic representation of factors and design steps to be considered in the design and implementation of agroforestry systems.

In light of the above, key elements for implementing coffee agroforestry systems are a good understanding of the context (including agroecological conditions, as well as management intensity in terms of input use and mechanization); clear objectives in terms of environmental, social and economic benefits; and ready access to the necessary resources (see Figure 3.8). In terms of system design and management, the following aspects or steps must be carefully considered: **(1)** the selection of shade, including commercial, tree species, **(2)** the spatial arrangement and density of trees and crops in the system, **(3)** system establishment, and **(4)** pruning management. These steps are described as follows:

1. Selection of tree species

Many potential shade and/or commercial tree species are available globally that can be integrated with coffee. Here we provide general criteria for their selection.

- **Tree morphology**
  Tree height, shape and crown size are morphological characteristics that determine the canopy's interception of solar radiation and rainfall, as well as the temperature, wind and humidity within the coffee stand. The shade tree species should have morphological characteristics that match the shade requirements of the coffee plants according to their production cycle and the prevailing climatic conditions. Trees should have crowns of large diameter and low density, covering as much area as possible, while allowing enough light to enter. Ideally, the tree species should naturally form perfect crowns above the coffee stock without pruning, as with *Albizia carbonaria*.

- **Tree physiology**
  The tree species should have the right physiological characteristics for the location, including its adaptation to soil and climatic conditions (e.g., its drought tolerance, growth rate and deciduousness). Evergreen trees always retain their leaves, regardless of the season, while (semi-)deciduous trees shed part or all of their leaves during the dry season. Some evidence suggests that evergreen species have lower transpiration rates when grown under sub-optimal conditions (high temperature and low precipitation), thus reducing water competition with coffee plants during critical periods [37].

- **Pruning requirements**
  Farmers should consider the tree species' response to pruning or pollarding and its resprouting ability. Moreover, pruning of shade trees for canopy formation, periodic maintenance and shade management requires significant labor. Some tree species are self-pruning, which farmers often dislike, since falling branches can be dangerous for farm workers and damage the crop beneath. High-value timber may require pruning to form knot-free, straight stems, which is not ideal for farms with limited labor.

- **Species *complementarity* and compatibility**
  To avoid competition for water and nutrients, shade tree species should have root systems that explore deeper soil layers (>30 cm) than the coffee roots. Deep rooting also allows for extraction of water and nutrients from deeper soil layers to the surface, known as *hydraulic lift* and *nutrient-pump effects*. When mixing different tree species, it is also important to consider their compatibility. This includes, for example, their tendency to host pests and diseases. Ideally, fruit tree species should have input requirements similar to those of coffee to optimize field operations, such as irrigation, whereas labor-demanding activities, such as harvest, should not coincide with that of coffee.

- **Capacity to fix nitrogen and other beneficial *functional traits***
  Legume trees such as *Inga* spp. and *Erythrina* spp. are of special interest, as they have the capacity to form *symbiosis* with soil microbes, allowing them to take up atmospheric nitrogen, thus reducing competition for this nutrient. The coffee crop can also benefit from this "cost-free" nitrogen when

the leaves and prunings of the legume trees decompose. Certain tree species, including species of the genus *Inga*, also offer nectar and pollen or a habitat for natural enemies of coffee pests and diseases [33].

- **Multifunctionality and economic value**
  It is advantageous to combine trees that can provide multiple services and products, such as fruit, resin, medicine, fiber, timber, fodder and fuelwood, especially if these have different harvest times throughout the year. Those species can help meet household needs and provide a more stable income, thus reducing risks in the face of price fluctuations in the coffee market. This is particularly important for smallholders. Intensively managed farms that have better access to fertilizer, irrigation and quality planting materials can focus on high-value, late-successional timber species, which have a longer lifespan, as well as on high-value fruit crops.

2. Spatial arrangement

This refers to the planting pattern as well as the spacing of coffee and shade trees, both horizontally and vertically.

- **Horizontal planting pattern**
  Regular or irregular arrangements and spacing distances can be used, depending on the shade morphology and requirements of the tree species, the climatic conditions, the intended economic and ecological benefits, and the level of mechanization. The design should allow enough light and air to enter the system, while limiting competition for nutrients and water. In places where plant production is constrained by abiotic factors, such as high temperatures or water stress, farmers should prioritize higher shade tree density. In erosion-prone areas, trees can be planted interspersed or along contour lines. Some tree species should not be planted inside coffee plots because of strong competition or because it is difficult to harvest them without damaging the coffee plants. Those tree species can be used for live fences.

- **Vertical spacing**
  The vertical distance between the coffee canopy and shade canopy should be at least 2 m for young coffee plants and 5 m for mature stands. This allows enough air to circulate and provides adequate shade at different hours of the day. Especially in regions with high humidity, farmers should prefer tall canopy trees with large, low-density crowns, which favor good air circulation in the understory. Depending on the complexity of the agroforest, multiple strata of woody plants may be present (Figure 3.9), including:

  - Coffee plants (up to 2 m), being the main cash crop
  - Bananas and small trees (up to 7 m) for food security and extra income from fruits, fodder, firewood, etc. (e.g., citrus, mango, avocado, jack fruit and durian)
  - Medium-sized woody species (up to 15 m) for shade and nitrogen fixation (e.g., *Gliricidia* spp., *Inga* spp. and *Erythrina* spp.)
  - Tall, high-value tree species for shade and timber.

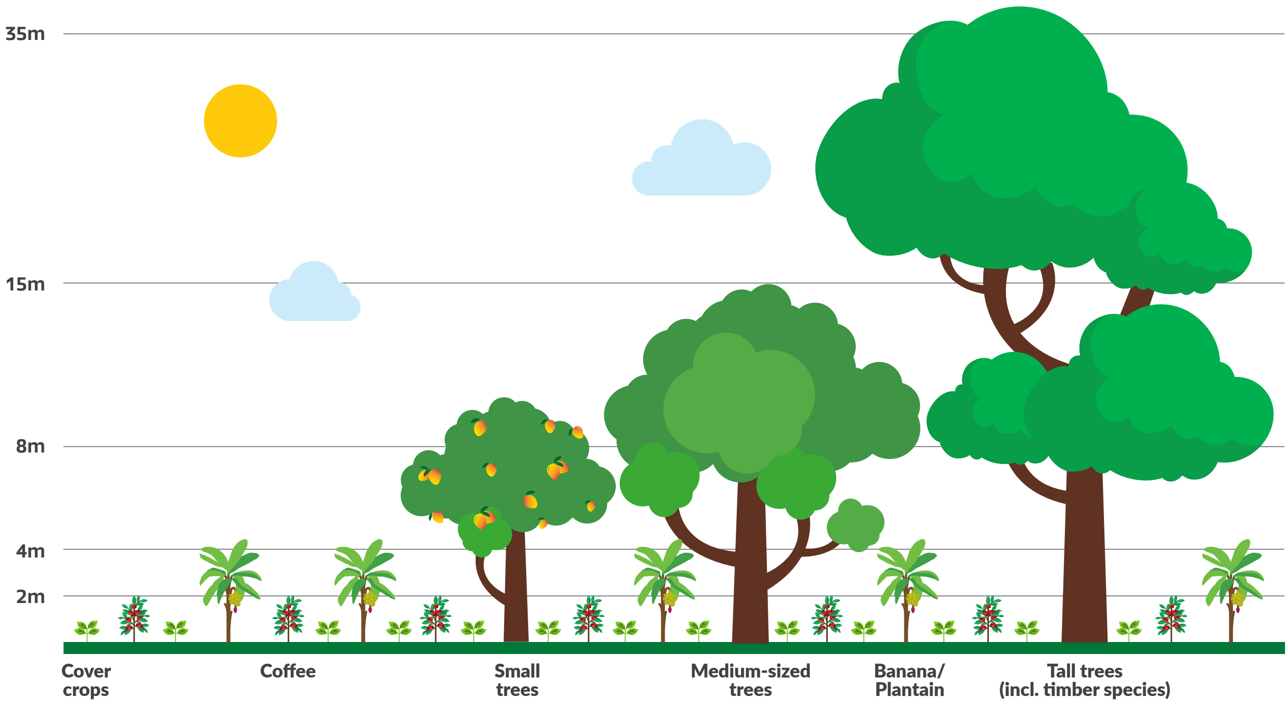


Figure 3.9. Schematic representation of different canopy layers in a multi-strata coffee agroforest.

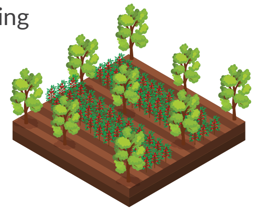
3. System establishment

As with natural forests, agroforests develop over time from a newly established system into a more stable and mature one. Ideally, a year before introducing coffee plantlets, growers should plant pioneer tree species adapted to full-light conditions, such as N-fixing trees (e.g., *Gliricidia sepium*). These trees will protect young coffee seedlings, guard the soil against radiation and other climatic pressures, and provide organic residues for soil improvement and nutrient enrichment. In the early years of the system, the integration of short-cycle, small leguminous trees (e.g., *Tephrosia* and *Crotalaria*) or intercropping with food or cash crops, such as maize or bananas, can provide shade and ground cover (see Chapters 3.4.3 and 3.4.4). Slow-growing trees that provide permanent shade (such as high-quality timber species) are introduced in parallel. With time, thinning or pruning will be needed to regulate shade and avoid resource competition with coffee.

4. Pruning management

Pruning of companion trees ensures optimal light and microclimatic conditions for coffee growth, flowering and fruit development. Regulating temperature and humidity in the understory is also important to control pests and diseases. Ideally, pruning should be planned according to climatic conditions and pruning calendars. For example, in places that have an intense dry season combined with high temperatures, shade trees can reduce stress on the coffee plants underneath; pruning during or before this period will be counterproductive. The optimal amount of shade may vary over time, depending on agroclimatic conditions (temperature, annual rainfall, length of the dry season and cloud cover), the physiological stage of the coffee plants and fertilizer use. After coffee harvest,

Table 3.2. Examples of planting designs for coffee agroforestry systems, depending on the specific context and objectives.

CONTEXT	FARMER'S OBJECTIVES/ BENEFITS	SPATIAL ARRANGEMENT	TREE SPECIES CHARACTERISTICS	CONSIDER
High altitude, moderate soil fertility, low income	• Soil conservation • Frost protection • Support nutrient cycling and pest control • Diversify income • Household food security	Scattered mix (low density) 	• N-fixers • Sparse crowns • Deep rooting species (>30 cm) • Deciduous or resprouting species • Providing fruit, fodder and fast growing timber • Species that provide pollen/nectar	• Pruning management
Low altitude, low soil fertility, low income	• Improve microclimate • Resilience to extreme climate • Improve nutrient cycling and soil health • Sequester carbon, support biodiversity • Diversify income • Household food security	Dense mix 	• N-fixers • Pioneer species[1], hardy and fast growing • Fruit, fodder and timber species	• Pruning management
Low altitude, low soil fertility	• Improve microclimate, and resilience to extreme climate • Optimize resource-use efficiency (incl. irrigation water) • Diversify income	Alley cropping 	• Fruit trees and other cash crops • Deep rooting systems (>30 cm)	• Also suitable for mechanized farms • Shorter term investments compared to timber
High altitude moderate soil fertility	• Windbreaks • Soil conservation (when planted on contour) • Barriers to pests and diseases • Timber production • Delimit the farm	Live fences 	• Tall and dense canopies • High-value timber trees • Offering nesting and food resources to natural enemies	• Also suitable for mechanized farms • Suitable for tree species that would compete with coffee when grown inside the coffee plot • Long-term investment

[1] Tree species can be classified according to their successional stage. Pioneers generally have lower wood density, faster growth, and better adaptation to poor soils than climax species. Tree species that belong to the latter group often include timber species with high canopy and slow-growth. Some of these species are shade tolerant in early growth stages.

vertical branches in the shade trees should be thinned to encourage coffee blossoming. With more light and ventilation during the rainy season, the conditions are less likely to promote the development of fungal diseases, such as coffee rust. Pruning residues also contribute to nutrient cycling.

Table 3.2 shows examples of planting designs for coffee agroforestry systems, according to the specific context and objectives. Catalogues, fact sheets and digital tools that can support technicians and farmers in developing the most suitable design and select species based on the desired characteristics (see "Further reading and useful tools"). Local extension services can provide more specific information for different agroecological regions, such as technical manuals that offer guidelines for agroforestry models adapted to local contexts, including planting distances and performance of different tree species. Digital tools can also help identify appropriate planting designs to achieve an adequate amount of shading [39].

Agroforestry | Nestlé.

What challenges does adoption of the practice pose, and how can these be overcome?

Successful coffee agroforestry systems can be found in all coffee-growing regions. To ensure that these systems improve farmers' income and livelihoods, it is important to combine agroforestry with overall good agricultural practices and to address possible trade-offs. On highly technified, intensive plantations, where coffee productivity is not limited by nutrient or water availability, increased shade may reduce coffee yields. However, the ecosystem services that agroforestry systems provide can help to reduce production costs and offset yield losses over time, as a result of enhanced natural weed and pest control, increased plant longevity, improved soil health, and more efficient use of fertilizers.

On the other hand, the adoption of agroforestry systems can create important trade-offs if these systems are poorly designed or managed (e.g., with inappropriate tree species and excessive shade). Lack of knowledge about agroforestry designs and management poses a significant barrier to adoption, especially if farmers lack adequate technical advice and support. In addition, establishing agroforestry systems requires investment and labor, including specific skills and tools (e.g., to prune tall canopy trees), and it can take a long time (typically 5–20 years for fruit and timber trees) before farmers reap the economic benefits. They, therefore, need special credit schemes that allow them to pay back loans over longer periods, or policies and financial instruments to support them during the transition.

Some niche markets pay a premium for shaded coffee, and coffee producers can increasingly take advantage of carbon credit schemes compensating them for sequestering additional carbon on their farms. Such mechanisms are still under development and are less accessible for smallholder farmers, but see for example this initiative: https://acorn.rabobank.com/en/

Further reading and useful tools

Video explaining the basic benefits and principles of agroforestry systems:

- Basics of Agroforestry https://www.youtube.com/watch?v=jLZ0KtNx354

Further reading on the design and management of agroforestry systems:

- Gassner A; Dobie P. 2022. Agroforestry: a primer. Design and management principles for people and the environment. Bogor. http://doi.org/10.5716/cifor-icraf/BK.25114

Further reading on the design and management of coffee agroforestry systems (in Spanish):

- Farfán F. 2014. Agroforestería y Sistemas Agroforestales con Café. Cenicafé, Manizales, Caldas (Colombia). 342 p. ISBN 978-958-8490-16-8

Web-based tools that provide information on tree species characteristics:

- The Agroforestree database offers information about more than 600 common agroforestry species, including their functional, morphological and physiological traits. https://apps.worldagroforestry.org/treedb/

- The Africa Tree finder tool offers similar information specific to the African context. https://www.worldagroforestry.org/output/africa-tree-finder

Web-based tools that support the planning and learning focused on agroforestry systems designs:

- Shademotion – A simulation tool developed by CATIE. It explores different shade tree species arrangements, according to the canopy morphology, geographic location, slope, etc., to achieve a specific shade pattern. www.shademotion.net

- AgroforestryX – A planning and learning tool for designing multistory agroforests. https://www.agroforestryx.com/

- The Shade Catalog. This catalog gathers existing data on trees found in coffee landscapes and helps farmers select shade trees that are good for coffee, support and diversify household incomes and provide benefits to wildlife and ecosystem services. Regional versions are available for Indonesia (in English and Bahasa) and Peru (in English and Spanish). https://worldcoffeeresearch.org/resources/the-shade-catalog

Book with beautiful illustrations of trees planted on coffee farms (in English and Spanish):

- Trees and lives https://bit.ly/trees-and-lives

- Árboles y vidas https://bit.ly/arboles-y-vidas

Coffee-black pepper intercropping, Vietnam | Nestlé.

3.4.3. Intercropping

Overview of the practice

Intercropping involves growing non-woody crops simultaneously with coffee in the same plot so as to harvest additional agricultural products. The practice enables farmers to diversify and intensify production, and enhances the resilience of farm households and coffee-farming communities by providing a wider variety of food and income-generating products [40]. Intercropping may be permanent or may be practiced temporarily to provide income during coffee establishment or renovation. A wide range of non-woody crops are commonly intercropped with coffee, including annuals (such as beans and maize) as well as semi-perennial crops, such as banana, black pepper, vanilla and forage grasses. Practices involving the association of coffee with trees or cover crops are discussed under Chapters 3.4.2 and 3.4.5. respectively (see Box 3.5).

Box 3.5. What are the differences between agroforestry, intercropping and cover cropping?

Agroforestry, intercropping and cover cropping are three different strategies to diversify coffee production systems. These strategies can be combined within the same production system. Different definitions are used for the three terms, which can be confusing. In this guidebook, we define them as follows:

Agroforestry involves the association of coffee with trees (including palm trees); in most cases, the trees provide coffee plants with substantial and continuous shade. These systems – especially complex agroforestry systems – generally contribute more strongly than intercropping to biodiversity and *ecosystem services*, such as microclimate regulation, nutrient cycling, carbon sequestration and soil conservation. Agroforestry also provides complementary products that contribute to income, or household food and fuel security. These benefits are often not immediate, as newly established fruit trees or timber, for example, take a couple of years to provide revenue.

Intercropping involves the association of coffee with non-woody plants, which offer food or income in the shorter term. Intercropping is especially worthwhile during coffee establishment or renovation. Intercrops help cover bare soil and may generate biomass for mulching when harvested, but their most important function is to provide food or income.

Cover crops do not have direct economic value but rather are used primarily for soil protection (e.g., erosion control, water retention and soil temperature buffering) and soil fertility improvement (e.g., through nitrogen fixation and mulching). Unlike intercrops, cover crops are not removed from the field but their biomass may be cut to provide mulch or be incorporated into the soil.

Agroforestry system, intercropped with vanilla, Uganda | IITA.

Note: Agroforestry and intercropping, or cover cropping, may be used in combination – either sequentially over time or simultaneously – as part of a regenerative coffee farming approach. Simultaneous use of these practices requires intercrops or cover crops that are shade tolerant. Some spices, such as cardamom and vanilla, benefit from the microclimate and shade provided in agroforestry systems. Shade trees can also provide physical support for the growth of climbers, like vanilla (see photo above) and black pepper.

What are the most important benefits?

The principal benefits of this practice, compared to coffee monocropping, derive from its potential to (i) increase productivity per unit of land, (ii) diversify incomes, and/or (iii) strengthen local food or fodder security. Well-designed and managed intercropping systems can achieve greater total productivity (i.e., combined coffee plus intercrop yields) compared to monocropping, while using resources more efficiently. This advantage is based on the *complementarity* of different crop species in terms of resource requirements (space, light, nutrients and water), as well as on the *facilitation* role of some crops (e.g., legume crops in nitrogen fixation).

For example, in low-input coffee-banana systems of Uganda [41] and in high-input coffee-pepper intercropping in Vietnam [42], it has been shown that the combined yields and profits per unit of land area are higher than those obtained in monocropping systems. Higher combined yields and economics have also been obtained from intercropping of ginger, cardamom and turmeric with coffee [43]. The land-use efficiency that results from combining different crops is expressed as the *land-equivalent ratio* (LER) [44]. A LER >1 means that intercropping is advantageous in terms of total productivity, compared to the same crops grown in monoculture. Similarly, the *monetary equivalent ratio* (MER) can be used to assess the economic advantage of intercropping [44]. Successful intercropping systems can thus provide farmers with important economic benefits, while also helping to reduce pressure on ecologically important areas, such as forests.

IMPACT AREAS	TEN POTENTIAL BENEFITS
Soil health	1 Intercropping can protect the soil against erosion 2 Growing a diversity of crop species may favor belowground biodiversity
Water conservation and quality	3 Water retention can be improved due to improved soil cover, especially during coffee establishment and after renovation
Biodiversity and land use	4 Well-designed intercropping systems allow for more efficient use of land for crop production, thus reducing pressure on forests 5 Depending on the crop species, intercropping can provide shelter and resources (nectar and pollen) for functional biodiversity
Greenhouse gas mitigation	6 Intercropping may increase soil carbon storage (e.g., when using intercrops with deep rooting systems)
Coffee productivity and input use	7 Intercropping improves weed control, especially after establishment and renovation, thus reducing the need for herbicides
Farm income and livelihoods	8 Intercropping has the main advantage of enhancing household food security 9 The practice enables farmers to generate additional income 10 Diversifying income through intercropping helps farmers achieve greater resilience to economic and environmental shocks

Figure 3.10. Ten potential benefits of intercropping.

Intercrops can also contribute to microclimate regulation, weed suppression, water retention and soil protection, especially during establishment, when coffee plants are still young and much of the soil area is bare. Finally, intercrops can provide habitats for beneficial organisms that contribute to pollination or biological pest control, or they can act as barriers to the dispersal of coffee-specific diseases and pests, such as nematodes [45-47]. Fava beans, for example, produce extrafloral nectar that sustains parasitoid wasp populations [48]. The use of legume crops can also help to reduce competition with the coffee plants for nitrogen. If large amounts of crop residues remain after harvest, they may also be used for mulching (see Chapter 3.4.4) or to produce organic fertilizers (see Chapter 3.4.10).

Where should the practice be implemented?

Diversified production is particularly important for reducing the vulnerability of farm households to income loss or food insecurity caused by economic or environmental shocks, including market price fluctuations, climate-related disturbances and disease outbreaks. Intercropping with food, fodder or cash crops is, therefore, well suited for smallholder coffee producers that have limited access to land but no major labor constraint. For large, more intensively managed farms, intercropping may offer an attractive strategy for *sustainable intensification*, as it permits a more efficient use of land and external inputs, while increasing labor productivity.

Intercropping is particularly important during coffee establishment or renovation, when intercrops can protect young coffee plants and otherwise bare soil against erosion and harsh climatic conditions (heat and drought), while also helping control weeds. At this stage, before coffee plants have become productive, intercrops provide an essential source of food and income. If the objective is to generate additional income from a cash crop, then the success of the intercropping system will depend greatly on market access and price as well as costs for labor and inputs. Certain intercrops (e.g., fruits and vegetables) may be more suitable for areas that are close to cities or have adequate infrastructure for transport or processing.

What should be considered in implementing intercropping

Key to success is designing and managing the intercropping system in a way that contributes to near-optimal conditions for coffee growth and development, while also permitting successful development of other crops on the same land. Ideally, the intercrop(s) used should provide the farmer with ecological services, besides from food and income, thus creating synergies in the system design (see Box 3.6).

To function optimally, an intercropping system, as with agroforestry, must maximize the positive interactions between different crop species (*complementarity* and *facilitation*), while minimizing any negative effects of the intercrop on coffee and vice versa. Crop combinations should thus be selected with care, considering potential benefits but also the risk of *resource competition* and *allelopathy*. Intercrops that host coffee pests or diseases should be avoided or managed carefully; it is also essential to use high-quality planting materials that are free of pests (e.g., plant parasitic nematodes).

Aligning cropping calendars is critical. Coffee and intercrop(s) must be compatible in terms of their labor requirements for field operations as well as their nutritional requirements, timing of crop protection measures, and the methods or products used. Intercropping models for mechanized farms also require compatibility with machinery use.

Depending on local conditions and farmers' objectives, two broad types of intercropping systems can be distinguished: temporary and permanent.

Temporary intercropping

This involves growing annual or biennial crops between coffee rows during the early phases of establishment or after renovation/rehabilitation – i.e., when coffee is not yet productive and the plants are still small and require shading. Temporary intercropping of coffee with the non-woody perennial banana or plantain is well known; further options include maize and other (semi-)annual crops, such as food legumes or fodder crops. Intercropping with maize and jack bean (*Canavalia ensiformis*), for example, has been found to suppress weeds at this stage, increasing coffee yields by up to 20%, compared to monoculture [49]. In Colombia, studies have shown that maize with beans or cassava can be successfully intercropped with coffee after renovation and rehabilitation, especially in conjunction with integrated weed management. Maize proved to be more suitable for hillsides, since it was more effective than beans or cassava in protecting the soil against erosion and in retaining soil moisture [50]. Another example of temporary intercropping is the combination of young coffee plants with aromatic herbs [51].

Permanent intercropping

This generally involves the association of mature coffee plants with non-woody (semi-)perennial crops. For example, pasture-coffee intercropping has been successfully integrated with small ruminants, such as sheep, as part of a silvopastoral system on farms with low planting density, high interrow spacing and low shading [52]. The sale of animals and/or consumption of meat and dairy products offer farmers important economic benefits, while also strengthening income and food security, and maximizing land productivity. In addition, animal manure serves as organic fertilizer [53]. Other species that smallholder coffee growers commonly use for permanent intercropping and that offer a viable alternative to diversify farm income are spices – such as ginger, turmeric, cardamom, vanilla, black pepper and chili – as well as banana or plantain (see Box 3.6 and Figure 3.11). The success of these systems depends on market access, commodity prices and the production system's level of technification. There are many examples of successful intercropping; the suitability and benefits of any given option depend on the crops used and local conditions (see Figure 3.11).

Box 3.6. Management of coffee-banana intercropping.
Based on Van Asten et al. [54]

Banana and plantain (from the Musaceae or banana family) are among the most common options for intercropping with coffee, on either a temporary or permanent basis. Permanent coffee-banana systems are common in East Africa, for example, in Uganda. The benefits of this system depend on successful management of *resource competition* between coffee and banana. It is important to choose banana varieties that are tall enough to exceed the coffee canopy and thus avoid excessive competition for light. Short/dwarf coffee varieties work best under the banana canopy. This is particularly necessary for Robusta, which is usually taller and has superficial, dense root systems, creating competition with banana for light, water and nutrients. If young bananas are planted in an existing Robusta plantation, coffee density must be limited to about 1,100 trees per hectare to reduce competition. The banana plantlets should be free of nematodes. Coffee canopy size can also be adapted through correct pruning. If left unmanaged, coffee will ultimately outcompete bananas. Conversely, under good management, coffee benefits from the shade and mulch that banana provides.

Coffee-banana intercropping, Rwanda | CIAT/N. Palmer.

TYPE OF INTERCROP	EXAMPLES	
Coffee + banana/ plantains		Coffee intercropped with banana | Nestlé
Coffee + cash crops/ spices (e.g., black pepper, cardamom, ginger and chili)	 Coffee intercropped with ginger | Nestlé	 Intercropping with chili peppers | Nestlé
Coffee + legume crops (e.g., soybeans, common beans and groundnuts)	 Coffee intercropped with beans | Nestlé	 Coffee intercropped with beans | CIAT/M. Pulleman
Coffee + vegetable crops (e.g., sweet potato, pepper and tomato)	 Coffee intercropped with tomatoes | CIAT/N. Palmer	 Coffee intercropped with pepper | CIAT/N. Palmer
Coffee + staple crops (e.g., maize and cassava)		Coffee intercropped with maize | Nestlé
Coffee + papaya (mechanized)		Coffee intercropped with Papaya | Nestlé

Figure 3.11. Examples of intercropping systems that combine coffee and crops for income diversification or food security.

What challenges does adoption of the practice pose, and how can these be overcome?

Some of the possible limitations and trade-offs involved in agroforestry also apply to intercropping. One of the most important trade-offs relates to the risk of excessive *resource competition* between coffee plants and intercrops, which can stunt coffee growth and reduce yield. Another risk is that intercrops may host diseases or pests (e.g., plant parasitic nematodes) that damage coffee; the use of quality planting materials is critically important. Some crops may also require pesticide applications, which can negatively impact coffee production. Conversely, coffee residues, because of their high caffeine content, may have allelopathic effects on intercrops [51].

Furthermore, some crops may involve disturbing the soil for seed drilling or altering the soil structure at harvest (as in the case of sweet potatoes or cassava); this may damage soil physical characteristics and contribute to erosion, especially on hillsides and when few crop residues are left to cover the soil. If the practice is to meet the objectives of regenerative farming, intercropped species must be selected with care, based on successful experiences.

The adoption of intercropping depends on social and economic factors as these systems demand more labor and investment. They also require that farmers can access technical knowledge about the management of intercrops and their interactions with coffee plants, as well as markets for the products [42]. In some cases, the labor and financial investment may outweigh that of coffee, but the economic benefits may also be considerable, as in the case of spices. On mechanized farms, intercrops may interfere with coffee management, for example, by hindering the use of machinery. However, this is not generally the case if intercrops used during establishment are planted in the same row as coffee, as is done with papaya-coffee intercropping in Brazil (see Figure 3.11).

Further reading and useful tools

Practice Brief: Coffee-Banana Intercropping.

- Van Asten P; Ochola D; Wairegi L; Nibasumba A; Jassogne L; Mukasa D. 2015. Coffee-Banana Intercropping: Implementation guidance for policymakers and investors. https://hdl.handle.net/10568/69017

Technical brochures about intercropping of coffee (in Spanish):

- Moreno AM; Sánchez PM. 2012. Reduzca los costos en el establecimiento del café: Intercale cultivos transitorios. Avances técnicos Cenicafé, 419. https://bit.ly/3OUegde
- Jaramillo S; Salazar HM. 2021. Cultivos intercalados: Una alternativa para aumentar los ingresos y la sostenibilidad de cafetales. Avances Técnicos Cenicafé 534. https://bit.ly/3QC7D0o
- Jaramillo S. 2023. Maíz y fríjol biofortificados intercalados con café. Avances Técnicos Cenicafé, 547. https://bit.ly/3s7hZLI

Cover cropping between terraces, Thailand | Nestlé.

3.4.4. Soil conservation practices and cover cropping

Overview of the practice

Soil conservation practices protect the topsoil against water and wind erosion, while also improving soil health and water retention. These practices include the use of soil cover, specific planting designs (such as contour planting, terracing, erosion barriers and micro planting basins), and reduced soil tillage. Soil conservation may further involve integration with other regenerative practices that protect or enhance the soil, such as agroforestry and integrated weed management. Of particular interest are *cover crops*, which are planted primarily to protect and improve the soil, and can provide a wide range of benefits to coffee production systems.

Much of the area dedicated to coffee cultivation, especially Arabica, is found on steep slopes in mountainous regions with high rainfall, making the land particularly susceptible to soil erosion. This results in the loss of fertile topsoil rich in soil organic matter, leading to soil degradation, including the loss of capacity to hold water and nutrients. Erosion can also contribute to the pollution and sedimentation of waterways and surface water. Soil degradation can occur even on relatively flat lands, in the form of surface crusting due to heavy rain impact on bare soil. This affects the soil's capacity to absorb and store water. Soil conservation is thus a key component of regenerative agriculture. This chapter discusses measures that can be implemented in individual fields. Complementary landscape actions (see Chapter 3.4.11) can greatly increase the effectiveness of these measures [55].

What are the most important benefits?

This practice aims to control or reduce soil erosion, while improving the soil's physical, biological and chemical condition. Those gains increase the soil's capacity to hold water, carbon and nutrients, and better enable it to provide a favorable habitat for soil biodiversity. The most important direct benefit of soil conservation practices is thus to safeguard soil health and the land's productive capacity now and in the future. These practices include mulching and the use of cover crops, which together have the advantage of controlling both weeds and soil erosion, while improving water retention and soil biodiversity [56,57]. These measures also help buffer soil temperatures. Soil conservation practices are thus crucial for enhancing farm resilience to climate change impacts, such as extreme temperatures and rainfall as well as extended droughts. Important benefits can be obtained across entire watersheds, reducing erosion and vulnerability to extreme weather, enhancing water quality, and reducing damage to infrastructure downstream.

Coffee with *Brachiaria* grass as cover crop planted in interrows, Brazil | Nespresso/G.Amado.

Deep-rooting grasses, such as *Brachiaria*, when grown in lanes between coffee rows, have been found to improve soil temperature, soil aeration, porosity and soil hydraulic conductivity, while also controlling aggressive weeds [57,58]. In addition, the deep roots of these grasses and the use of grass clippings as mulch improve soil structure and nutrient cycling. Using these grasses as cover crops has great potential to increase soil organic carbon in deep soil layers. *Brachiaria* grass must be managed carefully, however, to ensure that it does not outcompete coffee for water [57,59,60].

IMPACT AREAS	TEN POTENTIAL BENEFITS
Soil health	1 The practice reduces the loss of fertile topsoil 2 Mulching and cover cropping also enhance nutrient cycling, especially when living roots are present, as with cover cropping, and when N-fixing crops are used 3 Mulching and cover cropping help buffer soil temperatures, thus favoring soil biodiversity
Water conservation and quality	4 Soil conservation practices improve water infiltration and retention 5 Less soil erosion and leaching of nutrients contribute to improved water quality
Biodiversity and land use	6 Green barriers along the contour can provide habitat and nesting sites for wild biodiversity 7 Cover crops can support functional biodiversity, such as pollinators and natural enemies
Greenhouse gas mitigation	8 The use of trees in erosion barriers and of deep-rooting cover crops can support carbon sequestration in standing biomass and soil, respectively
Coffee productivity and input use	9 The practice permits more efficient use of agrochemicals by controlling erosion and runoff, and by providing an alternative to chemical weed control
Farm income and livelihoods	10 The practice further enhances resilience to climate change and extreme events, such as landslides and flooding

Figure 3.12. Ten potential benefits of soil conservation practices and cover cropping.

Where should soil conservation practices and cover cropping be implemented?

Soil conservation practices are important in any coffee production system to prevent soil degradation but should receive especially high priority on farms with the following conditions:

- Steep slopes with high rainfall intensity
- Soils that are poorly structured or that are sensitive to slaking and compaction (e.g., because of surface crusting)
- Systems that are prone to heat and drought stress
- Wide spacing between coffee rows, as in mechanized systems
- Systems that currently use tillage for weed control or land preparation
- During coffee establishment or renovation, when the young coffee plants provide limited soil cover


Coffee on terraces with cover crops and shade trees, Thailand | Nestlé.

What should be considered in implementing conservation practices and cover cropping?

Soil conservation relies mainly on the principle of maintaining a permanent soil cover in the form of cover crops or mulching (though agroforestry and intercropping can also perform this function). Guidance on how to put the principle into practice is provided below:

Mulching

Mulching involves spreading organic residues on the soil surface, for example, after renovation/rehabilitation or between coffee rows. Ideally, these materials should be harvested in situ or sourced on-farm to limit the costs and labor associated with their transport. Examples are crop residues (such as maize and banana), grass clippings or hay, and waste from coffee processing. Besides controlling soil erosion, mulching reduces soil temperature and evaporation, suppresses weed growth and benefits soil biota [61]. Ideally, mulching material should be relatively resistant to degradation (i.e., with a high C:N ratio), thus ensuring that it keeps the soil covered. Over time, soil fauna and decomposition by microorganisms will work the mulching material into the soil. Mulching with woody materials, in contrast, is sometimes considered problematic, as it may attract certain termite species. Moreover, their high C:N ratio may initially cause the immobilization of nitrogen or other nutrients, thus reducing nutrient availability to coffee plants. In those cases, applying a combination of organic materials and mineral nutrients, or low- and high-quality organic materials, is recommended (see Chapter 3.4.7).

Cover cropping

Cover cropping consists of planting species whose main purpose is soil conservation and that are retained in the field rather than removed after harvest. Cover crops are also called “living mulch.” Their growing roots offer the further advantages of improving soil structure, promoting soil organisms and providing belowground carbon inputs. Since cover crops require sun to thrive, they may be more suited than mulches to full-sun systems or during crop establishment. Perennial cover crops can be used as living mulch, and can be mowed for use as on-site mulch and as green manure to enhance soil fertility (see Chapter 3.4.7). Cover crops generally benefit coffee production by improving water and nutrient availability, but they may also compete with coffee plants for water or nutrients to some degree, resulting in yield losses [62]. Cover crops should therefore be limited to the interrow spaces. The area around the coffee plant canopy can be covered with cover crop clippings (referred to as “dead mulch”). In order for cover cropping to succeed, it is important to select the right species, based on the potential for adapting to agroecological conditions on the farm and thus ensuring good ground coverage. Species may also be selected because of additional benefits, while climbers should be avoided. Many commonly used cover crop species are leguminous (see Table 3.3) contributing to nitrogen fixation [63]. Cover crops have also been found to enhance the presence of natural enemies of coffee pests [64].

Intercropping

With annuals or semi-perennials (e.g., maize, beans or bananas) during coffee establishment may offer an attractive alternative to cover crops for maintaining ground cover between coffee rows, while also generating food or income. The ability of intercrops to protect the soil adequately depends greatly on the species selected and its management – for example, whether it requires tillage for soil preparation as well as the amount of crop residues left after harvest and their rate of decomposition (see Chapter 3.4.3).

Agroforestry

The integration of mixed trees within the system – offers various benefits that help protect the soil (as a result of litter accumulation), acting as a wind barrier, reducing rainfall energy and improving root structure [[65]] (see Chapter 3.4.2 for more information).

In addition to soil cover, physical structures can be used in the coffee system to control erosion and improve water infiltration, especially on steep slopes:

Physical structures

Physical structures, such as terraces, trenches, vegetative erosion barriers or stone barriers, can help control erosion and runoff. Drainage canals and planting on furrows can allow water to infiltrate into the soil during high-rainfall events. Terracing has the additional advantage of facilitating farm operations on steep hills but requires considerable labor and initial investment. Vegetative solutions should be prioritized over the construction of physical structures whenever possible, as the latter generally involve considerable investment in labor and/or machinery. Shrubby hedgerows, such as *Desmanthus* [[66]], and perennial bunch grasses, such as Vetiver grass [[67]], have been widely and successfully used to stabilize slopes, and can also provide mulching material. Vegetative erosion barriers can further lead to the formation of natural terraces. On a smaller scale, farmers can adopt “half-moon” planting, which involves digging into the slope above the coffee tree and heaping the soil in a half-moon shape to create individual terraces (basins) around each plant [[68]].

Other important considerations

Contour planting

All of the aforementioned practices should take into consideration the local topography. The coffee plants should ideally be planted on the contour. Other elements, such as barriers and shade trees, can be integrated through alley cropping along the contour lines. The contour lines can be identified manually using a handmade A-frame or water level, and marked with pegs in the field at appropriate distances, depending on the degree of slope [[69]].

Soil tillage

Intensive mechanical tillage is not commonly used in coffee, though in regions where coffee farming is mechanized (e.g., parts of Brazil), growers generally plough the land before establishing coffee and practice interrow tillage to control weeds between coffee rows. In some countries, farmers practice hand hoeing, even on slopes, to remove weeds [[56]]. Tillage initially loosens the soil and increases infiltration for a short time, but this also leaves the soil bare, making it vulnerable to erosion and compaction, and undermining water storage over the long term. Therefore mechanical soil disturbance should be minimized, especially on slopes. Strongly degraded and compacted soils are an exception. In such soils, deep tillage may be used for land preparation during coffee establishment, thus allowing coffee roots to grow deeper. Deep tillage can be done with a subsoiler, taking care to avoid mixing or inverting soil layers. Subsequent planting of interrows with deep-rooting cover crops, such *Brachiaria* grass, can further improve soil structure and water infiltration [57]. Regular tillage for weed management, however, should not be encouraged [70,71].

Pinto peanut (*Arachis pintoi*) planted as cover crop with coffee, China | Nestlé.

Tephrosia planted as cover crop in young coffee stand, Colombia | Nespresso/D. Sánchez.

Table 3.3. Leguminous cover crop species used in coffee systems, their characteristics and uses.

COMMON NAME	SCIENTIFIC NAME	CHARACTERISTICS	USES
Sunn hemp	*Crotalaria juncea*	Erect, short-cycle species that must be cut back early before harvest, produce high biomass in low shade, and show tolerance to drought and poor soils.	Provides pollen for pest natural enemies, a source of fiber and weed suppression, while improving soil fertility.
Jack bean	*Canavalia ensiformis*	A short-cycle species that provides good early cover but is only partially shade tolerant; best cut for mulching at full blossom.	Provides livestock fodder and good weed suppression, and also repels CBB.
Lablab	*Dolichus lablab*	Needs trimming to prevent climbing onto coffee, performs well in low or high shade, is suited for all soils and tolerates drought.	Suitable both for livestock fodder and human consumption, while providing high N fixation.
Pinto peanut	*Arachis pintoi*	A persistent species with medium establishment, medium drought tolerance, fast regrowth and high shade tolerance.	Provides livestock fodder and high weed suppression, while repelling nematodes.
Tropical kudzu	*Pueraria phaseoloides*	A persistent species with slow establishment; needs trimming to prevent climbing onto coffee, shows poor tolerance to damage (easy to terminate) but tolerates acidic and heavy wet soils as well as shade.	Provides livestock fodder, very high weed suppression and high N fixation, while protecting crops from nematodes.
Desmodium	*Desmodium ovalifolium*	Shows slow establishment and must be cut back during dry spells for mulching; has good regrowth, high shade tolerance, tolerance to wet and poor soils and medium drought tolerance.	Provides livestock fodder, acts as a trap-crop for nematodes and achieves good weed suppression after full establishment.
Mucuna or velvet bean	*Mucuna pruriens*	A short-cycle species (<6 m) that needs trimming to prevent climbing onto coffee, shows poor tolerance to damage (easy to terminate), is restricted to non-degraded soils, prefers a hot, wet climate. Low drought and shade tolerance.	Provides livestock fodder as well as high allelopathic weed control and high N fixation.
Centrosema	*Centrosema pubescens*	A persistent species with slow establishment but good regrowth; needs trimming to prevent climbing onto coffee, shows moderate shade tolerance and medium-poor drought tolerance. Requires well-drained soils.	Provides livestock fodder and protects crops from nematodes.
Calopo	*Calopogonium*	A short-cycle, shade-tolerant species that needs trimming to prevent climbing onto coffee, achieves fast establishment and shows poor drought tolerance.	Provides good weed suppression in the first year.
Tephrosia	*Tephrosia* spp., *T. candida*	A shrub (2-3 m high) used for temporal shade and green manure in coffee systems; must be pruned various times a year due to vigorous growth [72,73].	Good for nutrient provision. (see Chapter 3.4.7 for more information).

What challenges does adoption of the practice pose, and how can these be overcome?

Most soil conservation measures require planning and adaptation of the cropping system at the time of establishment or renovation, which is also the moment when those measures are most critical. To adapt the planting design and ensure that physical erosion control structures or vegetative barriers follow contour lines can pose challenges. These measures also take time to implement, and training is required for farmers to trace contour lines in the field. In areas with rugged topography, contour planting can result in lower coffee plant densities and irregular interrow distances, which may complicate farm operations and lead to lower labor-use efficiency.

Although cover crops can be established in existing plantations, this may prove challenging in plantations with high planting densities and shade levels (e.g., in agroforestry systems). The practice is most suitable in the first years after crop establishment or on farms with larger interrow distances and/or no shade (as on mechanized farms and in coffee monocultures). During the first years after coffee establishment, smallholders may prefer to use intercropping (e.g., with banana, which also provides sufficient biomass residues) and thus strengthen household food and income security.

Farmers may face difficulty in finding quality seeds or cuttings of cover-crop species, and planting them is labor intensive. An alternative is to use naturally occurring species for soil cover through integrated weed management (see Chapter 3.4.5). Cover-crop species must be selected and managed with care, since they can occasionally grow vigorously, competing with coffee plants for water or nutrients. Creeping cover crops can quickly attain high coverage, but the farmer must then invest time in keeping them away from areas close to the coffee canopy, preventing the cover crop from becoming a weed.

Another way to reduce competition for water, especially under very dry conditions, is to use crop residues as mulch. Whether the farmer can readily adopt this practice depends on the availability of locally produced mulching material. When mulching materials decompose too quickly, they must be re-applied frequently. Agroforestry systems offer a good strategy for soil conservation, because they provide constant litter input and a canopy to protect the soil.

Further reading and useful tools

Technical publications on cover crops for coffee production systems (in Spanish):

- Mayerly A; Suárez F; Valencia F; Morales-Londoño C. 2005 . Biomasa seca y contenido de nutrientes de *Cajanus cajan, Crotalaria juncea* y *Tephrosia candida* empleadas como abonos verdes en cafetales. Cenicafé 56. https://www.cenicafe.org/es/publications/arc056%2802%29093-109.pdf

Technical publications on soil and water conservation in coffee (in Spanish):

- Hincapié Gómez E; Ramírez Ortiz FA. 2013. Riesgo a la erosión en suelos de ladera de la zona cafetera. Avances Técnicos Cenicafé 400. https://biblioteca.cenicafe.org/bitstream/10778/404/1/avt0400.pdf
- Rivera Posada JH. 2013. Sistemas de drenaje con filtros vivos para la estabilización y restauración de movimientos masales en zonas de ladera. Avances Técnicos Cenicafé 413. https://biblioteca.cenicafe.org/bitstream/10778/337/1/avt0413.pdf
- Salazar Gutiérrez LF; Hincapié Gómez E. 2013. Manejo de suelos y aguas para la prevención y mitigación de deslizamientos en fincas cafeteras. Avances Técnicos Cenicafé 401. https://biblioteca.cenicafe.org/bitstream/10778/354/1/avt0401.pdf

Nicaragua | L. Navarrete.

3.4.5. Integrated weed management

Overview of the practice

Integrated weed management (IWM) aims to keep weed pressure below an economic threshold in a sustainable manner through a combination of preventive and corrective methods. Weeds can negatively affect coffee production, with significant yield losses, by competing for water, nutrients and light [74]. Occasionally, weeds can also act as alternative hosts for plant pathogens [75,76].

Many plant species are classified as weeds, and all have diverse life cycles and survival strategies. Consequently, weeds interact with coffee plants in different ways, mainly depending on the weed species and their density [74], so no single weed control measure can be generally effective. In fact, routine application of a single type of weed control can result in the selection of more aggressive weed species, allowing them to adapt [77]. For example, intensive use of specific herbicides may favor herbicide-resistant weeds [78]. Excessive herbicide use has several other negative impacts as well, including health risks, environmental contamination and pollution and the loss of natural vegetation and associated biodiversity above and belowground. An additional risk consists of economic losses due to market restrictions, if residue levels in harvested products exceed the allowed limits [79]. By contrast, IWM, as a key regenerative agricultural practice, encourages nature-based solutions and reduces the need for chemical inputs.

IWM is based on several general principles: **(1)** using agronomic practices that limit weed introduction and spread (prevention), **(2)** helping the crop outcompete undesirable weeds, and **(3)** using practices that prevent weeds from adapting to control measures [80].

What are the most important benefits?

IWM provides both environmental and economic benefits. When designed and implemented appropriately, it has the potential to restrict weed competition, keeping weeds below economic thresholds and reducing the negative environmental impacts of chemical weed management. At the same time, by putting ecological principles into practice, IWM can reduce or optimize the use of external inputs (e.g., herbicides) and labor, compared to using either chemical or mechanical weed management methods alone.

Reduced herbicide use and selective maintenance of certain "spontaneous plant species" can create habitats and resources for a variety of animal and insect species, including pollinators and natural enemies of crop pests. IWM is highly compatible with other regenerative practices, such as agroforestry, soil conservation, cover cropping, and integrated pest management (IPM). By using selective weed control measures, IWM helps maintain a permanent soil cover, enhances (functional) biodiversity, reduces erosion and runoff, and improves soil health. IWM also reduces health risks for farm workers (Figure 3.13).

IMPACT AREAS	TEN POTENTIAL BENEFITS
Soil health	1 The permanent soil cover due to IWM helps to control soil erosion and runoff 2 The practice also helps to buffer soil temperatures, maintain soil moisture and favor soil health and biodiversity
Water conservation and quality	3 Reduced herbicide use leads to less contamination of water bodies with herbicides 4 Improved water infiltration/retention due to permanent soil cover
Biodiversity and land use	5 Less negative effects of herbicides on wild plants favors (functional) biodiversity
Coffee productivity and input use	6 Improved coffee productivity due to better weed control, and less resistant weeds 7 Reduced use of herbicide inputs
Farm income and livelihoods	8 Improved labor productivity 9 Reduced health risks to farm workers due to the reduced use of herbicides 10 Lower risk of economic losses due to food safety regulations (e.g., when residue levels in harvested products are above the allowed limits)

Figure 3.13. Ten potential benefits of integrated weed management (IWM).

Where should integrated weed management be implemented?

This practice is relevant for all coffee farms, regardless of the agroecology, farm type and coffee production system. IWM should receive especially high priority, however, on farms where weed pressure is high, as in the following situations:

- Recently established plantations, where coffee plants and shade trees are still small.
- Plantations that lack shade trees and where the soil between coffee rows is left bare (e.g., in mechanized plantations or plantations with low coffee plant density).
- Sloping coffee fields that are sensitive to soil erosion and runoff.
- Farms with high herbicide use, including those where herbicide-resistant weeds are present.
- Small farms with resource constraints (e.g., labor or capital), where it may be risky or not economically feasible for the farmer to rely on corrective control measures that involve physical and chemical methods.

In well-established agroforestry or intercropping systems or high-density farms, the amount of direct sunlight reaching the soil is reduced, and leaf litter from trees or mulch accumulates, thus hindering weed germination. In such systems, (additional) weed control is less important and less labor intensive.

What should be considered in implementing IWM?

IWM involves a combination of control methods at different stages of coffee establishment and maturity. As with IPM, the selection and combination of IWM methods depend on the coffee farming context. For instance, the ecological context, soil properties and nutrient management determine which weed species proliferate. The system design also determines the weed species and their abundance by defining the amount of soil cover and shade, by modifying the soil microclimate, and by influencing the amount and composition of litter.

Decisions about control do not necessarily depend on the level of weed cover but on the characteristics of specific weed species. Some can attain high cover but have a root system that interferes very little with coffee productivity. Other weeds require preventive control well before they begin to compete with coffee to keep them from going to seed and spreading across the farm or from climbing up the coffee trees. Designing an effective IWM strategy involves the five key steps described in Table 3.4.

Table 3.4. Five key steps in an integrated weed management approach.

1	**Identify the weed species present, their traits and life cycle** Consider the seed bank present, species' seed persistence, germination conditions, growth and reproduction. Ask key questions such as: Is the weed annual or perennial, and can it resprout from vegetative parts?
2	**Consider the potential effects of different weed species on coffee productivity** These include the weed's ability to compete for resources (its root architecture or structure is a good indicator of this) or its specific *allelopathic effects*. Weeds that are alternative hosts of coffee pathogens should be avoided, whereas those that harbor beneficial species (such as natural enemies of coffee pests) should be selectively preserved.
3	**Determine which of the weed species present require (selective) control** This should be based on their specific **traits** and abundance/density, as determined in steps 1-3.
4	**Determine the best control measure and best timing for application** The optimal method should attempt to reduce the weed's seed bank and germination, while weakening its belowground reserves. The timing should coincide with the critical crop phase, when competition is greatest, as well as with the weed's critical phase (i.e., before it sets seed).
5	**Prevent future weed infestation by means of cultural control** This requires mapping of areas in which heavy or recurrent weed infestations occur to identify where the action is most needed. This also helps the farmer understand how system design influences weed growth and germination (e.g., by leaving ample areas of bare ground or providing low shade).

Remember that changes in the design or management of the coffee production system can modify weed communities.

Weed control can involve preventive and corrective methods. Preventive methods mainly consist of cultural practices aimed at reducing the emergence and reproduction of undesired weed species. Corrective methods include physical and chemical controls, in which herbicides are used only as a last resort, when weed pressure reaches the economic threshold. This is the point at which the negative effect of weeds on coffee production exceeds the cost of preventive or non-chemical control measures.

Preventive methods

Those include:

- **System designs**
  Limiting the availability of light and the temperature at the soil surface suppresses weed growth [81]. Therefore, increasing the coffee planting density and using shade trees can inhibit weed

development and competition. Intercropping and cover cropping also help to inhibit weed germination, especially in young coffee stands [81]. Agroforestry systems provide better soil cover than monoculture systems due to the increased canopy cover and litter accumulation on the soil surface from leaves, clippings and prunings [82]. An alternative is to spread mulching material (e.g., residues from intercrops and grasses) over the soil. Cover crops can also suppress weed growth and germination through *allelopathic effects* [83]. These practices are not only effective as preventive weed control methods but can also create synergy with other regenerative practices, such as soil conservation, IPM or integrated nutrient management (INM).

- **Selective weed management**
  Selective weed management aims to suppress more aggressive weeds by favoring or promoting the growth of naturally occurring species that have no negative interactions with coffee plant, so-called "noble weeds" [78,84]. This involves removing only aggressive weed types (such as vines, tall and broad-leaved herbs, and perennial grasses). Harmless or beneficial species are selectively preserved, thereby creating a permanent soil cover and promoting biodiversity. Examples of such noble weeds are *Arachis pintoi*, *Commelina* spp. and *Desmodium* spp. [85]. Weed species need to be monitored routinely to identify and eradicate highly aggressive weeds before they can spread or set seed.

Corrective measures

- **Physical control**
  This involves manual trimming of weeds through cutting, mowing or slashing, or complete removal of the weeds by uprooting them. Although the latter option is very labor intensive, it can be effective for controlling highly aggressive weeds when they first appear and before they reach high densities. Slashing and mowing with a machete or mechanical strimmer can control non-perennial weeds effectively or prevent weeds from flowering and seeding. Animals such as sheep or ducks can accomplish the same purpose through short grazing rotations [52]. Recurrent mowing, especially when done during dry spells, can weaken belowground reserves of perennial weeds.

- **Chemical control**
  If the use of chemical herbicides cannot be avoided, the product applied should be as specific as possible to reduce negative effects on non-target species and human health. Spot applications of herbicides on aggressive weeds can optimize chemical use, reducing the number of applications and dosage. The rooting zone of the coffee plants – which is directly proportional to the age of the coffee plants and their canopy diameter – is the main focus area to reduce weed competition for water and nutrients [74]. Another strategy for efficient herbicide use is to combine mowing and application of herbicides on resprouting tissues [86]. Correct dosage, the use of protective clothing as well as proper storage and disposal of the products along with packaging materials are imperative for reducing risk to the environment and human health. Only herbicides that are permitted by sustainability standards should be used, and label directions must be followed precisely.

Box 3.7. Experiences with integrated weed management in Nicaragua

A long-term field experiment was established at Masatepe research station in Nicaragua (700 masl) during the cropping season of 2000–2001 to study IWM in coffee plots. Coffee is grown with shade trees of the species *Inga laurina* and *Simarouba glauca*, combined with selective weed management under conventional fertilization. The pictures below were taken during the rainy and dry seasons.

L. Navarrete.

As a result of selective weed management in the rainy season, *Oplismenus burmannii* provides near complete cover in the interrow, with few other herbs or grasses present. Particular attention to control of vines is very important.

E. Navarrete.

Permanent soil cover with *O. burmannii* in the dry season reduces competition for water, since the herb species dies before coffee plants show signs of water stress. The dry biomass starts decomposing at the beginning of the next rainy season, thereby releasing the nutrients accumulated in the biomass.

What challenges does adoption of the practice pose, and how can these be overcome?

IWM can create significant synergy with other regenerative practices, such as agroforestry, soil conservation and integrated pest management or integrated nutrient management. As a result, farmers who are already transitioning towards regenerative practices may encounter few barriers to the adoption of IWM.

A major hindrance to adoption is the time required to implement this practice fully and reap its benefits. In other words, farmers must be prepared to invest in labor and inputs (e.g., more expensive selective herbicides or small equipment for more selective herbicide application) during the initial stage of implementation, knowing that IWM will not yield immediate benefits (in the form of reduced costs). Careful planning and a good understanding of when to implement IWM are, therefore, key to success. Another challenge to adoption is the knowledge intensity of the practice. Farmers must make the effort to identify and monitor weed species and their abundance in the field, and obtain knowledge of weed species traits through training and experience. To help farmers overcome those challenges, the public and private sector need to invest more in IWM research (including bioherbicides), while providing farmers and technicians with training in IWM techniques as well as with effective decision-support tools.

Further reading and useful tools

Illustrated manuals on noble weed species and IWM in coffee plantations (in Spanish, with many pictures):

- Guía Ilustrativa del Manejo Integral de Hierbas en Cafetales. CATIE and Rainforest Alliance. 2021. https://bit.ly/3oepWx9
- Salazar Gutiérrez LF. 2020.Reconozca las arvenses nobles en el cultivo del café. Avances Técnicos Cenicafé 517. https://doi.org/10.38141/10779/0517

Other technical publications on IWM in coffee (in Spanish):

- Hincapié Goméz E; Salazar Gutiérrez LF. 2007. Manejo integrado de arvenses en la zona cafetera central de Colombia. Avances Técnicos Cenicafé 359. https://biblioteca.cenicafe.org/bitstream/10778/379/1/avt0359.pdf
- Torres Angarita FA; Salazar Gutiérrez LF. 2020. Manejo de arvenses en el cultivo del café: Alternativas de control químico en la zona del plato. Avances Técnicos Cenicafé 520. https://doi.org/10.38141/10779/0520

Insect trap in coffee field, Thailand | Nestlé.

3.4.6. Integrated pest management

Overview of the practice

Integrated pest management (IPM) combines a variety of nature-based solutions for pest and disease prevention and control. IPM requires a good understanding of the life cycles of pests and diseases, and their response to environmental factors. In practical terms, regular monitoring of pest and disease populations is needed to enable timely application of a combination of preventive and corrective actions. Decisions are based on careful assessment, with the aim of keeping pests and diseases below economically significant levels.

Yield losses due to pest and disease outbreaks pose a major challenge for coffee farmers worldwide and are further aggravated by climate change. The most important coffee pests and diseases globally include: coffee berry borer (CBB), coffee leaf miner (CLM), coffee stem borer, root-knot nematodes, coffee leaf rust (CLR) and coffee berry disease (CBD). Recent CLR outbreaks in Central America have reduced coffee yields by 10–55% [5], compared to pre-rust levels. Economic losses have led to widespread food insecurity in this region. In Colombia, the 2008 outbreak of CLR required about 45% of the country's coffee area to be replanted with resistant varieties [5]. In parts of Africa, CBD has been reported to have caused yield losses of up to 90% [87]. Globally, estimated economic losses resulting from insect pests such as CBB exceed US$500 million per year [88].

Some pests and diseases cannot be controlled effectively with pesticides. Moreover, frequent use of pesticides can generate resistance in pests and diseases, reducing the efficacy of chemical control measures over time. There are substantial environmental and human health risks as well. IPM addresses this issue by implementing a range of complementary methods – cultural, physical, genetic, biological and chemical. IPM can be implemented both on farms and in wider landscapes (see Chapter 3.4.11 for further information on landscape actions).

What are the most important benefits?

When implemented correctly, IPM can keep pest and disease incidence below economically important levels. Moreover, rational and timely application of control measures, based on economic and ecological thresholds, can help optimize the use of labor and inputs. IPM can thus offer important benefits to farmers in terms of coffee yields and income. The practice requires farmers to routinely evaluate the local situation, and on this basis, respond and adapt to threats or changes in the system. In this way, IPM can help enhance farmers' resilience to climate change, which is expanding the range of pests and diseases and increasing pesticide resistance. The practice can also act as an early warning system against newly introduced pathogens that expand their range due to climate change.

By prioritizing preventive measures rather than relying exclusively on control, IPM offers multiple benefits. These include reduced health risks for farm workers and less detrimental impacts of pesticides on non-target organisms in the ecosystem. In fact, IPM methods can enhance biodiversity on farms and in landscapes, thus strengthening natural control of pests and diseases, while also enhancing pollination. This cost-effective approach is particularly advantageous in low-input and organic coffee systems.

IPM permits the use of narrow-spectrum pesticides and biopesticides only as a last resort. Sporadic and selective use of lower doses of these products, despite being often more expensive than broad-spectrum alternatives, may require less labor and thus lead to an overall reduction in production costs. This practice can also prevent the development of pesticide resistance in coffee pests and diseases (Figure 3.14).

IPM can be usefully combined with other regenerative practices. Landscape actions, for instance, can enhance the impact of IPM on individual farms. Similarly, agroforestry, natural vegetation along field borders and soil conservation practices can improve microclimatic conditions in coffee plantations or introduce certain plant species that attract natural enemies, thus making IPM more effective. IPM may provide further benefits through synergy with pollination.

IMPACT AREAS	TEN POTENTIAL BENEFITS
Soil health	1 Increased soil biodiversity resulting from less use of harmful pesticides
Water conservation and quality	2 Reduced contamination of surface and ground water with pesticides
Biodiversity and land use	3 Reduction in the harmful effects of pesticides on non-target organisms on the farm and in the surrounding landscape 4 Conservation of biodiversity habitats, which attracts natural enemies, thus enhancing biological control, and favors pollination
Coffee productivity and input use	5 Better and more stable crop productivity and coffee bean quality 6 Less use of chemical inputs 7 Greater awareness of changes in pests and diseases as well as increased capacity to adapt, including to changes caused by climate change
Farm income and livelihoods	8 Less risk of pest and disease populations developing pesticide resistance 9 Reduced yield and income losses due to pests and diseases 10 Lower pesticide-related health risks for farm workers

Figure 3.14. Ten potential benefits of integrated pest management (IPM).

Where should IPM be implemented?

Given the importance of coffee pests and diseases worldwide, all coffee farms (whether large or small and intensively or extensively managed) can benefit from applying IPM. The practice is particularly important for farms that suffer from high incidence or recurrent outbreaks of pests and diseases, and where single control methods have not been successful, or where there is a high risk that diseases or pests may build up pesticide resistance. IPM is highly relevant in Arabica, which is more susceptible to pests and diseases, as well as on farms using traditional, susceptible varieties. Moreover, farms close to conservation areas or waterbodies should adopt IPM to reduce the risk of environmental pollution and possible harmful effects on wild fauna and flora. Those farms can also benefit most from IPM, due to the presence of natural vegetation that can provide additional resources and shelter for sustaining continuous and stable populations of natural enemies.

What should be considered in implementing IPM?

The different components, that need to be implemented when adopting IPM are shown in Figure 3.15. Each step and component is described in more detail in the text below.

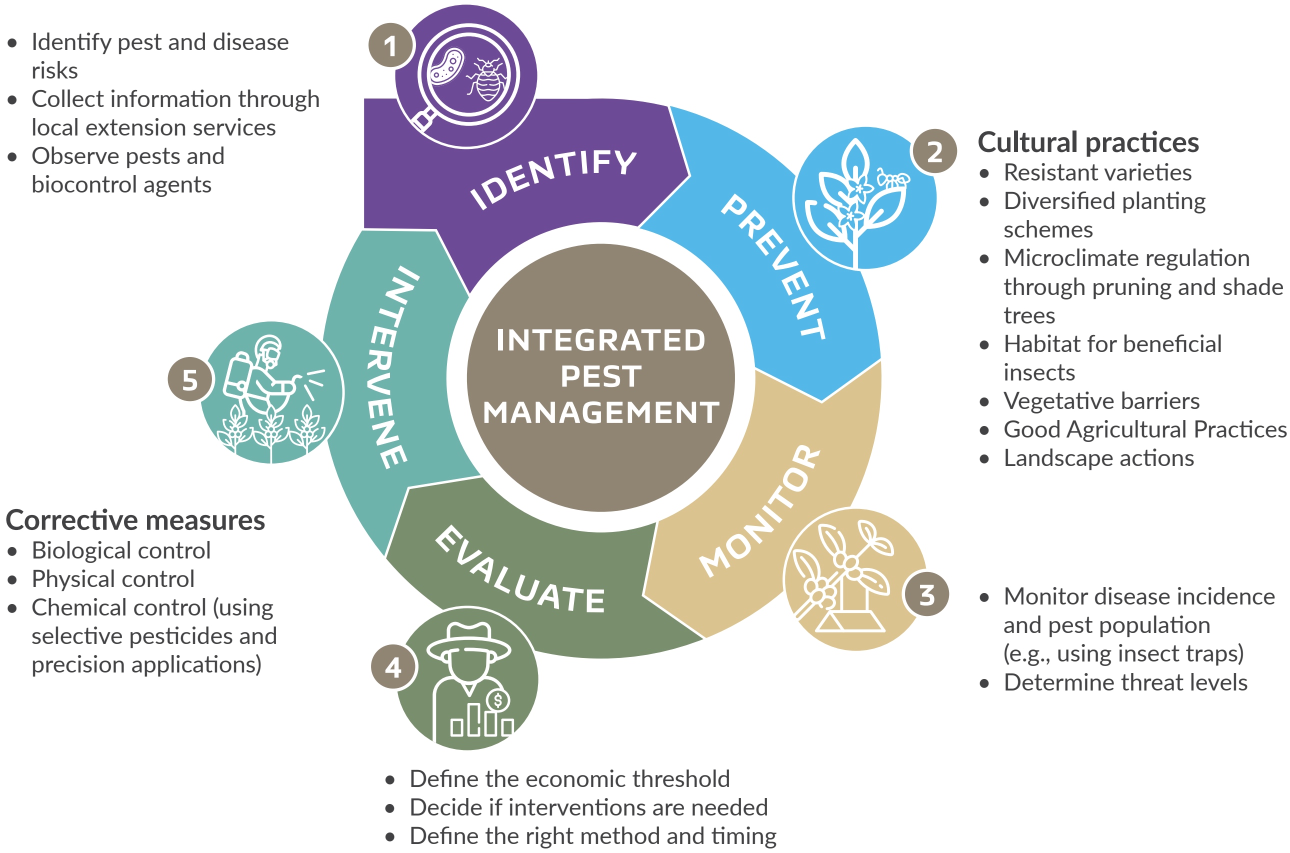


Figure 3.15. Key components of an integrated pest management approach.

A first requirement for successful IPM implementation is for farmers and technicians to **identify (1)** the organisms that constitute potential pest or disease problems in the region. It is also important to obtain information on pest and disease life cycles, including (i) their dispersal and reproduction in relation to the productive cycle of the crop(s), (ii) their response to variation in (micro)climatic conditions, and (iii) their alternative hosts and biocontrol agents. Such information may be available through local extension services.

The next step is to implement **preventive measures (2)**, consisting of cultural practices ranging from the use of resistant varieties, diversified planting schemes, microclimate regulation, and provision of habitat to support natural enemies of pests and diseases. Cultural measures also include Good Agricultural Practices that reduce the risk of pest or disease proliferation, such as removal and appropriate composting of infected plant organs. Effective prevention of some pests and diseases may require interventions beyond the coffee plot, that is, involving the whole farm or landscape (see Chapter 3.4.11).

Field monitoring (3) of pest and disease infestation as well as the presence and activity of biocontrol agents should be done routinely throughout the cropping cycle and combined with data on coffee crop phenology and weather conditions. Alcohol-baited funnel traps are effective for detecting the activity of pest insects and also provide information on their relative abundance over time, thus alerting the farmer about threat levels at any given moment [89]. **Careful evaluation (4)** of the information obtained through monitoring allows farmers to decide whether interventions are needed and choose the method and timing to achieve effective control (see Box 3.8).

Intervention (5) refers to the implementation of corrective measures, which includes physical, chemical and biological control. Decisions about such interventions should be based on routine field monitoring. Corrective control measures should be implemented when the threat exceeds the economic threshold, that is, when potential yield losses outweigh the cost of control. The economic threshold depends on the context, specifically pest or disease incidence, the availability of resources to support their growth (e.g., the presence of coffee cherries for CBB), the presence and abundance of natural enemies, and climatic conditions. The economic threshold also depends on coffee prices and labor costs. Chemical controls should be applied only as a last resort, since they can cause problems, such as negative environmental impacts, development of pesticide resistance and unwanted chemical residues on products (Figure 3.15).

Methods for preventive (cultural) control

- **System design**
  - Select resistant or tolerant, certified planting materials for coffee establishment or renovation. Preferably use seedlings or plantlets produced in protected nurseries with uncontaminated (e.g., nematode-free) growing media. See also Chapter 3.4.1.
  - Use the right planting design. The structure of the plantation in terms of horizontal and vertical spacing and the shade density affect pest and disease proliferation by altering microclimatic conditions [90]. For instance, moist and shady conditions have been shown to reduce the incidence of insect pests such as CLM, while increasing that of fungal pathogens [91].
  - Preserve and enhance native populations of natural enemies in coffee farms: birds, lizards, ants, lady beetles, mites, predatory and parasitoid wasps, and beneficial microorganisms can help control coffee pests and diseases [92-94]. This requires protecting natural habitats on farms or enhancing the habitat quality of the coffee production system. These measures strongly complement other regenerative practices, such as agroforestry, intercropping, cover cropping and integrated weed management. Selective conservation of noble weeds, intercropping and cover crops can be helpful when the species provide resources for beneficial insects. Shade trees can also favor the abundance of natural control agents, such as predatory ants that reduce CBB [95]. Shade trees have further been found to enhance the suppression of insect pests by *entomopathogenic fungi* [96].
  - Create alternative or additional habitats for natural enemies around coffee fields. Flower strips and hedgerows provide shelter and nesting resources for natural enemies together with

complementary food sources, such as nectar and alternate prey [97]. It is important that these flowers have accessible nectar for parasitoids. They can be plants with open nectaries as is common in Apiacaea or plants with extrafloral nectar, such as faba bean.

- Trees in or around coffee fields can act as barriers to spore dispersal for diseases such as CLR and CBD [98] by reducing the splash effect from raindrops as well as wind speed. However, those effects depend greatly on tree characteristics, such as canopy shape, height and leaf characteristics [99]. Moreover, high humidity from excessive shading favors fungal diseases, highlighting the need for careful agroforestry design and management where diseases are of concern.

- **Good Agricultural Practices**
  - Coffee plants possess natural defenses against pests and diseases. So, it is key to promote plant health by reducing nutrient, water and heat stress. Management of shade trees, integrated nutrient management (INM), and soil and water conservation enhance plant resistance, significantly overlapping with other regenerative practices.
  - Both coffee and shade trees should be pruned regularly to maintain optimal microclimatic conditions and prevent excessive humidity.
  - Sanitary harvest involves removing damaged or diseased plant tissue and overripe fruits. Other important sanitary measures are to clean pruning tools and seal wounds. In some cases, it may be necessary to uproot and dispose of diseased trees. Composting is preferred over burning, provided that adequate temperatures are achieved during composting to eliminate diseases.

Methods for corrective control

- **Biological control methods**
  - The introduction of specific biocontrol agents, such as *microbial inoculants* or releasing beneficial insects. This has been done successfully with fungi and bacteria such as *Trichoderma* and *Bacillus*, to control CLR [100,101], as well as with different entomopathogenic fungi such as *Beauveria bassiana* to control CBB [102]. Biological control strategies for CBB include the release of exotic parasitic wasps in coffee plantations [89]. The effectiveness of the method varies, depending on inoculum quality, the timing and efficiency of application, and survival of the introduced organism under field conditions.
  - The application of biopesticides, derived from plant tissues, microbes or insects (e.g., pheromones). These products can be produced locally or obtained commercially. Neem oil (*Azadirachta indica*) and castor bean oil (*Ricinus communis*) have been used to control CBB [89,103].
  - The use of companion plant species that either attract or repel insect pests in a push-pull strategy. This has proved promising for CBB management [104].

- **Physical methods**
  - Different types of traps – mechanical, light, pheromone or alcohol – may be used for this purpose. They may contain chemical substances that attract or repel insect pests in a push-pull strategy [[105]]. The timing of installation is important; for example, to control CBB populations, traps should be placed during peak cherry production, when females leave the berries.
- **Chemical methods**
  - Pesticide use may sometimes prove indispensable. But regenerative agriculture requires that it be kept to a minimum:

    i. Selective pesticides should be used whenever possible; broad-spectrum pesticides should be avoided.

    ii. The need for pesticides as well as the timing and location of their application should be assessed carefully, based on routine field monitoring. Precision application to control early infection is preferred.

    iii. Correct dosage, the use of protective equipment as well as proper storage and disposal of pesticides are imperative to avoid human health risks.

    iv. Only pesticides meeting sustainability standards should be used (e.g., Rainforest Alliance and 4C).

    v. Directions for usage, as described on the label, should be followed precisely.

Trybomia sp. feeding on extrafloral nectar of *Inga* trees | M.Venzon (CC-BY 4.0).

Formicidae feeding on extrafloral nectar of *Inga* trees | M.Venzon (CC-BY 4.0).

Table 3.5. Characteristics of common coffee pests and diseases, their life cycle, and responses to environmental factors.

Modified from Staver et al. [82]. Suggested IPM methods are based on the scientific literature, as indicated in the first column.

NAME AND SCIENTIFIC REFERENCE(S)	SPATIAL DISTRIBUTION	VISUAL FEATURES FOR DIAGNOSIS / IMPACT	LIFE CYCLE	RESPONSE TO ENVIRONMENTAL CONDITIONS	SUGGESTED IPM METHODS
Coffee berry borer (CBB) *Hypothenemus hampei* [89,106]	Most coffee-growing regions worldwide.	Small holes (1 mm) on berries and sometimes white larvae.	Females lay eggs inside berries >120 days old. The entire life cycle occurs within the berry and takes 25 days.	High relative humidity (after rainfall) and high temperature stimulate female emergence.	• Over-ripe, dry berries are a main reservoir for infection, so their removal from the ground and branches is crucial. • Shade can support the presence of natural enemies (ants and parasitoid wasps), while enhancing the effectiveness of biocontrol with entomopathogenic fungi. • Timely insecticide use is effective, when direct contact with adults is ensured. • At 2% infection rates, spraying with *Beauveria bassiana* can be effective, especially after harvest during female emergence from berries. *B. bassiana* is most effective at high humidity levels.
Coffee leaf miner (CLM) *Leucoptera coffeella* [107,108]	Latin America and the Caribbean, East Africa.	Irregular brown spots or paths on the leaves made by small, white caterpillars.	Larva feeds on coffee leaves. Cycle takes 22 days to adulthood. Adults are nocturnal moths.	Attacks are more severe in dry periods and with higher temperatures.	• Neuro-insecticides used to control CLM are non-specific as well as highly persistent and generate resistance. • Botanical alternatives, such as insecticides based on *Azadiracta indica* (neem), are highly effective. • Ecologically complex coffee systems with diverse vegetation promote abundance of parasitoid wasps and ants that control CLM. • Entomopathogenic fungi, such as *Metarhizium anisopliae* and *B. bassiana*, can be sprayed to control CLM populations. • Pheromonal traps can be used.
Coffee leaf rust (CLR) *Hemilleia vastatrix* [109]	Most coffee-growing regions worldwide (mostly on Arabica).	Yellow-orange-brown spots on the underside of leaves. Heavy infections can lead to complete defoliation and die-back.	Latent fungus infection occurs during the wet season and sporulation during the dry season.	High humidity and hot temperatures induce sporulation. Spores are dispersed by rain splash (especially unseasonal rain) and wind.	• The use of resistant varieties is the main mean of control. • Shade management and pruning during the wet season reduce leaf wetness. • Shade trees can reduce rain splash dispersal of spores. • Biological control with fungi and bacteria such as *Trichoderma* and *Bacillus subtilis* can be effective. • Control with fungicides can be costly, and farmers should consider the secondary impact on beneficial fungi (e.g., entomopathogenic) as well as the risk of developing resistant disease strains when using a single active substance.
Coffee berry disease (CBD) *Colletotrichum kahawae* [110,111]	Worldwide.	Dark brown-black sinking spots on green berries.	Fungus can infect all plant parts, but most losses are due to attacks on green berries. Inoculation period varies between 5 days and 3 weeks.	Low temperatures (20°-22°C) and high humidity favor disease development.	• Resistant varieties are available. • Manual removal of diseased berries is crucial. • Shade management and pruning reduce leaf wetness and infection. • Biological control with antagonistic fungi is possible, but no commercial inoculants are available. • Control with fungicides is not recommended due to the high cost, impact on beneficial fungi (e.g., entomopathogenic) and risk of developing resistant disease strains. • Application of Bordeaux Mixture can be effective.

NAME AND SCIENTIFIC REFERENCE(S)	SPATIAL DISTRIBUTION	VISUAL FEATURES FOR DIAGNOSIS / IMPACT	LIFE CYCLE	RESPONSE TO ENVIRONMENTAL CONDITIONS	SUGGESTED IPM METHODS
Root-knot nematodes *Meloidogyne* spp. [112]	Worldwide.	Nematode infestations can be diagnosed by identifying root galls in plants when leaves are yellowing and drooping, and beans ripen early or are aborted. Blue-black discoloration of wood below the bark is also a sign.	Females lay eggs in soil, and hatching juveniles migrate towards the coffee plant, entering the root tip. Once inside, they become sedentary and feed. Nematodes grow within roots, causing the formation of root galls. Eventually, males emerge.	Life cycle is accelerated at high temperatures (28°-32°C) and favored by high rainfall.	• Nematodes are hard to eradicate; the best way is through green fallow with a non-host species such as *Crotalaria*. • Nematicides are very toxic and expensive but usually do not resolve the problem. • Renovation can be effective, using tolerant rootstock material, mainly from Robusta and Liberica/Excelsa. • Infected plants should be immediately uprooted and burned. • Digging furrows can help prevent nematode migration downhill from infected areas through runoff. • Biological control has been used successfully with *Pasteuria penetrans*. • The right intercropping archetypes and clean planting material are important. • Water used for irrigation must be free of nematodes.
Coffee stem borer - *Monochamus leuconotus* White coffee stem borer - *Xylotrechus quadripes* [113–115]	Africa, Asia.	Ridges around the stem, wilting, and yellowing. Circular exit holes.	Females lay eggs under the bark scales; they prefer Arabica with rougher bark. Early on, larvae feed on cambium and later start boring galleries in the stem. The larval stage lasts 20 months and the full life cycle up to 24 months. Some wild Rubiaceae plants can act as alternate hosts.	Higher infestation is reported under shade and at altitudes above 1500 masl, due to better temperature regulation. They are sensitive to cold temperatures. Egg laying and emergence peak during the rainy season.	• Care should be taken, since larvae can spread through cut coffee wood. Diseased plants should be uprooted and burned. • Control efforts should be targeted during the rainy season. • Manual control can be done during adult emergence, or stem bands with insecticides can be used. • Biological control has been used successfully with *B. bassiana* but requires direct contact with adults. • Grafting onto Robusta rootstock is an alternative prevention method. • Little is known about natural enemies.

Box 3.8. An example of IPM – The case of CBB

Life cycle and response to environmental conditions

All stages of CBB occur within the berry, and the insect's life cycle can only be completed in coffee plants. Females lay their eggs within the berry; although they may infect younger berries, they can only reproduce successfully in fruits older than 120 days or with >20% dry weight. Higher temperatures and relative humidity accelerate the reproductive cycle. Overripe and fallen berries act as the main source of infestation, which can promote CBB reproduction during the dry season or in full sun-grown coffee systems.

Suggested control strategy

The strategy depends on weather conditions and system design because of complex interactions between environmental conditions and the CBB reproductive cycle. The following practices are recommended:

1. **Tracking *plant phenology*:** Time of flowering is essential to predict CBB outbreaks. In Arabica, the critical period for infestation begins in the first 120 days after flowering. Non-synchronous flowering throughout the year provides a constant source of infestation.

2. **Monitoring pest populations:** Mapping incidence can help identify focal points of infestation on the farm. CBB can be monitored by using alcohol traps and counting of infected berries. Alcohol traps make it possible to detect when CBB adults are emerging from beans and to identify areas where outbreaks are most severe.

3. **Cultural/sanitary control:** Removing overripe and CBB-infested cherries from the ground and branches between harvest periods is crucial (sanitary harvest). Diseased berries can be buried (at least 10 cm deep), placed in hot water or dried at 55°C for an hour. Females can escape harvested coffee and return to the field, so postharvest measures are necessary (e.g., emptying containers, sealing coffee bags and processing beans quickly).

The following corrective methods may be taken once infection rates rise above 2%:

1. **Biological control:** Release of CBB natural enemies, such as entomopathogenic fungi (including *Beauveria bassiana* and *Metarhizium anisopliae*), has been successful. Several formulations of commercially available spores are environmentally safe and non-toxic to workers. The effectiveness of this method can vary, depending on inoculum quality, the strain, concentration, application efficiency and microclimatic conditions at time of application. The best time for application is shortly after harvest, when adult females emerge from the beans. The persistence of *B. bassiana* under field conditions is relatively short (<6 months), so it requires re-application. The use of entomopathogenic fungi should not coincide with fungicide applications to treat foliar diseases such as CLR.

2. **Chemical control:** The only time CBB is exposed is when the insects leave the bean where they were born to find a new one, so there is a narrow window for insecticides to be effective. Insecticide applications to control one pest may eliminate the predators of another, resulting in unchecked growth of a pest population that had previously been biologically controlled.

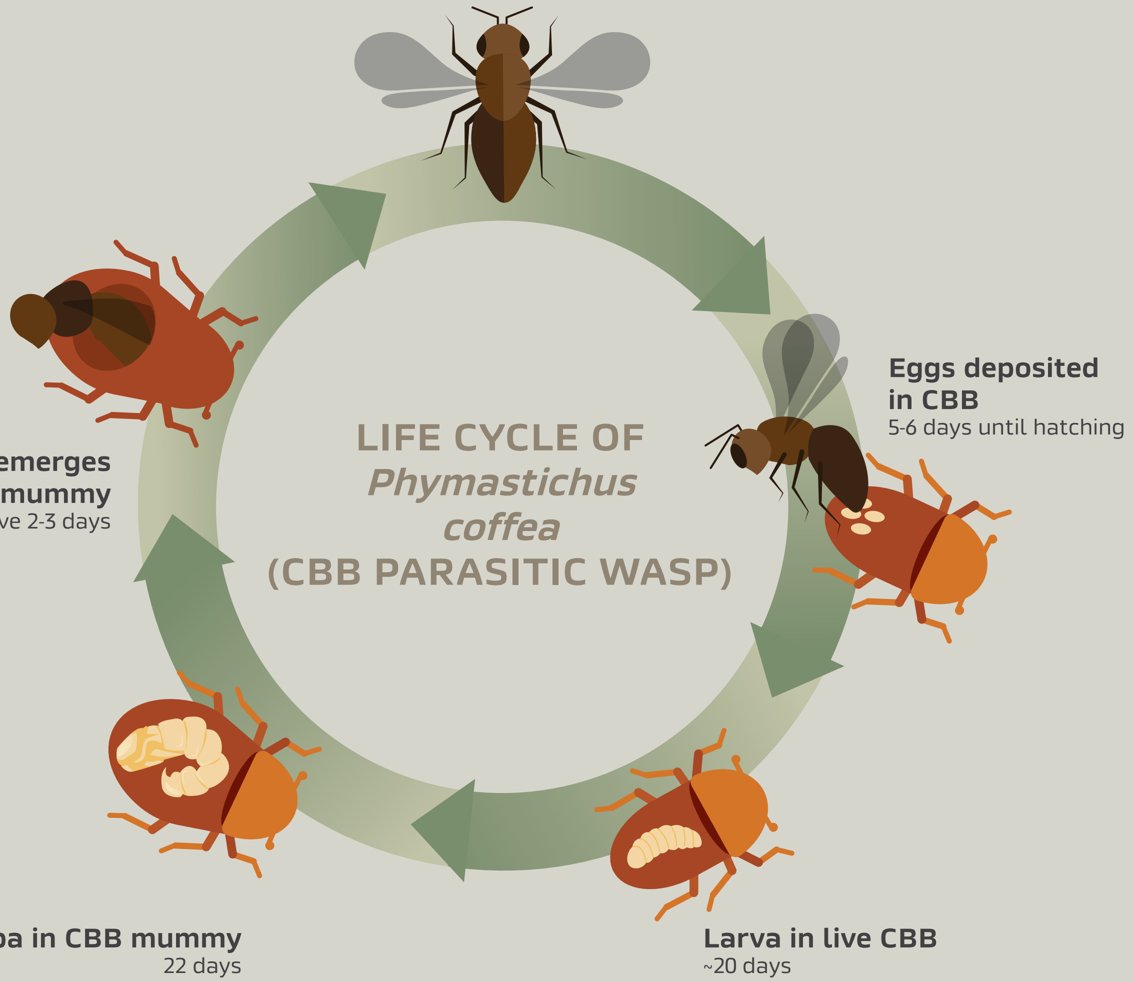


Figure 3.16. The life cycle (egg to adult) of *Phymastichus coffea*.

P. coffea is an effective parasitic wasp of CBB (*Hypothenemus hampei* (Ferrari)) at a mean temperature of 23.2°C. The larvae feed on adult coffee berry borer, causing beetle death before it can penetrate the coffee berry and lay eggs thus preventing damage to berries.
Based on Espinoza et al. [116].

Because CBB spends most of its life cycle inside the coffee bean, the efficacy of corrective control is limited. Therefore, farmers should consider long-term **preventive control** based on **systemic measures**. Large, continuous areas under coffee cultivation facilitate the spread of CBB. Forest patches between coffee fields are especially effective at preventing CBB dispersal. Natural enemies of CBB include parasitoids, such as *Cephalonomia stephanoderis*, *Prorops nasuta* and *Phymastichus coffea* (Figure 3.16); different species of predatory ants; and entomopathogenic nematodes, among others. Conservation practices that promote biodiversity and improve microclimatic conditions (such as the use of shade trees, intercropping and natural vegetation around field borders) can enhance the potential for control by natural enemies in their native range. Different African species of parasitoids have been introduced to Latin America. The establishment and level of CBB control achieved with these exotic parasitoids has been variable, depending on local agroecological conditions.

Sources: Njihia et al. [105], Aristizábal et al. [89, 106], Armbrecht and Gallego [95], Castro et al. [104], Lemma and Abewoy [110], Espinoza et al. [116], Escobar-Ramírez et al. [117].

What challenges does adoption of the practice pose, and how can these be overcome?

The main challenge in promoting adoption of IPM is that it requires a deep understanding of both pest and disease ecology as well as their natural biocontrol agents. Fortunately, only a limited number of pests and diseases significantly affect coffee yields in particular regions. Moreover, these organisms have been the subject of much scientific research, as is the case with CBB and CLR. It is crucial for farmers and agricultural advisors to receive technical training either through local research organizations or public institutions.

In addition, limited access to labor may limit the implementation of cultural control methods as well as routine monitoring. For example, while alcohol-baited traps are effective for monitoring, they may capture large numbers of native non-target insects. Sorting and identifying specimens may thus prove tedious.

Finally, IPM does not offer one-size-fits-all solutions. Biological control is a long-term strategy that relies on adequate production system design, and its benefits take time to materialize. In managing field conditions to inhibit pest and disease reproduction, it is often necessary to strike a delicate balance, as with shade levels, and this may entail trade-offs, since methods used to control one pest or disease might create a beneficial habitat for another. Ecological balance can be especially difficult to maintain in highly disturbed or altered environments, where the success of biological control partly depends on landscape dynamics, which are beyond the control of individual producers.

Coffee berry borer, Colombia | CIAT/N. Palmer.

Further reading and useful tools

Free online tool to discover natural, registered biocontrol and biopesticides around the world:

- The CABI BioProtection Portal https://bioprotectionportal.com

Simulation tool, developed by CATIE, that computes interactions between disease, host, cropping practices and weather to forecast the risk of CLR:

- Motisi N et al. 2022. Improved forecasting of coffee leaf rust by qualitative modeling: Design and expert validation of the ExpeRoya model. Agricultural Systems 197. https://doi.org/10.1016/j.agsy.2021.103352
- Software and manual ExpeRoya. https://www.redpergamino.net/app-experoya

Technical publications on IPM and biological control of coffee pests and diseases (in Spanish):

- Benavides Machado P; Góngora CE. (Eds.). 2020. El control natural de insectos en el ecosistema cafetero colombiano. Cenicafé. https://doi.org/10.38141/cenbook-0001
- Constantino LM et al. 2011. Minador de las hojas del cafeto: Una plaga potencial por efectos del cambio climático. Avances Técnicos Cenicafé 409. https://publicaciones.cenicafe.org/index.php/avances_tecnicos/issue/view/374
- Gil Palacio ZN et al. 2021. Dispersión de la broca del café. Avances Técnicos Cenicafé 531. https://publicaciones.cenicafe.org/index.php/avances_tecnicos/article/view/100/67

Coffee pulp applied to coffee plants in intensively managed large-scale plantation, Zambia | Wageningen University/K.Giller.

3.4.7. Integrated nutrient management

Overview of the practice

Integrated nutrient management (INM) emphasizes the efficient and balanced use of mineral fertilizers along with the management of organic resources to ensure optimal crop nutrition, sustain soil health and minimize negative environmental impacts. The loss and removal of nutrients during crop production and harvest, with little or no replacement in the form of nutrient inputs (see Figure 3.18), will depress crop productivity and reduce soil nutrient stocks over time. Excessive fertilization, on the other hand, results in high nutrient losses, leading to eutrophication of water bodies and contributing significantly to the carbon footprint of coffee farming. Fertilizer also accounts for a significant part of most coffee farmers' production costs, underscoring the economic importance of INM.

Key components of INM include: (i) addressing constraints that limit crop response to fertilization, such as soil acidity, aging of coffee plants and shade density; (ii) balanced and efficient fertilizer use based on the 4R concept (right source, right rate, right time and right place); and (iii) management of organic resources to improve soil health and stimulate biological nutrient cycling. In line with the principles of *circular agriculture*, INM seeks to recycle nutrients from residue and waste streams generated on and around the farm. Agroecological conditions (such as soil type, topography and climate), production practices and the age as well as phenological stage of the coffee plants all have a strong effect on nutrient requirements, and this should be taken into account when making fertilization plans.

Fertilizers should be applied in accordance with local recommendations from extension services and should ideally be based on regular soil (and foliar) analyses and/or *nutrient balance* calculations. A nutrient balance approach estimates inputs and outputs of nutrients from the system. The difference between nutrient outputs and inputs, together with the quantity of nutrients required by the plant to grow, needs to be replaced to prevent nutrient depletion in the soil system (Figure 3.18).

NB: It is beyond the scope of this guidebook to describe in detail crop nutrition and soil fertility management in coffee. For background information on the different macro- and micro-nutrients required during different stages of crop development, along with their sources and dynamics in agroecosystems, see the section "Further reading and useful tools".

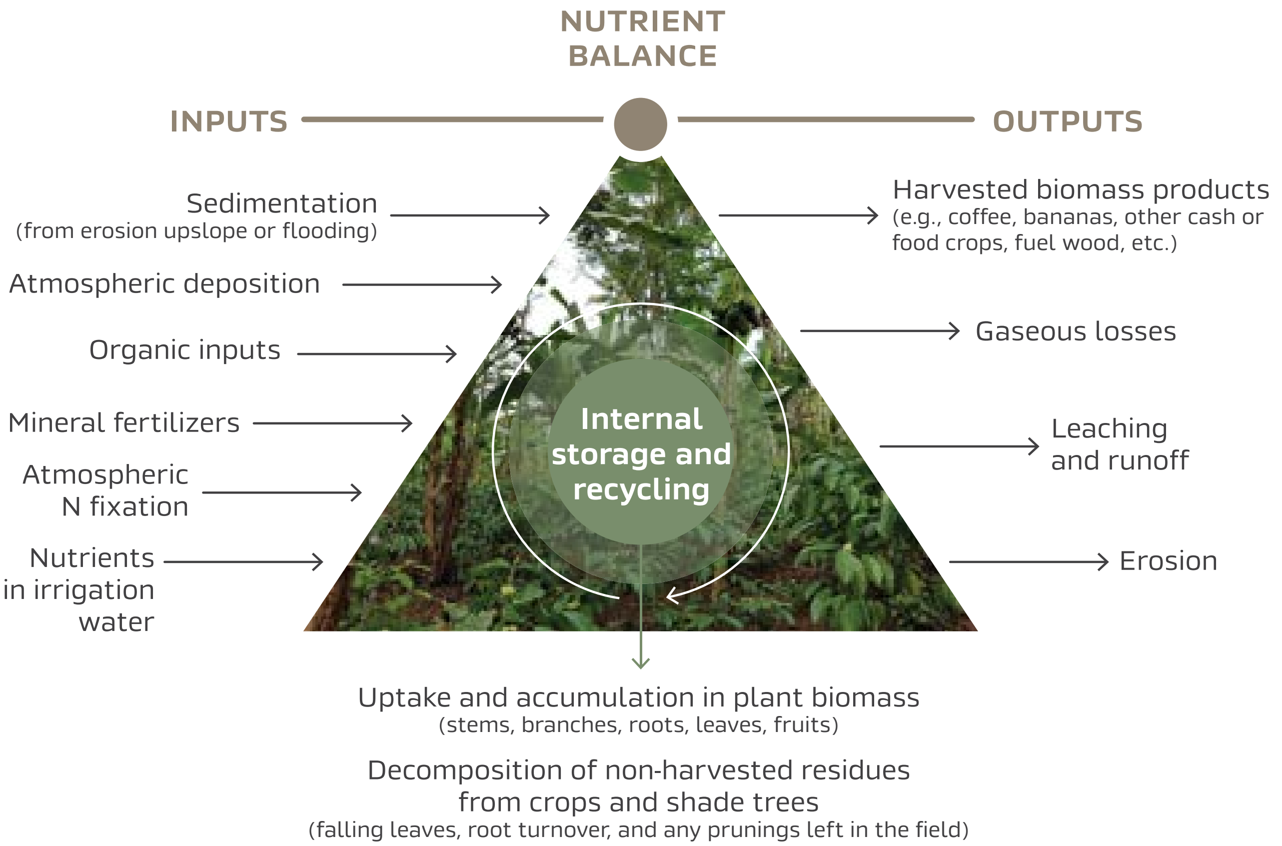


Figure 3.18. The main nutrient inputs and outputs in coffee production as well as internal nutrient flows within the system.

What are the most important benefits?

INM is crucial for the agronomic performance as well as the environmental and economic sustainability of coffee production (Figure 3.19). As with other regenerative practices, knowing the baseline farm conditions is critical for determining what benefits INM can offer farmers. For low-input coffee farms, this means addressing nutrient deficiencies and increasing soil fertility to boost productivity and profitability. In contrast, on high-input coffee farms with high yields, INM can lower production costs through more efficient use of fertilizers. Many coffee-producing countries rely on relatively expensive, imported fertilizers. By improving nutrient cycling and reducing dependence on these inputs, INM can enhance farm resilience against changes in agricultural policies and currency exchange rates as well as geopolitical crises.

The practice also offers important environmental benefits. INM reduces nutrient losses from volatilization and leaching, thus protecting water quality and biodiversity on the farm and in the surrounding landscape. INM is particularly important for reducing the carbon footprint of coffee production, as the production of mineral nitrogen fertilizers is energy intensive and their application to soil can generate significant nitrous oxide (N_2O) emissions [15,120].

Lastly, INM improves soil health over time through efficient and balanced use of fertilizer inputs, combined with organic resources and soil amendments to alleviate soil acidification, where needed. The practice can also help gradually build up soil carbon stocks through the use of cover crops and organic inputs. It takes several years, however, for a measurable increase in soil carbon to be realized. Whether INM effectively contributes to carbon removal through soil carbon sequestration depends directly on the origin and quality of the organic inputs used and indirectly on whether INM leads to increased plant biomass production, which in turn leads to higher plant residue inputs into the soil (see Chapter 3.4.10).

IMPACT AREAS		TEN POTENTIAL BENEFITS
Soil health	1	The combined use of mineral fertilizers and organic resources helps stimulate nutrient cycling and retention
	2	The use of organic resources, such as crop residues, cover crops and organic soil amendments, helps improve soil structure and soil life
Water conservation and quality	3	Enhanced nutrient cycling and retention reduce contamination of water bodies with excess nutrients
	4	Improvements in organic resource management can positively affect soil water retention through soil cover or improved soil structure
Biodiversity and land use	5	Reduced contamination of soils and water bodies with excess nutrients limits *eutrophication*, thus helping protect wild biodiversity on farm and in the surrounding landscape
Greenhouse gas mitigation	6	GHG emissions due to the production and application of mineral nitrogen fertilizers are reduced
	7	Organic resource management may contribute to soil carbon sequestration, depending on soil conditions at the baseline and on the type and source of organic matter
Coffee productivity and input use	8	Higher coffee yields can be obtained on low-input farms
	9	High-input farms may reduce their fertilizer use
Farm income and livelihoods	10	The practice enables farmers to boost profitability, while reducing dependance on imported fertilizers (and vulnerability to associated price fluctuations)

Figure 3.19. Ten potential benefits of integrated nutrient management (INM).

Where should this practice be implemented?

INM is important for all coffee farms, regardless of their size and management intensity. The practice is especially necessary for coffee farms on soils that are degraded or naturally poor or acidic as well as for organic or low-input coffee farms. Coffee farms where low levels of inputs are used, especially those lacking shade trees and soil cover, and occupying steep slopes, are at high risk of soil nutrient depletion, leading to low or declining crop yields [121]. Since INM helps reduce nutrient runoff and leaching, the practice should also receive high priority in vulnerable watersheds with intensive coffee farming, which are prone to reduced water quality and biodiversity loss resulting from high nutrient loading.

The economic and environmental benefits of INM are not restricted to intensively managed farms with high production levels. As reported by Van Rixkvoort et al. [15], fertilizers are often wasted on farms and their application provides no substantial yield benefits, because yields are limited by other constraints, such as high soil acidity, excessive shade, low water availability, or the age of the coffee plants. In such cases, there is great potential for a more efficient use of fertilizer inputs, provided that the constraints that limit the fertilizer response of coffee plants are addressed.

What should be considered in implementing INM?

The key components of an INM approach can be described as follows:

1. Alleviation of local constraints that limit crop response to nutrient inputs

For INM to be implemented successfully, it is essential to address factors that limit crop response to fertilizer applications [27]. This means that INM is highly compatible with other regenerative practices, such as the renovation of unproductive coffee trees and the use of well-adapted varieties and adequate planting densities (Chapter 3.4.1), agroforestry management with adequate shade levels (Chapter 3.4.2), and integrated weed and pest management (Chapters 3.4.5 and 3.4.6). Soil conservation measures (Chapter 3.4.4) are also a basic prerequisite for efficient fertilizer use and reduced nutrient losses.

Strong soil acidity and soil compaction or degradation caused by previous land use can also limit crop response to fertilizer applications. The implementation of INM should thus begin with the identification of local soil constraints that limit root growth and the availability of nutrients to the crop, such as waterlogging, compaction, acidity and phytotoxicity. Though soil analysis can help identify certain constraints, visual observation of the prevailing soil conditions is particularly important.

Strong soil acidity (pH <5) is a common constraint affecting fertilizer effectiveness across coffee-growing regions. It reduces the availability of several nutrients, especially P, Ca and Mg. In some cases, it can also cause Al and Mn toxicity to plants, with negative effects on root development and crop productivity. Liming is generally effective for raising the pH of acidic soils, while mitigating Al and Mn toxicity and providing Ca and Mg. Raising the pH also increases biological activity in the soil, and hence the availability of N and other nutrients derived from the decomposition of soil organic matter (SOM), as well as the rate of biological N fixation. Changes in soil fertility resulting from the incorporation of lime before sowing can persist for several years. Using the right dose and application method is important, as over-liming can cause deficiencies of some micronutrients, such as Fe and Zn. Liming can also increase the carbon footprint by increasing emissions of N_2O from soil as well as CO_2 and other GHGs associated with limestone extraction and transportation [122]. An alternative to liming is to buffer extreme soil pH by raising the SOM content using either organic amendments (such as compost) or cover crops. These strategies may also reduce soil compaction, improve rooting patterns, raise SOM content and enhance soil biological activity [57].

2. Balanced and efficient fertilizer management using the 4R concept

INM aims to satisfy the nutritional requirements of coffee plants and other crops in the system, while sustaining soil fertility and future productivity. Fertilization schemes can include mineral or organic fertilizers, or a combination of the two. The right rate of fertilizer application depends on the soil nutrient supply, and varies with climate and terrain conditions, tree age and the type of production system. Fertilization schemes should be developed in accordance with local recommendations from extension services and supported by regular soil (and foliar) analysis (see Box 3.9). Fertilization should also be adjusted according to farm and crop characteristics, such as the age and phenological stage of the trees as well as planting density, shade management, and quantity and distribution of rain, among other factors [123]. For example, Robusta generally has higher yield potential than Arabica and thus higher nutrient needs. Similarly, coffee plants in monoculture have higher nutrient requirements than shaded coffee, due to lower harvestable yields as well as improved nutrient cycling and soil health in the latter. Finally, coffee and fertilizer prices are another important factor that farmers need to consider when deciding on fertilization rates and products.

Chemical soil analysis is the main diagnostic tool to assess the soil's nutritional status and to inform decisions about INM. The results give an indication of which nutrients are likely to be limiting plant development, which are sufficient and which are available in excess, potentially causing plant toxicity or harming the environment (see Box 3.9) [124]. Techniques that can provide complementary information include the assessment of visual symptoms of nutritional deficiencies in the plant and foliar analysis, as well as the use of tools that help to estimate nutrient requirements based on nutrient balance calculations [124,125].

The 4R nutrient stewardship concept [119] provides important guidelines for using fertilizers in ways that maximize crop uptake and minimize losses to the environment. These guidelines refer to the source, rate, time, and place of fertilizer applications, considering site-specific factors that affect the efficiency of fertilizer use. They are particularly relevant for fertilizers that are applied in large quantities and are very mobile and thus easily lost to the environment through leaching and/or volatilization. This is especially the case for N, which is often the most limiting nutrient that affects coffee yields and is also a key factor affecting the carbon footprint of coffee production [15]. The type of N fertilizer further affects the balance between volatilization losses and leaching. In the case of urea, losses through volatilization are greater, whereas nitric sources, such as nitrate calcium, magnesium nitrate and ammonium nitrate, are more prone to leaching. The net effect on fertilizer-use efficiency and coffee production may be the same when urea or ammonium nitrate is used, but the implications for water quality versus GHG emissions differ [123].

Using fertilizer in coffee plantation. Thailand | Nestlé.

Box 3.9. Soil and foliar testing to inform locally adapted fertilization schemes

Soil testing generally includes chemical parameters, such as soil pH, organic matter content (as an indicator of soil N stocks), *cation exchange capacity* (CEC), macro (P, K, Ca, Mg and S) and micronutrients and Al availability. *Soil texture* (clay, silt and sand content) may be included, as these are important in determining the risk of nutrient leaching, which needs to be considered when scheduling fertilization. In addition to conventional laboratory analyses, spectroscopic techniques, such as NIRS and MIRS, have been used successfully to estimate some soil properties, such as organic C and total N content, provided that reference libraries are available to allow for reliable predictions [126]. Soil testing must be done at the right time (at least 3-4 months after the last fertilization) and repeated regularly (every 2 to 3 years). The use of proper sampling protocols is also critical for ensuring that results are representative of the specific plot or farm; large, heterogeneous farms require multiple tests.

Soil test results are interpreted based on definable levels of individual nutrients in the soil, below which crops respond to the application of fertilizers with a certain probability and above which there will be no response. Farmers may need support from an agronomist trained in INM to generate a fertilization plan that takes into account farm and crop conditions and yield potential. Ideally, the soil test interpretation should take into account reference values from calibration studies performed in coffee systems, but those are not generally available across coffee regions.

Foliar analysis may be included for a complete diagnosis that provides more detailed information on plant uptake and nutrient deficiencies [125]. Nutrient concentrations in leaf samples generally reflect deficiencies in the soil but can also result from physiological factors, including biotic and abiotic stresses that affect plant nutrient uptake and distribution at a particular time. As a rule, leaves that have recently reached maturity (the third or fourth pair of leaves) should be collected for analysis. Sampling is recommended 6 months before the main harvest [123].

Soil test kits can provide smallholder farmers with low-cost assessments in the field. Such kits are of particular interest as an educational tool [127].

For further information about soil testing and interpretation, see “Further reading and useful tools”.

Using soil testing kits in the field. Thailand | Nestlé.

The 4R concept focuses on optimizing fertilizer-use efficiency and effectiveness by applying the "right source of nutrients, at the right rate, at the right time and in the right place" [119]. The following guidelines apply:

Right source

"Right source" means matching fertilizer composition to crop needs and soil characteristics. Balancing fertilizer application according to the various macro- and micro-nutrient needs is a major challenge for improving nutrient-use efficiency, since plant nutrient demand varies at different physiological stages and depends on the availability of nutrients in the soil. For acid soils (pH <5.5), the use of products that can acidify the soil, such as ammonium-based fertilizers, should be avoided.

Right rate

"Right rate" means matching the quantity of fertilizer applied to the needs of the crop, taking into account the age of the plants, target yield, crop residue or cover crop management, and the presence of shade trees or associated crops, among other factors. Adding too much fertilizer leads to losses to the environment and also represents an economic loss. The challenge is to find the right balance between crop needs, environmental risks and cost-benefits for the farmer. For this purpose, it is important to keep in mind the law of diminishing returns (i.e., the relation between the amount of nutrient applied and the resulting increase in crop yield) [119].

Right time

"Right time" means ensuring that nutrients are available when the crop needs them. Ideally region-specific and weather-based coffee crop calendars, indicating the optimal timing of field operations, are used to aid farmers and advisors synchronizing fertilizer application with plant demand.

Some fertilizers, such as ammonium nitrate, urea and magnesium sulfate, are highly soluble in water and are readily available to plants, but with the risk of leaching and, in case of nitrogen, volatilization. Splitting applications is required to reduce losses. Additionally, the use of slow and controlled release fertilizers, or nitrification inhibitors can be used to slow down the release of nutrients. A key consideration is the soil's capacity to retain nutrients. More split applications may be needed for sandy soils – especially in high-rainfall areas – soils with low SOM content and soils on steep slopes. It is also important to consider weather conditions, seasonal variations and climatic phenomena such as La Niña and El Niño when timing fertilizer applications.

Organic inputs generally release nutrients more slowly, as decomposition by microorganisms is required for the nutrients to become available for plant uptake. Therefore, synchronizing nutrient release with plant uptake tends to be more challenging for organic fertilizers.

Right place

"Right place" means applying nutrients precisely where crops use them. Fertilizer placement can improve fertilizer-use efficiency significantly. In coffee production, this means:

- Applying fertilizers in the rooting area of coffee trees, using the size of the coffee canopy as guidance.
- Covering the fertilizer to limit potential losses. This recommendation may pose some limitations in coffee production, as fertilizers are mostly applied on the soil surface without incorporation and a dense litter layer may be present.
- Adjusting fertilizer application techniques to terrain characteristics (e.g., using the half-moon technique on steep slopes).
- Maintaining buffer zones without fertilizer application near waterbodies to avoid pollution.
- Applying fertigation to more precisely allocate nutrients at the place of plant uptake. This can be relevant at intensively managed coffee farms.

3. Managing organic resources to improve soil health and stimulate biological nutrient cycling

Managing organic resources is central to regenerative agriculture. This involves integrating (leguminous) cover crops and shade trees, as well as using organic inputs. These organic resources contribute to INM principally in two ways. First, they can partly substitute or complement the fertilizer needs of the crop. Second, their management has a positive effect on overall soil health, thereby increasing the use efficiency of applied fertilizers. Organic resource management thus allows farmers to diminish the amount of mineral fertilizers required while also enhancing the resilience of the production system in the face of biotic and abiotic stresses. Organic resource management might further include a focus on beneficial soil biota, either by stimulating the native soil community or by introducing microorganisms using *biofertilizers* or other *biostimulants*. The use of different types of organic resources as part of an INM approach is shown in Figure 3.20, and is described in more detail below.

- **Organic inputs,** such as crop residues, animal manure, compost and biochar, enrich the soil with nutrients and help to maintain or increase the organic matter content of the soil. They promote soil life, strengthen natural nutrient cycling, improve soil structure, enhance the water retention capacity of the soil, and can help to buffer soil pH and mitigate Al toxicity. Organic inputs can be produced from crop residues or waste streams available on the farm (see Chapter 3.4.10) or be obtained (commercially) outside the farm. They can be applied on the soil surface or be incorporated during planting. Depending on the characteristics of the organic material used, its application should positively affect coffee productivity on farms where little or no mineral fertilizer is applied, including organic farms. In more intensively managed farms with higher yields, the combined application of mineral fertilizers and organic inputs is highly recommended to ensure optimal crop nutrition and decrease nutrient losses, while also enhancing soil health [128]. In those systems, organic inputs often prove insufficient to fully satisfy the nutrient demands of the crop, in terms of both composition (nutrient content) and availability.

  The benefits that can be expected from organic inputs in terms of nutrient supply and soil health enhancement depend to a large extent on the nutrient contents and decomposability of the organic amendments being used. These characteristics vary greatly with the feedstock used and the pretreatment (if any, for example, composting or pyrolysis; see Chapter 3.4.10). Performing a chemical analysis before applying organic inputs is strongly recommended. This helps to ensure their safety in terms of contaminants, while information on their nutrient contents and other quality parameters provides an indication of the rate of decomposition and nutrient provision (see Box 3.10).

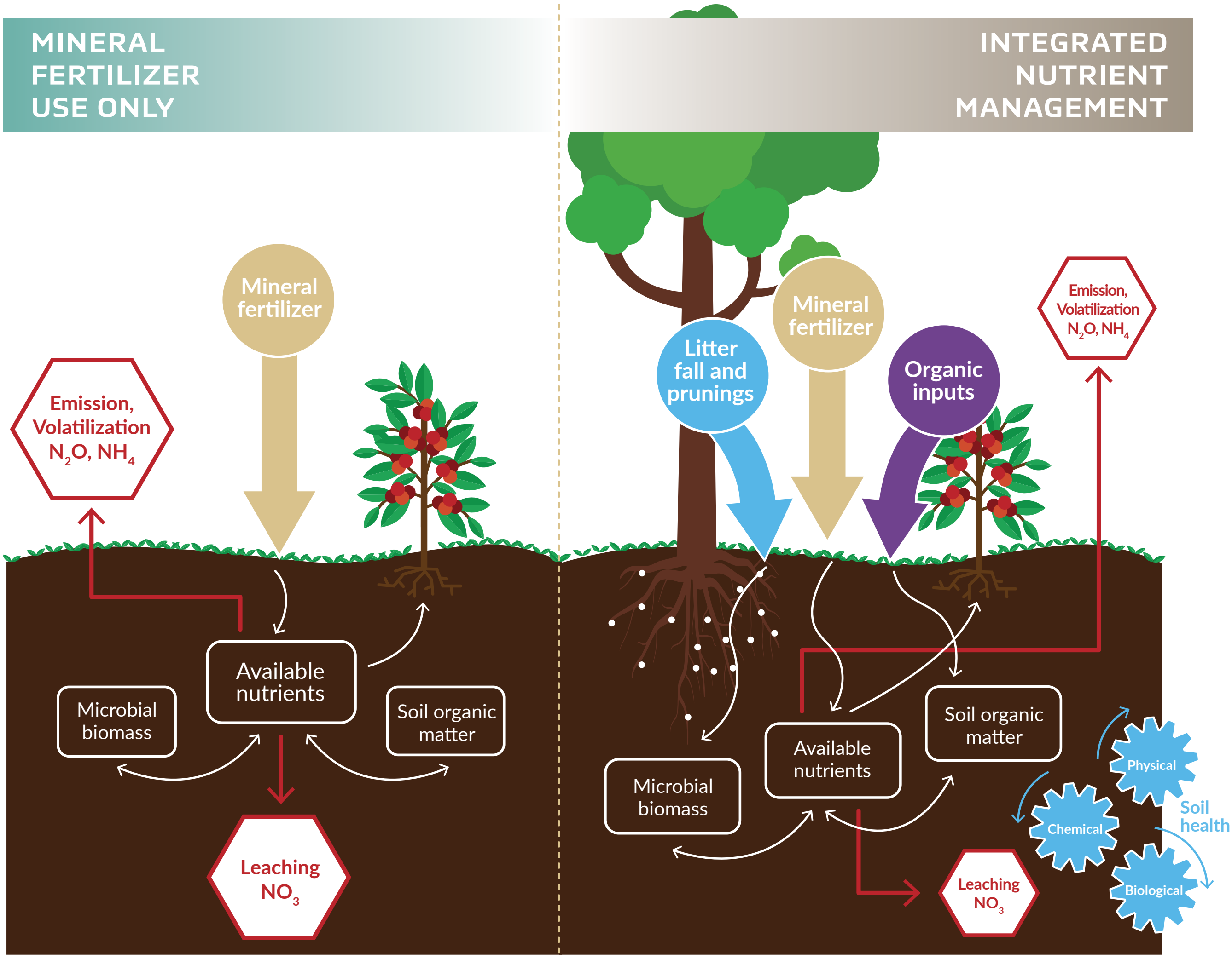


Figure 3.20. The importance of organic resource management for efficient use of mineral fertililzer inputs, while stimulating biological nutrient cycling and soil health.

The rate at which organic inputs decompose and release nutrients further depends on the conditions during decomposition, such as humidity, oxygenation, temperature, pH and nutrient availability in the soil, as well as the composition of the microbial community [123]. In turn, the type of organic inputs used and their quality parameters affect the composition of the soil community; for example, certain groups of fungi are favored by more ligneous materials with a higher C:N ratio. The combined use of organic inputs and mineral fertilizers thus allows farmers to better steer the availability of nutrients according to crop needs, while at the same time strengthening soil health [128,129].

For more information about sources and types of organic matter inputs, including their production through the valorization of local waste streams, see Chapter 3.4.10.

Box 3.10. Why is the carbon-to-nitrogen (C:N) ratio of organic matter important?

The quality of organic amendments is largely determined by their C:N ratio, as it relates to how fast the applied N will become available to plants. Upon decomposition of organic material, microorganisms require C and N (and other nutrients) to grow, while part of the C is respired as CO_2. Therefore, as decomposition proceeds, the C:N ratio of the organic matter decreases. As a result, the application of amendments with a high C:N ratio, for example, wheat straw, leads to immobilization of N from the soil solution into microbial biomass. High-quality amendments with a C:N ratio of around 10, such as composts, contain more N than microbes need and release mineral N during decomposition [130].

Applying large quantities of organic material with a low C:N ratio ensures mineralization of sufficient N for crop growth, but might lead to N losses depending on how much mineral N (mainly nitrate) is taken up by the crop. Using organic inputs with a high C:N ratio decreases the risk of N leaching and volatilization, but might also diminish crop growth.

Managing organic amendments requires finding the right balance of C:N ratio, quantity and timing. A C:N ratio from 10 to 20 is generally optimal to provide enough N to crops while minimizing losses. If the C:N ratio exceeds 25, plants and microbes might compete for N. Additional N can be added (e.g., in the form of mineral fertilizer) to speed up decomposition and prevent negative effects on crop development.

Apart from the C:N ratio, other quality parameters such as lignin and polyphenol content also influence the decomposition rate and nutrient release of organic inputs. Available databases that contain information on organic resource quality parameters for different types of organic matter, including macronutrient, lignin and polyphenol contents, can be used to support decisions on the integrated management of organic resources in tropical cropping systems [128,129].

- **Shade trees and cover crops (including legumes)** can have a significant impact on nutrient cycling in coffee production systems. These plants can capture nutrients from deeper soil layers, thereby reducing leaching losses. They further affect nutrient availability and uptake by coffee plants through improvements in soil structure and water retention. Leguminous species are of particular interest due to their capacity to fix N_2 from the atmosphere in *symbiosis* with rhizobium bacteria. The fixed N, along with other nutrients, becomes available to the coffee crop through the decomposition of residues and prunings. Nitrogen can also be transferred directly from legume to coffee plants through root exudates and common mycorrhizal networks [131].

The amount of N fixed by leguminous species varies depending on the species, management and environmental factors, including soil acidity and nutrient deficiencies [72,131]. A study in Minas Gerais, Brazil, quantified the contribution of different cover crop species planted in between coffee rows at 36–100 kg N/ha. An estimated 13–44 kg was derived from the atmosphere via biological N fixation and the remainder was taken up from the soil [132]. Several widely used leguminous cover crop species can also accelerate P cycling by mobilizing less available soil P pools, e.g., through root exudates [133]. The total N contribution from shade trees, which can provide up to 14 Mg/ha of litterfall and pruning residues per year, can be as high as 340 kg N/ha/yr [134]. However, fixation of atmospheric N by leguminous shade trees such as *Erythrina* or *Inga* spp. grown at a density of 100 to 300 trees per hectare generally does not exceed 60 kg N/ha/yr [134]. Although these figures show that the contribution of atmospheric N fixed by legumes to coffee production can be substantial in low-input systems, it is also evident that the beneficial effect of shade trees on nutrient cycling via the prevention of N losses and the extraction of N and other nutrients from deeper soil layers should not be overlooked. This benefit is not limited to leguminous species [135].

Integrating cover crops or shade trees, especially leguminous species, into coffee plantations can thus partly replace external N inputs, reduce N_2O emissions and enhance coffee yields. For example, using *Tephrosia* as a green manure cover crop grown in between coffee rows in Rwanda added significant amounts of N, P and K to the soil, resulting in increased coffee yields by 23–36% over the two years using Tephrosia alone, and by a further 25–42% when NPK was also added, showing a clear synergistic effect of *Tephrosia* mulch on the efficiency with which coffee used mineral fertilizer [72]. In Australia, pinto peanut (*A. pintoi*) grown in between coffee rows as a green manure resulted in significantly lower N_2O emissions when compared to poultry manure, despite similar inputs of N into the system [63]. The incorporation of cover crop biomass into the top soil, instead of using it as a mulch, can minimize losses caused by N volatilization and enhance contact of the residues with the soil to stimulate decomposition [136], although it may generate a trade-off with soil conservation objectives (see Chapter 3.4.4).

Apart from improving N use efficiency and reducing the carbon footprint, shade trees and cover crops can contribute to greenhouse gas mitigation through carbon removal. Leguminous species can enhance overall system productivity and increase carbon inputs into the soil, potentially leading to soil carbon sequestration [137]. However, the magnitude of the soil carbon stock increase depends on the species, environmental factors and management practices, and it might take several years to be realized [133].

- **Beneficial soil biota:** Soil biota, consisting of diverse soil fauna as well as bacterial and fungal species, play a key role in nutrient cycling. In most coffee systems, soil disturbance is relatively low, while the amount of organic matter returned to the soil is relatively high, compared to annual cropping systems. Therefore, well-managed coffee systems generally favor the presence of a diverse and active soil community. Unless the soil community has been severely degraded by previous land use, benefits from soil biota can be harnessed by ensuring a good habitat quality for the soil community already present in the soil. This means moderating soil moisture and soil temperature conditions, applying high organic matter inputs, and preventing soil compaction and use of toxic agrochemicals. Regenerative practices, such as the use of cover crops, shade management, and use of organic inputs, are excellent strategies to stimulate soil life, including keystone species that help transform nutrients, such as mycorrhizal fungi, N-fixing bacteria, nitrifying bacteria and soil *ecosystem engineers* (see Chapter 2.2.2). Many of those groups of species also benefit from a neutral soil pH and thus show a positive response to liming of acidic soils.

Farmers are increasingly involved in the application of beneficial soil microorganisms, also called biofertilizers, as a strategy to stimulate plant production. Beneficial microorganisms, except for N-fixing bacteria, do not add nutrients to the system directly. Instead, they enhance plant health and growth by increasing the availability and uptake of nutrients already present in the soil. Few scientific studies have been conducted on *biofertilizers*, such as N-fixing bacteria, plant growth-promoting rhizobacteria (PGPR) and arbuscular mycorrhizal fungi (AMF) in coffee plantations. Some evidence suggests, however, that the combination of compost application and AMF inoculation can improve the performance of young coffee plants during the nursery stage [[138]]. Less convincing are the effects on coffee growth of biofertilizers applied under field conditions [[123]]. Their effectiveness depends strongly on the ability of added microorganisms to establish in the field, depending on local soil conditions (such as nutrient availability, pH and moisture) and on the composition of the native soil community [[139]]. The use of commercial rhizobium inoculants in combination with leguminous plant species may occasionally enhance biological N fixation [[140]]. Non-microbial biostimulants, such as seaweed-based products can also have potential to promote plant growth [[141]].

Finally, the preparation of *biofertilizers* on farms, building on the concept of effective microorganisms (EM), is becoming popular. However, scientific studies demonstrating the effectiveness and consistency of such biofertilizers are lacking, and the underlying mechanisms are not well understood [[142]]. Further research is needed to fully understand the effectiveness of biofertilizers in coffee production as well as the underlying mechanisms, so that scientifically robust recommendations can be provided. Moreover, the supply chain logistics and quality control systems for those products need to be improved.

Enriching soils through application of organic matter, Indonesia | Nestlé.

What challenges does adoption of the practice pose, and how can these be overcome?

On low-input farms, INM has great potential to increase crop yields, but the high costs of external inputs may discourage smallholders from applying recommended rates. The use of organic residues and waste, such as coffee pulp, can improve the efficiency of mineral fertilizer applications and thus help meet crop needs. On more intensively managed farms, INM can deliver significant economic and environmental benefits by lowering external fertilizer inputs and associated costs. In both situations, the net impact on farmer income will depend on fertilizer costs and coffee prices.

One of the challenges for the adoption of INM is that the practice is knowledge intensive and requires information on local soil conditions and nutrient inputs and outputs from the system. Access to reliable soil testing and interpretation may be limited, especially among smallholders. Adopting the practice requires an understanding of nutrient cycles and crop demand, as well as production and environmental risks. Farmers must learn to analyze nutrient balances and efficiencies, based on nutrient input-output relationships, or receive support from field agronomists or extensionists trained in INM. Practical digital tools should be developed and disseminated to provide trained farmers and technicians with the means to interpret soil testing results, make simplified nutrient-balance calculations and estimate nutrient needs. Digital tools can also deliver recommendations on the use of organic resources, building on databases that describe the quality parameters of these resources. One such database and decision-support tool, although not specific to coffee cultivation, is described in Palm et al. [129].

Finally, the availability of organic residues determines to what extent organic inputs can substitute for or complement mineral fertilizers. Coffee farms generally do not generate sufficient organic residues to fully satisfy plant nutrient demand. Synchronization of nutrient availability with crop demand can also pose challenges when organic inputs are used. Therefore, combined use of mineral and organic fertilizers is the recommended option. The establishment of local capacity to produce quality organic inputs from local waste streams on larger coffee farms or in smallholder coffee communities should also be encouraged (see Chapter 3.4.10).

Further reading and useful tools

General descriptions of plant nutrient requirements, nutrient cycles, soil fertility and fertilizer management in agroecosystems (in English):

- FAO. 2023. Technical guidelines on soils for nutrition – Sustainable soil management for nutrition-sensitive agriculture. https://doi.org/10.4060/cc5069en

General information on nutrient management in coffee production (in Spanish):

- Díaz-Poveda V; Sadeghian S. 2020. Calidad de las enmiendas para corregir la acidez del suelo en la zona cafetera de Colombia. Avances Técnicos Cenicafé 516. https://doi.org/10.38141/10779/0516
- Sadeghian S; Duque Orrego H. 2021. Dosis óptimas de nutrientes para cafetales en producción. Consideraciones económicas. Avances Técnicos Cenicafé 533. https://doi.org/10.38141/10779/0533
- Sadeghian S. 2022. Nutrición de café. Consideraciones para el manejo de la fertilidad del suelo. Cenicafé. https://doi.org/10.38141/cenbook-0017
- Sadeghian S; González Osorio H. 2022. Fertilizantes nitrogenados. Implicaciones agronómicas para el cultivo del café en Colombia. Avances Técnicos Cenicafé 544. https://doi.org/10.38141/10779/0544

Literature on nutrient-use efficiency and nutrient balances in coffee (in English):

- Sadeghian et al. 2022. Determinants of nitrogen-use efficiency in coffee crops. A review. Revista de Ciencias Agrícolas. 39. https://doi.org/10.22267/rcia.223902.183
- Van der Vossen H. 2005. A critical analysis of the agronomic and economic sustainability of organic coffee production. Experimental Agriculture 41. http://doi.org/10.1017/S0014479705002863

Manual for visual soil assessment to understand, monitor and address soil conditions and constraints.

- FAO 2008. Visual Soil Assessment (VSA) Field Guides. Orchards. Rome, Italy. https://www.fao.org/3/i0007e/i0007e03.pdf

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Literature on soil testing and fertilizer plans focused on coffee production systems (in English and Spanish):

- Sadeguian S. 2018. Interpretación de los resultados de análisis de suelo. Soporte para una adecuada nutrición de cafetales. Avances Técnicos Cenicafé 497. https://doi.org/10.38141/10779/0497

Educational tools and field kits for low-cost soil testing in the field:

- Training modules and Educational Soil Kits developed by the FAO Global Soil Partnership as part of the Soil Doctor Program. https://www.fao.org/global-soil-partnership/soil-doctors-programme/educational-material/educational-soil-kits/en/

Information on foliar analysis in coffee (in English and Spanish):

- Sadeghian S. 2020. Análisis foliar: Una guía para evaluar el estado nutricional del café. Avances Técnicos Cenicafé 515. https://publicaciones.cenicafe.org/index.php/avances_tecnicos/article/view/125/86
- Wairegi LWI; Van Asten PJA. 2012. Norms for multivariate diagnosis of nutrient imbalance in Arabica and Robusta coffee in the east African highlands. *Experimental Agriculture* 48. http://doi.org/10.1017/S0014479712000142

A research example on the use of cover cropping and mulching for INM in coffee:

- Bucagu et al. 2013. Managing *Tephrosia* mulch and fertilizer to enhance coffee productivity on smallholder farms in the Eastern African Highlands. *Agronomy* 48. http://doi.org/10.1016/j.eja.2013.02.005

India | Nestlé.

3.4.8. Efficient water use

Overview of the practice

Efficient water use requires interventions that enable farmers to use water resources sustainably, while ensuring good and stable coffee yields and quality. Such interventions reduce the use and loss of water, promote water recycling and avoid contamination of water sources, thus reducing the *water footprint* of coffee production. Water harvesting techniques can further optimize water availability for coffee farming and other uses. Efficient water use requires action across spatial scales – from field to watershed – as well as at the pre- and postharvest stages of coffee production.

Optimizing water management on farm and across landscapes is key for securing water availability for agriculture and other local uses. This requires regenerative practices that increase crop yields and reduce losses through evapotranspiration, while retaining and storing water in the soil to aid groundwater recharge [143]. Combinations of such practices are discussed in other chapters, covering renovation/rehabilitation (Chapter 3.4.1), agroforestry (Chapter 3.4.2), soil conservation practices and cover crops (Chapter 3.4.4), and landscape actions (Chapter 3.4.11).

Efficient water use requires particular attention in coffee regions where uneven rainfall distribution creates dependence on irrigation, as in parts of Brazil, India and Vietnam [144,145] (see Chapter 2.2.3). Under those conditions, ensuring that coffee production remains economically, socially and ecologically viable requires the adoption of precise recommendations for irrigation frequency and volumes as well as water-saving techniques on farm and in communities. Inadequate irrigation management, in contrast, can damage crops, while causing soil erosion and runoff, leaching as well as nutrient runoff, potentially leading to soil pollution or salinization, depending on the quality of the water used.

Lastly, coffee wet processing contributes significantly to the *water footprint* of coffee farming. Minimizing water use and treating wastewater to allow for its release or re-use (see Chapter 3.4.9) are essential steps for efficient water use on coffee farms or in centralized coffee processing facilities.

What are the potential benefits of efficient water use?

Since coffee plants are highly susceptible to changes in rainfall amounts and patterns [6], efficient water use is key to securing coffee productivity. Coffee farmers who rely on clean water for irrigation and postharvest processing are particularly vulnerable to water scarcity and contamination. Helping farmers conserve water through efficient irrigation and processing is, therefore, a priority for climate change adaptation.

Improved irrigation systems and postharvest processing technologies that save water offer the additional benefit of reduced labor and energy costs [145,146]. Moreover, water savings during coffee processing facilitate the treatment of wastewater afterwards, and this, in turn, reduces greenhouse gas (GHG) emissions as well as contamination of soils and water (see Chapter 3.4.9).

Another benefit of efficient water use is that it improves the availability of clean water in watersheds for household use, food production, industry and natural ecosystems. In contrast, unsustainable water use leads to the loss of water sources as well as the depletion of reservoirs and aquifers, causing severe water scarcity and frequently giving rise to socio-economic conflict. Therefore, practices that enhance water-use efficiency contribute to the sustainability of coffee production, while enhancing the resilience of farms and local communities (Figure 3.21).

IMPACT AREAS		TEN POTENTIAL BENEFITS
Soil health	1	Measures that enhance water-use efficiency by improving soil water retention, drainage and water quality also tend to favor soil biodiversity and overall soil health
Water conservation and quality	2	Efficient water use seeks to prevent aquifer depletion and secure water availability in watersheds
	3	The practice focuses on protecting water quality and limiting contamination caused by untreated wastewater from postharvest processing
Biodiversity and land use	4	Conserving water resources (quality and quantity) is key to protecting and restoring wild biodiversity
Greenhouse gas mitigation	5	Reducing water consumption during coffee processing helps limit GHG emissions from postharvest wastewater
Coffee productivity and input use	6	Efficient water use is essential to secure yields, especially in irrigated coffee
	7	Improved irrigation techniques can reduce fuel use per unit of coffee produced
Farm income and livelihoods	8	Water-saving techniques can reduce production costs associated with fuel use and labor
	9	The practice helps secure water for household use and food security
	10	Managing water resources efficiently and responsibly helps prevent socio-economic conflicts related to water

Figure 3.21. Ten potential benefits of efficient water use.

Where should efficient water use be implemented?

Efficient water use benefits both rainfed and irrigated coffee production, and is particularly important for farms that rely on water availability for irrigation and/or postharvest wet processing. Across many coffee-growing regions, the practice can help secure coffee yields and quality, while reducing the vulnerability of coffee farming households to climate change.

Coffee should be grown only where total annual rainfall is sufficient (>1,200 mm/year) [147]. In regions with a seasonal water deficit, irrigation may be an economically viable option, and in that case, efficient use of irrigation water is a key priority for regenerative coffee farming. For example, in Vietnam's Central Highlands, where most of the country's Robusta coffee is produced, excessive irrigation causes groundwater depletion and water shortages, affecting many coffee farmers [148,149]. Reliable and efficient water monitoring and irrigation techniques for small-scale farming are urgently needed to secure the production of coffee (and other crops) and reduce production costs. Other important coffee origins where irrigation is used during the dry period are Espirito Santo (Robusta) in Brazil and parts of the country's Cerrado Mineiro, where large-scale, intensive coffee farming is practiced using more technified irrigation systems. Improvements in irrigation management [146] and coordinated landscape action are needed to enhance water security.

Finally, efficient water use should also receive priority in regions where annual rainfall is relatively low, where climate change is making environmental conditions less suitable for coffee cultivation as well as where water demand is high (e.g., near cities) and agricultural use competes with household and industrial demand.

In summary, efficient water use should be a high priority under the following conditions:

- Seasonal water deficit, making irrigation necessary.
- Farms that use water inefficiently for postharvest processing.
- Marginal coffee-growing regions and those where climate change increases the probability of drought.
- Areas where water demand is high (e.g., near cities), and agricultural use competes with other demands.

What should be considered in implementing efficient water use?

Efficient water use can be achieved using diverse interventions. It requires knowledge of water requirements of the crop at different phenological stages [150] and close monitoring of water availability and use, combined with improved production practices. Investments in infrastructure for irrigation or postharvest processing may be needed. Interventions should not be considered in isolation but rather as part of an integrated strategy that takes into account how water management interacts with other aspects of the production system as well as with the farm's position within a watershed. For example, investment in efficient irrigation systems should be combined with cultural or structural measures that optimize soil water retention and reduce soil water losses through runoff and evaporation.

Some general recommendations and examples are provided below. Options for efficient water use during coffee cultivation are considered first, distinguishing between cultural measures that apply to all coffee farms and measures that pertain specifically to irrigated farms. Then, options for saving water during postharvest processing are discussed.

Cultural or structural measures for water-efficient coffee cultivation

In rainfed coffee production, water-use efficiency can be improved before harvest by improving cultural practices or by introducing structural measures that are part of the regenerative practices discussed elsewhere in this chapter. Improving rainwater-use efficiency requires measures that prevent water loss from runoff and evaporation and enhance the infiltration and water retention capacity of the soil. At the same time, the soil should have good drainage conditions to avoid water logging and allow percolation of excess water to replenish groundwater reserves. Recommendations may include:

- Plant drought-tolerant material or rootstock (see Chapter 3.4.1).
- Optimize shade management through intercropping (during coffee establishment) and agroforestry (for permanent shade) to reduce water losses from evapotranspiration (see Chapters 3.4.2 and 3.4.3).
- Maintain soil cover to reduce runoff and evaporation, using cover crops, mulching or integrated weed management (see Chapters 3.4.4 and 3.4.5).
- Increase soil organic matter content and improve soil structure through practices that use organic inputs or by means of deep-rooting cover crops [57]. This not only improves soil water infiltration and retention but also attracts soil fauna, such as earthworms, which create soil pores and thus further promote water infiltration (see Chapter 3.4.7).
- Use structural measures where needed (such as infiltration swales, trenches, planting basins and terraces) to slow down surface runoff and facilitate infiltration during irrigation or rainfall events.
- Dig trenches or pits (60–100 cm from coffee plants) that can be filled with organic amendments to maintain soil humidity and stimulate new root growth. One example is the Rorak technique from Indonesia [151].
- Harvest rainwater using reservoirs or collection basins. Water can be collected from impervious surfaces, such as the roofs of farm buildings, or from sloped terrain, using contour ditches connected with ponds or water collection tanks. Multifunctional fishponds can be an interesting option, combining water harvesting with income diversification.

Rorak technique [151].
Photo: Indonesia | CGIAR.

Multifunctional fish pond, combining water harvesting and income diversification.
Photo: Vietnam | CGIAR.

Efficient use of irrigation water for coffee cultivation

The amount of water used by farmers to irrigate coffee often exceeds recommendations, as has been reported for Vietnam [145] and Brazil [146]. This indicates a key opportunity to improve water-use efficiency in coffee cultivation. Irrigation requirements, and the role of irrigation in stimulating flowering, vary depending on the rainfall distribution, the severity of the dry season, soil type and depth and the type of production system (e.g., shade management). General guidelines for efficient use of irrigation water are:

- Avoid overuse of irrigation water, following crop-specific recommendations combined with monitoring of the water volumes applied and soil moisture levels.
- Plan irrigation needs and timing, based on the phenological stage of the coffee crop, climatic conditions, and soil type and depth. Consider the need for irrigation to ensure synchronization of flowering.

  Note: According to coffee phenology, a period of water stress is needed to prepare flower buds for blossoming, which is then stimulated by rain or irrigation. Flowering takes place a week after the first rain or first irrigation round. Water must be freely available during the period of rapid fruit expansion to ensure large, high-quality seeds [150].

- Use the most efficient irrigation technique that is technically and economically feasible.

  Note: Drip irrigation uses water more efficiently than sprinklers but also requires higher investments and is less efficient in triggering homogeneous flowering. Low-cost technologies suitable for smallholders include small (mobile) modules, such as mini sprinklers. Flood irrigation should be avoided. When a hose pipe is used, a basin around the coffee tree can be prepared to collect water. If applied well, this practice uses less water than sprinklers.

- Split applications to enhance irrigation water efficiency, especially when the soil has poor water retention capacity (e.g., sandy soils) and on sloped land.

- Use the topography to reduce the amount of energy needed for irrigation.
- Use clean water to avoid spreading of plant pathogens or pests such as nematodes. Test water quality (i.e. conductivity, hardness, heavy metals, etc.) to assess the risk of salinization and contamination.
- Perform maintenance and periodic checks of the irrigation system to make sure there are no leaks or obstructions.
- Consider the water requirements of other crops in the system, when applicable.
- Complement efficient irrigation techniques with less expensive, cultural and structural measures that reduce irrigation needs, as discussed above.

Reduce water consumption during postharvest processing

Efficient water use is especially relevant for farms or centralized facilities that use wet and semi-wet coffee processing, with the additional benefit of facilitating wastewater treatment afterwards (see Chapter 3.4.8). Much attention has been dedicated to reducing water use during coffee processing. Conventional wet processing systems, including the removal and transport of pulp and mucilage, use 25–50 l per kilogram of dry beans. Ideally, less than 10 l of water per kilogram of dry beans should be used during postharvest processing, taking into account the different steps from fruit sorting to washing of the equipment. The following recommendations can be used to reduce water consumption at different stages in the process:

- Harvest and process only ripe cherries.
- Transport the fruit and pulp without using water.
- Reuse water for the different separation and washing rounds in the same processing step, provided that this does not reduce coffee quality.
- Pulp without using water.
- Remove mucilage mechanically or naturally (through fermentation), using demucilaginators, mechanical scrubbers or fermentation tanks.
- Use tanks that do not need water to ferment the coffee (dry fermentation).
- Use mechanical washing (e.g., ecowasher technology) to optimize water use for pulping and washing after wet fermentation.
- Switch to semi-washed (pulped naturals or honey coffees) or dry processing (natural coffees). (Figure 3.22).

Washed
Coffee fruit is pulped; mucilage is "loosened" through fermentation; washed clean of mucilage; and then dried

Honey
Coffee fruit is pulped and dried with mucilage intact

Natural
Coffee fruit is harvested and dried as a whole fruit

Figure 3.22. Different coffee processing methods with different water consumption levels. CIAT/N. Palmer

Different types of processing technologies can be used to reduce water consumption. See also Figure 3.23.

- **Eco-demucilagers** remove the mucilage mechanically. Since berries do not undergo submerged fermentation, very little water is used.
- **Ecowasher** technology optimizes water usage for pulping and washing after wet fermentation. Although this method uses water for wet fermentation, it requires less water than conventional washing. The resulting product is wet-processed coffee.

What challenges does adoption of the practice pose, and how can these be overcome?

High costs are one of the main obstacles to the adoption of efficient water-use technologies. This is especially so for techniques requiring large capital investments, such as drip irrigation and eco-processing equipment. Farmers must also obtain the necessary knowledge and skills to correctly implement and manage irrigation systems, and switch to alternative processing methods. In addition, farmers may need support from trained agronomists and technicians, which is not always within the reach of smallholders. This is why water-use monitoring tools and low-cost, water-saving technologies need to be developed along with adequate financial and technical support.

Since many coffee farmers over-irrigate, there is a clear need for better recommendations concerning optimal irrigation management. Communicating these to farmers should receive high priority, particularly given the importance of such recommendations for reducing production costs. Current methods of calculating crop water requirements for irrigation scheme design and management are imprecise and probably subject to large errors, depending on local circumstances. Scientific knowledge on the role of water in the growth and development of coffee plants must be translated into practical advice that can help growers plan and use water efficiently [150]. Improved water planning and

RECEPTION OF SELECTIVELY PICKED RIPE CHERRIES FOR MECHANICAL SEPARATION

Option 1. Dry hopper or wet hopper using <2 l/kg of water *

Cherries move to the machines inside the mill using gravity only or with recirculation of the water to reduce water consumption.

Recommended for volumes <1000 kg of coffee cherries per day.

Option 2. Use of hydraulic separator with screw conveyer or syphon tank with recirculation *

More advanced hydraulic separators are efficient and effective for processing lines that handle large volumes.

PULPING & TRANSPORTATION TO THE DRYING OR FERMENTATION AREA

Mechanical pulping and transportation without water

- Removal of the skin and pulp without water and transport of the residues to the pits (using gravity).
- Transport the pulped coffee to the drying area using carts or other mechanical methods.

NB: This step can contribute strongly to reducing the negative environmental impacts of coffee wet processing, while the costs of implementation are relatively low.

REMOVAL OF MUCILAGE (LARGE VARIATIONS IN METHODS EXIST)$

Option 1. Wet fermentation

Removing the mucilage by natural fermentation, while reducing water consumption by soaking the pulp with water from the first two rinses of the washing process.

Option 2. Dry fermentation

Removing the mucilage by natural fermentation without water. Recommended for areas with limited access to water. Careful attention is needed to ensure consistency of the process.

Option 3. Mechanical demucilaging (DESLIM)

The mechanical removal of mucilage by rubbing a mass of pulped coffee with a rotor device.

WASHING

Washing with four rinses (tub tank) (in combination with option 1 above as mucilage removal and washing are the same process)

Rectangular tank with rounded corners, in which the natural fermentation and washing process is carried out.
Water consumption drops from 25 l/kg down to less than 5 l/kg.

Submersible pump

Washing passing the coffee from one tank to another multiple times, using a submersible pump recirculating the water from the third rinse.

Ecowasher

Mechanical washing system with minimal water use (<0.5 l/kg cps and zero-waste management of the residual water).

DRYING

* To prevent contamination, residual water should be treated and recycled in the production system.

$ Fermentation can occur during different steps throughout postharvest processing. Two main goals can be achieved with fermentation: (i) successful removal of mucilage, with minimal damage to the coffee seed and development of defective flavors, and (ii) specific or unique cup profile in the resulting coffee beans. Clarity about the goal helps make key decisions about the techniques to employ.

Figure 3.23. Different options to reduce water use during postharvest wet processing, based on Rodriguez Valencia et al. 2015 [152] and Rojas Acosta et al [153].

A coffee wet mill that combines three processing steps in a single machine and significantly reduces water consumption compared to conventional wet processing: The ripe coffee cherries are pulped and classified without water. The pulped coffee is then directed to the demucilating process with low water consumption (0.2 l/kg of cherries). A screw conveyor transports and mixes pulp and mucilage without water. The machine also measures water consumption (Colombia) | CIAT/M. Pulleman.

management in watersheds also requires the cooperation of different stakeholders, including close neighbors, communities and businesses downstream as well as local authorities. Effective governance of water resources requires appropriate institutional arrangements and investment.

Finally, the adoption of water-efficient techniques for postharvest processing may alter the quality profile of the final product. Consequently, market requirements for wet-processed coffee may limit the ability of farmers to adopt semi-wet or dry processing. Nevertheless, in most coffee origins, there is significant scope for achieving water savings, even when conventional wet processing is used, as described above.

Further reading and useful tools

Scientific overview of water requirements of coffee and recommendations for irrigation management

- Carr M. 2001. The water relations and irrigation requirements of coffee. *Experimental Agriculture* 37. http://dx.doi.org/10.1017/S0014479701001090

Articles and technical reports on irrigation and water savings in Vietnam

- Amarasinghe UA et al. 2015. Toward sustainable coffee production in Vietnam: more coffee with less water. *Agricultural Systems* 136. https://doi.org/10.1016/j.agsy.2015.02.008
- CCAFS. 2016. A CGIAR assessment report on the drought crisis in the Central Highlands of Vietnam, with recommendations on integrated responses. https://hdl.handle.net/10568/75635
- Tran DNL et al. 2021. Improving irrigation Water Use Efficiency of Robusta Coffee (*Coffea canephora*) Production in Lam Dong Province, Vietnam. https://doi.org/10.3390/su13126603

Information on water-saving postharvest processing technologies (In English and Spanish):

- Oliveros Tascón CE et al. 2018. Tanque de fermentación fabricado en plástico. Una alternativa para disminuir costos en la tecnología Ecomill®. Avances Técnicos Cenicafé 496. https://doi.org/10.38141/10779/0496
- Oliveros Tascón CE et al. 2022. Manejo y aprovechamiento de las aguas residuales del lavado del café con la tecnología ECOMILL®. Avances Técnicos Cenicafé 538. https://doi.org/10.38141/10779/0538
- Rodríguez Valencia et al. 2015. Beneficio del café en Colombia: Prácticas y estrategias para el ahorro, uso eficiente del agua y el control de la contaminación hídrica en el proceso de beneficio húmedo del café. Cenicafé. https://biblioteca.cenicafe.org/handle/10778/659
- Technoserve. 2022. Coffee Wet Mill Processing Guide. https://www.technoserve.org/wp-content/uploads/2022/03/TechnoServe-Wet-Mill-Processing-Guide.pdf

Guide for evaluating the water footprint in coffee production (in Spanish):

- Rojas Acosta et al. 2019. Guía para la evaluación de la huella hídrica del café de Colombia. https://www.wur.nl/upload_mm/9/a/0/acd601f3-edcd-4a5f-8068-492d4040f886_Huella_Hidrica.pdf

Pulp tank | Nestlé.

3.4.9. Wastewater management

Overview of the practice

Wastewater management on coffee farms or in centralized coffee processing plants aims to limit or eliminate the negative effects of residual water from postharvest processing on natural resources and human health. The practice also seeks to reduce the carbon footprint of coffee production.

During conventional wet processing, the cherries are pulped and fermented, and have their mucilage removed using large volumes of water before being dried. Inadequate disposal of byproducts (e.g., “aguas mieles”, pulp and mucilage) from coffee wet processing in waterways or on the land has significant harmful effects on natural resources. Wastewater from coffee processing is acidic and contains large quantities of organic compounds, such as tannins, phenolics and alkaloids. Its physicochemical properties make wastewater particularly harmful to the environment, and give this water its foul odor and dark color. Without adequate treatment, the release of this wastewater into the environment pollutes water downstream. Its high chemical and *biological oxygen demand* as well as opacity create anaerobic conditions, cause eutrophication and block light affecting photosynthesis, thus harming aquatic life [154,155]. Moreover, wastewater degradation under anaerobic conditions generates greenhouse gas (GHG) emissions, mainly in the form of methane (CH_4) and to a lesser extent nitrous oxide (N_2O) [15]. Both are potent GHGs with a greater warming effect than CO_2 (see Chapter 1.4).

The negative environmental impacts of wastewater can be significantly reduced by (i) lowering the volume of water used for coffee wet processing, including pulping and transport of coffee as well as pulping without water (see Chapter 3.4.8); (ii) adopting different technologies for treatment and/or reuse of wastewater; and (iii) reintegrating byproducts (pulp and sediment from wastewater) into farm processes, such as the production of organic fertilizers, feed/food and bioenergy [152].

What are the most important benefits?

The most important benefit of wastewater management is that it improves water quality in the watershed for aquatic life and human use. Studies in Colombia have shown that pulping without water and non-hydraulic transport of the pulp to a roofed pit avoid 74% of the potential contamination of water resources, without affecting product quality [152]. This practice offers the further benefit of reducing foul odors and GHG emissions from wastewater.

The use of anaerobic digestors can generate biogas, which may provide an alternative energy source for households and, where applicable, reduce extraction of firewood from surrounding forests. When fully treated, wastewater can be reused in wet processing or for irrigation and other farm operations, thus contributing to efficient water use (Figure 3.24).

IMPACT AREAS	TEN POTENTIAL BENEFITS
Soil health	1 Reuse of byproducts from coffee processing as compost and its application to coffee production system helps improve soil health
Water conservation and quality	2 Reduced water use in postharvest processing contributes to water security 3 Wastewater management avoids contamination of waterways with untreated wastewater
Biodiversity and land use	4 The practice helps conserve aquatic life
Greenhouse gas mitigation	5 Wastewater management aims to reduce GHG emissions from organic waste, especially methane 6 When used to produce bioenergy, byproducts from coffee processing can reduce fossil fuel use and deforestation
Coffee productivity and input use	7 Organic fertilizers made from byproducts contribute to crop nutrition and lessen the need for mineral fertilizer inputs
Farm income and livelihoods	8 Better recycling of water and reduced pollution of water for household use favor human health 9 Valorization of byproducts from coffee processing can provide opportunities to diversify income or reduce production costs 10 Reduced water use and pollution lessen the risks of social conflicts around water resources

Figure 3.24. Ten potential benefits of wastewater management.
See also Chapter 3.4.10 on waste valorization and production of organic inputs as these two practices are highly complementary.

Wastewater treatment tank | Nestlé.

Where should wastewater management be implemented?

Wastewater management should receive high priority on individual farms and in centralized processing facilities that employ wet (or semiwet) processing, which is widely applied to Arabica. Natural dry processing, which does not generate wastewater, is commonly used for Robusta, with few exceptions, as well as for a significant part of Brazilian and Ethiopian Arabica [156]. Large farms or centralized processing facilities (e.g., involving cooperatives) that wet process large volumes of coffee in one location present greater environmental risks but also possess greater capacity to adopt advanced wastewater treatment technologies. Smallholders practicing on-farm wet processing should also receive support to improve their wastewater management, as GHG emissions from wastewater can form a relatively large proportion of the total carbon footprint (expressed per kilogram of beans produced) of smaller, less intensively managed coffee farms. Wastewater management is often mandatory to comply with national legislation and/or certification standards (e.g., Rainforest Alliance and 4C) [157]. The practice is particularly relevant for farmers seeking carbon neutral certification for their products, as some cooperatives have done [158].

In regions that are drought prone or have limited access to water, efficient water use for coffee processing, wastewater treatment and recycling of wastewater for specific processing steps or irrigation should be key elements of a climate adaptation strategy. In summary, wastewater management should be prioritized in the situations listed below:

- Farms and centralized facilities where coffee is wet processed
- Farms close to water bodies and protected nature areas
- Farms that (aim to) engage in certification schemes
- Farms and regions with limited access to water

What should be considered in implementing wastewater management?

Wastewater management should form a key part of regenerative coffee farming on all farms, whether large or small, that employ coffee wet processing. Nonetheless, the most suitable technologies, their costs and benefits, as well as capacity for adoption, depend very much on the farm type and volumes of coffee being processed. In general, the implementation of wastewater management involves three areas of intervention, as described below.

1. Reduction in the amount of wastewater produced during coffee processing

Coffee producers should give priority to reducing the volume of wastewater generated, because this hugely facilitates treatment and disposal. Whereas natural dry processing is the simplest process and does not produce any wastewater, market demand may deter farmers from choosing this option. Honey-processed coffee has a niche market, based on its potential to improve certain organoleptic qualities of specific varieties [159]. However, this requires specialized skills and experimentation with different techniques, and fermentation must be monitored carefully. Wet processing is still considered the standard processing method for obtaining high-quality coffee. Therefore, changing the method is often not an option for producers, who are under pressure to comply with market demand for washed coffee. Yet, as shown in Chapter 3.4.8, drastic reductions in water consumption and hence in the volumes of wastewater generated during wet processing are still possible in most origins. Water consumption during wet processing can be reduced to less than 5 l per kilogram of dry beans without affecting bean quality, using equipment that minimizes water use during pulping, washing and transport, while also integrating a mechanical demucilager [152]. Modern eco-processing (e.g., with Eco Pulper Units) reduces water use by 80% [152]. See Chapter 3.4.8 for a detailed discussion of water-efficient alternatives for postharvest processing.

2. Treatment and reuse of wastewater

Although wastewater production during coffee wet processing can be considerably reduced, it still produces highly concentrated and toxic effluents [155], which require further treatment before they

Nicaragua | CIAT/A. Varón.

can be reused for irrigation or processing, or discharged into water bodies. Effluents can only be released into water bodies after testing and compliance with national environmental standards.

Water treatment is aimed at reducing the organic matter load and other toxic compounds as well as acidity. Biological wastewater treatment through decomposition and filtration is the most widespread and cost-effective method for treating coffee processing effluents. It uses a system of specialized stabilization tanks and ponds. The size and complexity of the infrastructure required (i.e., the number of tanks and stations as well as the type of treatments) for optimal wastewater management depends on the farm size and context. The first step consists of wastewater neutralization, which uses lime to raise the pH. Subsequently, the wastewater undergoes decomposition in open ponds. The disadvantage of this method is that it requires large areas to be effective and can result in seepage of polluted waters. Wastewater inflow often exceeds pond loading rates, resulting in improper treatment. Moreover, even in open-air ponds, degradation of organic matter in the water is mostly oxygen deprived, generating significant methane emissions, and it can become a breeding site for mosquitoes [[160]]. Additional water purification can be achieved through plant-based biofilters that use plants with phytoremediation potential (such as vetiver grass or wetlands) to absorb and filter the wastewater [[161]].

Vetiver tunnel used for filtering wastewater in Colombia | CIAT/M. Pulleman.

The use of anaerobic digestors for biological treatment, instead of open ponds, is more environmentally friendly, since this method captures the methane generated when organic compounds are digested in the wastewater. After pH neutralization, wastewater is placed in closed tanks for digestion. After about 50 days, up to 90% of the organic matter load is removed, producing high-quality biogas, which can be recovered for household use. Anaerobic digestion also increases the bioavailability of nutrients in the slurry, which is obtained as a byproduct [162]. After separation of water and sediment in the slurry, the liquid fraction can undergo further aerobic treatment through constructed wetlands, while the slurry can be used as organic fertilizer.

Physical pre-treatments, consisting of filtration or sedimentation processes to separate pulp and water before water treatment, can enhance the efficiency of biological treatments. Certain Ecomill technologies separate the pulp and mucilage, producing very small volumes of effluent. In those cases, wastewater is generated during hydraulic classification washing of the equipment. This wastewater is characterized by a low organic load and can be reused on the farm for such purposes as small-scale irrigation [152].

Experimental approaches include physicochemical treatments with absorbent materials, electrocoagulation, photo-fenton and membrane filtration [163]. These are not yet commercially viable but may become suitable for large processors. Activated carbon is the most commonly used material and gives good results [164], although it can be quite costly compared to biological treatment.

3. Reintegration of byproducts from coffee processing into farm processes

Pulp and mucilage generated during the wet-coffee beneficiation process should be reintegrated into farm processes, such as the production of organic fertilizer animal feed, edible mushrooms and bioenergy [152]. The simplest way to valorize these byproducts is to produce compost or vermicompost for producers to use as organic fertilizer. Alternatively, effective microorganisms (EM) plus lime or ashes are added to quicken pulp decomposition and remove any bad smell from rotting pulp [161]. Pulp should be stored and processed under a roof of solid and durable constructions (made with cement) to significantly reduce water pollution [152]. See Chapter 3.4.10 for further discussion on valorization of byproducts from coffee processing and production of organic inputs.

What challenges does adoption of the practice pose, and how can these be overcome?

The technical and economic feasibility of implementing wastewater treatment in coffee wet mills depends largely on its simplicity as well as on the volume and organic load of the waste generated [152]. Although anaerobic digestion of coffee wastewater could be an attractive solution in rural areas for the production of renewable energy in the form of biogas [165] (see Chapter 3.4.9), the majority of producers lack access to equipment for anaerobic digestion. The investments required in equipment and facilities to reduce water consumption and/or treating the effluents represent an obstacle for smallholders in particular, given the small coffee volumes they manage.

Moreover, tanks or ponds to store wastewater during treatment require a large amount of space. Instead, smallholder farmers could consider the option of collective postharvest processing in larger, shared facilities, perhaps through a cooperative. This way, they can improve wastewater treatment, while reducing costs, and gain the additional benefits of reducing environmental risks and achieving more consistent quality in the final coffee product [166]. In addition, biogas and compost production can be employed on an economically feasible scale.

Wastewater management thus presents multiple tradeoffs in terms of practicality, effectiveness and associated costs. Open-air, dug-out ponds can become a breeding site for mosquitoes, generate unpleasant odors as well as GHG emissions and are liable to seepage. On the other hand, closed tanks for anaerobic digestion are expensive, and require more technical knowledge to build and maintain. Whether processing is centralized or done directly on the farm, stakeholders in the supply chain should provide smallholder farmers transitioning to improved wastewater management with financial and technical support to ensure the sustainability of the final product. One way to create economic incentives for wastewater management is to integrate downstream users into a landscape strategy (see Chapter 3.4.11).

Further reading and useful tools

Information on wastewater management (in English and Spanish):

- Oliveros-Tascón CE et al. 2022. Manejo y aprovechamiento de las aguas residuales del lavado del café con la tecnología ECOMILL®. Avances Técnicos Cenicafé 538. https://doi.org/10.38141/10779/0538
- Quintero-Yepes L; Rodríguez-Valencia N. 2019. Extractos vegetales para el tratamiento de las aguas residuales del café. Avances Técnicos Cenicafé, 504. https://doi.org/10.38141/10779/0504
- Quintero-Yepes L; Rodríguez Valencia N. 2022. Uso de cales para el tratamiento primario de las aguas residuales del café. Avances Técnicos Cenicafé, 537. https://doi.org/10.38141/10779/0537
- Rodríguez Valencia et al. 2015. Beneficio del café en Colombia: Prácticas y estrategias para el ahorro, uso eficiente del agua y el control de la contaminación hídrica en el proceso de beneficio húmedo del café. Cenicafé. http://hdl.handle.net/10778/659
- Technoserve. 2022. Coffee Wet Mill Processing Guide. https://www.technoserve.org/wp-content/uploads/2022/03/TechnoServe-Wet-Mill-Processing-Guide.pdf

Agri-compost | Nestlé.

3.4.10. Waste valorization and production of organic inputs

Overview of the practice

Waste valorization in the context of coffee production refers to the process of recycling and converting various organic waste and crop residues generated on coffee farms into valuable products. The aim is to recover nutrients and carbon from these waste materials for reuse within the farm processes, thereby reducing the need for external inputs and minimizing contamination of watersheds. Additionally, waste valorization can help in reducing the carbon footprint associated with coffee farming.

There are several technologies available for transforming coffee waste into valuable products, and these can be adapted to suit small or large farms with different waste volume and levels of technification. These technologies include: composting, biochar production, anaerobic digestion, compressed husk pellet production, and insect and mushroom cultivation, among others (Table 3.5) [167]. The selection of the most suitable technology depends on various factors, such as the type and availability of waste streams, existing infrastructure, labor availability, and the potential for generating additional income or reducing production costs through the bio-based products generated.

Various solid residue and waste products generated during coffee production and postharvest coffee processing can be recycled, such as crop residues and prunings, coffee husks derived from dry processing, coffee pulp and mucilage from (semi-)wet processing, and coffee parchment. It is possible to recycle other residues produced on coffee farms as well, such as manure from farm animals, residues from other crop systems and trees present on the farms, and kitchen waste.

It is important to note that while utilizing woody residues for biochar production can be beneficial, sustainable sourcing and management of feedstock should be ensured to avoid negative environmental impacts. In particular, the practice should not encourage deforestation. Overall, the adoption of bio-based technologies for waste valorization in coffee farming enhances circularity in nutrient management at the farm or community level, leading to significant environmental and economic benefits.

What are the most important benefits?

Recycling and valorizing organic waste can help prevent watershed contamination and reduce GHG emissions associated with untreated waste streams from coffee wet processing. Technologies to recycle and valorize solid waste from coffee wet processing are therefore highly complementary with wastewater management (see Chapter 3.4.9).

Organic waste that is transformed into organic fertilizers helps to replenish the soil with essential nutrients that are lost during harvest and through processes, such as runoff, leaching and volatilization. Coffee pulp, for example, is rich in potassium (K) and can be applied as mulch or after composting to supply part of the nutrient requirements of coffee during all stages of development [124]. Combining organic inputs with inorganic fertilizers improves fertilizer-use efficiency and crop productivity (see Chapter 3.4.7). When combined with a reduction in the use of mineral fertilizer, it contributes to reducing the carbon footprint of coffee production.

Organic inputs, such as compost, generated from local waste streams are also important for soil health. They improve water retention, buffer soil pH, provide a source of energy for soil biota and can help to suppress soil-borne plant pathogens [168]. Over time, soil carbon content may be increased as well, if stable forms of organic matter, such as biochar, are applied in sufficient quantities.

Besides being used as a feedstock to produce organic inputs, waste valorization technologies can also generate energy, animal feed and substrate for high-value crops, such as mushrooms. Most of these technologies create byproducts that can be returned to the soil. Whether practiced by individual farms, whole communities or cooperatives, waste valorization offers new business opportunities, especially in rural areas with ample labor availability and significant organic waste generation. These economic benefits can help to reduce dependence on expensive fertilizers and animal feed, contributing to the financial resilience of coffee farmers.

It is important to consider that specific benefits vary depending on the type of waste valorization technology used. For example, biochar and compost have different effects on the soil and crops due to their composition and characteristics. Technologies such as anaerobic digesters that capture methane (CH_4), to be used as biogas, as well as biochar production, can significantly lower emissions compared to conventional composting methods [169]. However, overall, recycling of organic waste in coffee farming offers numerous advantages, including environmental sustainability, nutrient enrichment, reduced reliance on mineral fertilizers, improved soil health, economic opportunities and carbon footprint reduction (Figure 3.25).

IMPACT AREAS		TEN POTENTIAL BENEFITS
Soil health	1	Organic inputs generated from locally produced organic waste provide a source of energy for soil biota and enhance nutrient cycling
	2	Certain soil amendments generated through waste valorization (e.g., biochar) can enhance soil carbon, pH or water retention
Water conservation and quality	3	Recycling and valorizing organic waste help prevent watershed contamination associated with untreated waste streams from coffee wet processing
Biodiversity and land use	4	The practice avoids the negative effects of unprocessed coffee waste disposal on wild biodiversity on and around the farm
Greenhouse gas mitigation	5	Adequate waste processing and recycling help reduce CH_4 or nitrous oxide (N_2O) emissions from organic waste streams
	6	Combining organic inputs with inorganic fertilizers can increase fertilizer-use efficiency and/or soil carbon, providing an opportunity to reduce net GHG emissions
Coffee productivity and input use	7	Using organic inputs can increase coffee productivity through nutrient recovery and improved soil health
	8	Reuse of nutrients from waste streams reduces the need for mineral fertilizer
Farm income and livelihoods	9	Farmers may reduce expenditures on expensive (imported) fertilizers, animal feed or energy
	10	Waste valorization offers opportunities to earn additional farm income, while creating new employment and businesses in rural areas

Figure 3.25. Ten potential benefits of waste valorization and production of organic inputs.

Where should waste valorization and production of organic inputs be implemented?

Waste management and valorization are essential for all farms that employ coffee wet processing regardless of their size. The practice is also crucial for centralized wet mills involved in off-farm processing. Separation of solids from fluids, followed by wastewater treatment (see Chapter 3.4.9) and processing of the slurry, is needed to manage waste effectively. Pulp and mucilage should be reintegrated into farm processes. Mixed coffee farms that combine the crop with animal production must also prioritize recycling of manure to prevent surface water contamination.

Waste valorization can provide a solution for those farmers that cannot apply inorganic fertilizers, for example due to high costs or organic certification. Under those circumstances, organic inputs produced from farm residues and waste offer an excellent alternative for maintaining soil fertility, provided that sufficient amounts of these inputs can be generated.

Waste valorization techniques that generate energy, such as biogas production, are of particular interest for farms that currently rely on fuel wood for cooking or coffee drying. Replacing fuel wood with biogas not only improves indoor air quality and benefits human health but also helps reduce pressure on remaining forests.

What should be considered in implementing this practice?

Different types of residues and waste generated during coffee cultivation and processing can be recycled and valorized on the farm. Described below are various techniques that can be applied on a small or large scale.

Waste valorization techniques

- **Using fresh organic waste:** A first option is to apply organic waste, such as dry coffee pulp, parchment and husks, directly in the field as mulch. However, generating sufficient volumes of waste and transporting them to the field can pose a challenge. Moreover, care should be taken that applying large quantities of untreated fresh organic waste (e.g., pulp) does not result in soil acidification or nutrient immobilization. The latter is likely to happen when the material has a high carbon-to-nitrogen (C:N) ratio (see Box 3.10). Nonetheless, under certain conditions, using fresh organic waste as mulch can be cost-efficient. This technique also helps control soil erosion [170].

- **(Vermi-)composting:** This practice involves controlled decomposition of organic waste to produce nutrient-rich compost. Coffee crop residues, prunings, coffee pulp, coffee mucilage and other organic waste can be composted to create high-quality fertilizer for coffee cultivation. Composting is the spontaneous biological decomposition of organic materials in a predominantly aerobic environment. The practice helps reduce toxic organic compounds and pathogenic microorganisms before returning the organic matter to the field. During composting, the C:N ratio of the organic matter is reduced, preventing immobilization of nutrients by decomposing microbes once the organic inputs are applied to the crop field (see Box 3.10). The process requires controlled humidity (50–60%). It should occur under cover (e.g., under a roof, plastic tarp) and on a concrete floor to prevent leaching and reduce N_2O losses. Initially, the compost pile should be large enough to generate a natural increase in temperature to 55–60°C (thermophilic stage). The high temperature is needed to kill pathogenic microorganisms and sanitize crop residues.

  In traditional composting, organic waste is piled up in rows or heaps. Regular turning of the compost heap is needed to reaerate the pile, promote mixing and stimulate faster and more complete decomposition. Coffee husks and pulp can be composted alone with good results. However, co-composting with animal manure or food waste has the advantage of reducing the C:N ratio of the final product and accelerates decomposition [171].

  Vermicomposting uses earthworms to help decompose organic waste, while enhancing nutrient concentrations. This method is more efficient and less labor intensive than traditional composting,

Coffee producer Leonel Martínez Lodoño (left) showing the composting facility at his farm in Caldas, Colombia | CIAT/M. Pulleman.

which requires manual turning of the compost pile. Vermicomposting facilities can be constructed using basic materials, such as wood, bamboo and bricks. This method can process about a ton of coffee pulp per square meter of worm culture per year, making it feasible and efficient for managing coffee waste [172].

- **Anaerobic digestion:** This process involves the breakdown of organic waste by microorganisms in the absence of oxygen, resulting in the production of biogas and nutrient-rich digestate. Coffee wastewater (including pulp residues, mucilage and other organic waste) can be used as feedstock for anaerobic digesters. The main function is to capture CH_4 generated during the decomposition of organic matter. The biogas produced can be used to dry coffee or meet household needs. Given their simplicity and cost effectiveness, biodigesters offer an attractive solution for on-site wastewater treatment and renewable energy production in rural areas (see Box 3.11). Organic waste is thus used as an energy source, while reducing GHG emissions [162]. The residual slurry (digestate) can be used as a soil amendment. When digestate is stored, it should be covered to avoid N volatilization [173].

  Digestate of good quality does not smell and should not attract flies [173]. The digestate can be applied to the crop or can first be treated, for example, by adding lime and drying [167,173]. Further

Tubular biodigester, Ecuador | Source: Martí Herrero J. [173].

Biogas stove | Source: Martí Herrero J. [173].

research to optimize the use of digestate as an organic fertilizer and to improve soil health on coffee farms should help to further improve the benefits of the technology [162].

- **Biochar production:** This is a process that involves the conversion of biomass into a form of charcoal through pyrolysis or gasification. Pyrolysis occurs in the absence of oxygen, while gasification takes place in an oxygen-poor environment. These thermochemical conversion processes are well-suited for utilizing woody and lignin-rich residues. In the case of coffee production, coffee husks and woody residues such as prunings can serve as feedstock for biochar production.

  Besides biochar, these processes also generate gas that can be used as an energy source, such as for producing heat required in biomass conversion or cooking. The yield of biochar depends on factors such as temperature and residence time of the biomass in the reactor. To enable biochar production in rural areas, there has been significant attention given to the development of small furnaces [174]. Gasifier stoves as well as retort and rotary kilns can be used for small-scale pyrolysis or gasification. The biochar can be used as an absorbent for water treatment (see Chapter 3.4.9) or applied in the field as a soil amendment.

  Biochar is a stable form of organic carbon that persists in soil for hundreds to thousands of years. Biochar has a large surface area and *cation exchange capacity*. It has the potential to reduce soil acidity, improve soil fertility and increase soil C storage. Biochar can increase the pH of the soil and improve soil physical properties, including the aggregation, porosity and water-holding capacity. This way, biochar can create favorable conditions for root development and microbial functions, reduce phytotoxins and stimulate plant development [175].

  The properties of biochar and its effects within agricultural ecosystems largely depend on feedstock and pyrolysis conditions. Studies report a wide range of plant responses to biochars due to the diversity of biochars and contexts in which they have been applied. Biochars thus need to be tailored to address site-specific constraints through feedstock selection, by modifying pyrolysis conditions, through pre- or postproduction treatments, or co-application with organic or mineral fertilizers [175].

While biochar has been studied in various agricultural contexts, there is limited scientific research specifically focused on its use in coffee farming. Further research is necessary to explore the practical application of biochar in coffee farming to maximize its benefits and understand its economic viability.

- **Mushroom production:** Coffee waste can be used as a substrate for cultivating mushrooms to provide additional income. For this purpose, pretreatment is required to remove high concentrations of toxic compounds. An excellent way to detoxify coffee waste is to boil it in water, followed by filtering. Although this technique may not be feasible with large volumes, it has proven effective for enhancing commercial cultivation of mushrooms on coffee waste substrate [167]. The waste resulting from used substrate can be applied directly to the soil as an organic fertilizer [176].
- **Animal feed:** Coffee pulp contains up to 12% protein, making it an excellent nutritional supplement for animals on the farm. However, antinutritional components in coffee waste make it unpalatable to animals and limit nutrient bioavailability. For this reason, coffee waste should not account for more than 20% of the diet for cattle, 16% for pigs and 5% for poultry [167], unless it has been previously treated through, for example, fungal fermentation or boiling. Fungal fermentation degrades toxic compounds in coffee waste under aerobic condition. This may involve the use of naturally occurring fungi in coffee residues or inoculation with specific fungal species, such as *Rhizopus* [177,178]. Another option is to make silage by mixing coffee pulp with molasses (5%) to conserve coffee pulp/husks and partially detoxify them. However, reducing polyphenol content by 80% can take up to 223 days [179].
- **Insect cultivation:** This is a conversion process involving insect larvae, which transforms the residues into protein-rich insect biomass and frass. Residues such as coffee husks can be bio-converted to feed insect larvae – of black soldier fly, for example – producing high-quality protein, which can be used to feed chickens and fish. In addition, a compost of excellent quality can be produced from the residues/frass (insect feces), which reduces the C:N ratio and increases nutrient availability [180]. Insect frass also contains chitin and other compounds, which promote beneficial soil organisms, stimulating plant growth and enhancing disease/pest resistance [181]. Further study is needed to investigate the benefits in coffee cultivation.
- **Compressed husk pellets:** Coffee husks, a byproduct of dry processing, can be compressed into pellets or briquettes, and used as an alternative fuel source for heating or electricity generation. This significantly reduces the volume of residues, making transportation and sale more manageable. However, for most coffee farmers, it is not feasible to apply the high pressure needed to convert crushed or shredded coffee husks into pellets [182]. In Brazil, where large coffee farms and dry processing are common, resulting in substantial volumes of coffee husks, this option can be

commercially viable. It helps reduce dependence on nonrenewable energy sources. However, burning organic matter, even in the form of coffee husk pellets or briquettes, is undesirable because of its effect on coffee's carbon footprint.

Additional considerations

Low-quality compost, which may contain pathogenic microorganisms, can have a detrimental impact on crop growth. To ensure that compost is mature and suitable for application, it should have a C:N ratio below 25:1 [171]. This indicates that the organic matter has undergone sufficient decomposition and is less likely to negatively affect crop growth (see Box 3.10).

Organic fertilizers that have not reached maturity frequently create problems when applied during the seedling stage, causing toxicity in plants [152]. To mitigate potential toxicity, it is advisable to dilute immature organic fertilizers. However, farmers should prioritize the use of mature and stable organic matter. Chemical analysis of organic materials before applying them to the crop is strongly recommended.

Table 3.5. Summary of main waste valorization technologies and suitable feedstocks, and the types of products they generate in the context of coffee production.

VALORIZATION TECHNOLOGY	SUITABLE FEEDSTOCKS	EQUIPMENT OR INFRASTRUCTURE FOR ON-FARM IMPLEMENTATION	PRODUCTS
Anaerobic digestion	Wet, easy degradable residues (e.g., wastewater from food processing and liquid manure)	Low-cost tubular digesters and biodigestion installation	Biogas (energy) and digestate (soil amendment)
(Vermi-) composting	Solid harvest residues, food-processing residues (e.g., coffee pulp), animal manure	Compost piles, composters and earthworm farms	Compost (soil amendment)
Pyrolysis or gasification	Woody, lignin-rich residues (e.g., pruning residues, wood waste and coffee husks)	Gasifier stoves, retort kiln and small-scale gasifiers for power generation	Syngas (energy) and biochar (soil amendment)
Insect farming (e.g., black soldier fly)	Animal manure, food waste, coffee husks	Insect farming and breeding facilities	Larvae (animal protein), cast insect skins or shells and insect frass (soil amendment)
Compressed pellets	Dry biomass fragments (e.g., coffee husks, straw, wood chips, sawdust)	Machine presses	Briquettes and pellets (energy)

Box 3.11. Feasibility study on anaerobic digestion.
Based on Hernández Sarabia M, Sierra Silva J et al. [165]

The tubular "Taiwan type" biodigester offers the advantages of low cost and low maintenance as well as a simple design, that combines the digestion chamber, sedimentation tank and gasometer in a single unit. A study in Colombia examined the performance and financial viability of three different biodigesters fed with coffee waste and animal manure.

Co-digestion with pig manure and cow manure (as a microbial inoculant) performed adequately in generating biogas. Enough energy was produced for domestic use, replacing firewood and liquid propane gas (LPG) on coffee farms. However, the study emphasized the importance of maintaining stable environmental conditions and microbial diversity through the use of different substrates. This was found to be crucial for the efficiency and reliability of the system.

Economic analysis of implementing biodigesters on farms considered the investment, costs and benefits associated with the technology. The major costs include acquisition of the biodigester as well as operations and maintenance. Labor for activities such as collecting substrate, mixing feedstock and feeding the digester account for a significant part of the operational costs.

The benefits of the biodigester system included the generation of biogas for cooking and of digestate (organic fertilizer) as a byproduct together with improved human health and reduced negative impacts on the environment. The study found that reductions in labor for fuelwood collection, combined with the benefits of the biodigester activites (both cost savings on LPG and fertilizer inputs) could offset the investment costs (biodigestor equipment).

Whether the technology is economically viable for farmers depends strongly on the production of organic fertilizer and associated cost savings on external fertilizer inputs, hence the importance of fertilizer prices. In the absence of significant cost savings, government incentives would be needed to encourage the use of biogas from anaerobic wastewater treatment.

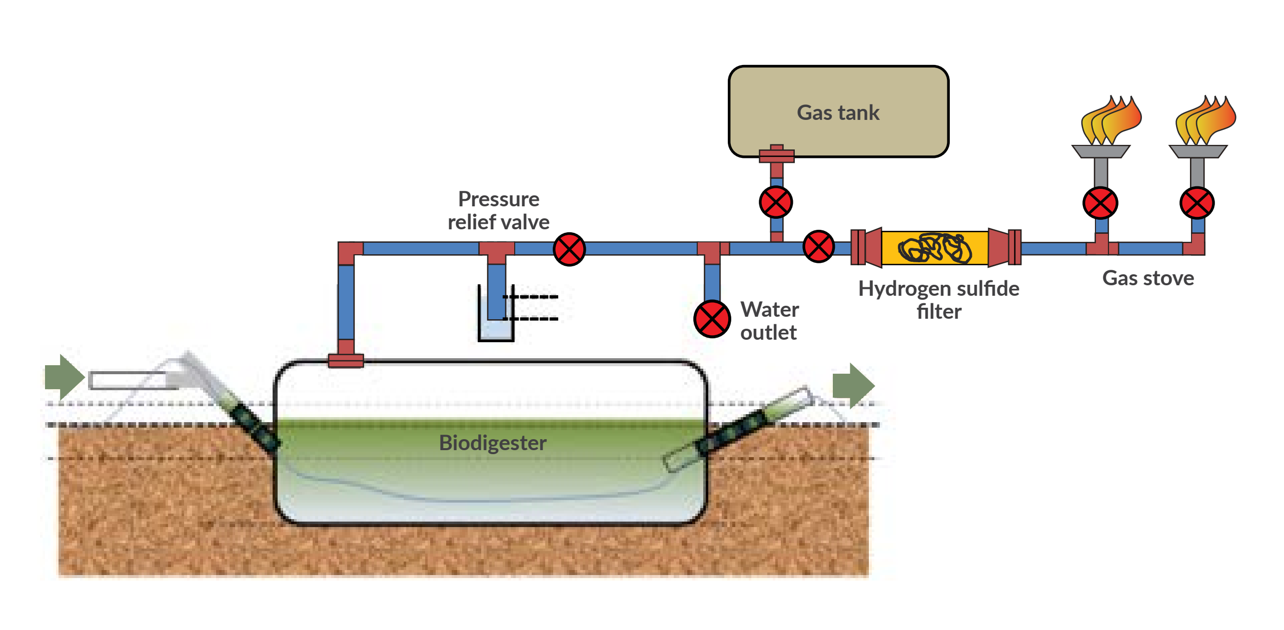

Figure 3.26. Schematic drawing of the components of a biodigester. Source: Martí Herrero J. [173].

What challenges does adoption of the practice pose, and how can they be overcome?

Despite their clear benefits, waste valorization technologies also have limitations, which have so far prevented widespread adoption of organic waste recycling. In general, recycling techniques are knowledge and labor intensive, and monitoring the processes to ensure compliance with quality standards requires considerable effort. These techniques also involve considerable investment in infrastructure.

Simpler techniques, such as composting, are easier to adopt. However, to perform the composting adequately, the construction of basic facilities, such as roofed spaces with concrete floors, is required. Moreover, to accelerate composting and obtain a good quality product, frequent heap turning is required, which is time-consuming and may not be feasible on farms with limited labor availability Vermicomposting may offer a good alternative, as it is less labor intensive, but instead requires more space and infrastructure.

Other technologies, such as anaerobic digestion and biochar production, require specialized and expensive structures. Relatively low-cost systems are available for smaller farms, but these may become profitable only after several years, as the cost analysis of Taiwan type biodigesters in Colombia shows (Box 3.11). The required investment may be partially offset by opportunities to generate additional products that permit savings in farm production costs (e.g., organic fertilizers and animal feed) or to create additional income streams (e.g., mushroom cultivation) [165].

Financial and technical support is essential for farmers, particularly smallholders, to adopt waste valorization practices, and use them correctly and efficiently. This support is especially necessary in the early stages of adoption. Moreover, governments or industry stakeholders may need to provide farmers with financial incentives to help them achieve more sustainable management of residues and waste, based on the principles of circular agriculture.

Waste can be treated either on farm or in shared facilities in the community; the latter can lower processing costs, while also improving efficiency and guaranteeing quality control. In addition, combining different technologies for different waste streams at a centralized location may create opportunities to develop blends of different waste recycling products, resulting in fertilizers that meet farmers' demand for nutrient delivery and soil improvement. It is also important to establish specialized community facilities, which offer a good way to improve technical capacity and quality control, while creating new business opportunities in rural areas. A possible limitation consists of the logistical challenges and extra costs related to transportation between the shared facility and the farm.

Further reading and useful tools

Practical guides on production of organic fertilizers (in English or Spanish):

- Cenicafé. 2004. Produzca abono orgánico en la finca. Cartilla cafetera Vol. 1, No. 8. https://www.cenicafe.org/es/documents/cartillaCafeteraCapitulo8.pdf
- Dávila MT; Ramírez CA. 1996. Lombricultura en pulpa de café. Avances Técnicos Cenicafé 225. http://hdl.handle.net/10778/4248
- FAO. 2013. Manual de Compostaje del Agricultor. Experiencias en América Latina. https://www.fao.org/3/i3388s/I3388S.pdf
- FAO. 2015. Farmer's Compost Handbook. Experiences in Latin America. https://www.fao.org/3/i3388e/I3388E.pdf

Practical manuals on design and installation of tubular biodigesters and gas stoves (in English and Spanish):

- Global Alliance for Clean Cookstoves; MIT D-Lab. 2017. Handbook for Biomass Cookstove Research, Design, and Development. A practical guide to implementing recent advances. https://cleancooking.org/wp-content/uploads/2021/07/517-1.pdf
- Martí Herrero J. 2019. Biodigestores Tubulares: Guía de Diseño y Manual de Instalación. Redbiolac. Ecuador. ISBN: 978-9942-36-276-6. https://bit.ly/3PSi4wM

Recent scientific review article on biochar (not specific to coffee) (in English):

- Joseph S et al. 2021. How biochar works, and when it doesn't: A review of mechanisms controlling soil and plant responses to biochar. GCB Bioenergy 13. https://doi.org/10.1111/gcbb.12885

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3.4.11. Landscape actions

Overview of the practice

Landscape actions are coordinated efforts to conserve and restore natural habitats and their functions. The aim is to protect watersheds, improve habitat quality and reduce habitat fragmentation, thus enhancing biodiversity and ecosystem services. These actions require collaboration among different landscape actors, such as farmers, communities, local governments, environmental authorities, water companies, NGOs and others.

An agricultural landscape can be seen as a mosaic that consists of patches of natural or semi-natural vegetation (e.g., forest remnants or complex agroforests) within an agricultural matrix (e.g., monoculture crops) (see Figure 3.27). The patches are particularly important for biodiversity conservation and must be connected with each other through biological corridors that allow wild species to move through the landscape and find resources (e.g., food), shelter and nesting sites. The habitat quality of the agricultural matrix and the patches, together with the connectivity of the landscape through the presence of green corridors strongly affect the capacity of the landscape to support biodiversity and ecosystem services. Several of those ecosystem services, such as pollination, natural pest control and protection of water quality, directly benefit coffee farmers and communities.

Landscape actions can focus on enhancing connectivity between patches or improving the habitat quality of the matrix, or both. The effectiveness of regenerative practices applied on individual farms or plots can thus be strengthened by complementary interventions at landscape level, and vice versa. Landscape actions are also important for enhancing resilience in the face of climate change and related extreme events, such as fires, floods and landslides. Some examples are:

- **Riparian buffers:** These are vegetation strips along waterways that help to protect water sources and their quality and buffer agricultural lands from floods, while also providing a habitat for fauna and flora. Riparian buffers can be very effective as green corridors.
- **Green corridors:** These are strips of vegetation that connect bigger patches of natural vegetation (e.g., forest remnants) within a landscape, thus decreasing habitat fragmentation.
- **Reforestation of hilltops:** Trees on hilltops are important for protecting or restoring water sources while controlling erosion and providing a habitat for wildlife.
- **Agroforestry:** Promoting the contribution of agroforestry systems in the landscape consisting of diverse tree species arrangements with a complex canopy structure helps to improve the habitat quality for wild species within the agricultural matrix.
- **Living fences or windbreaks:** These are green farm borders that can provide shelter and resources for wild animals, and also help to control soil erosion and the spread of coffee diseases.

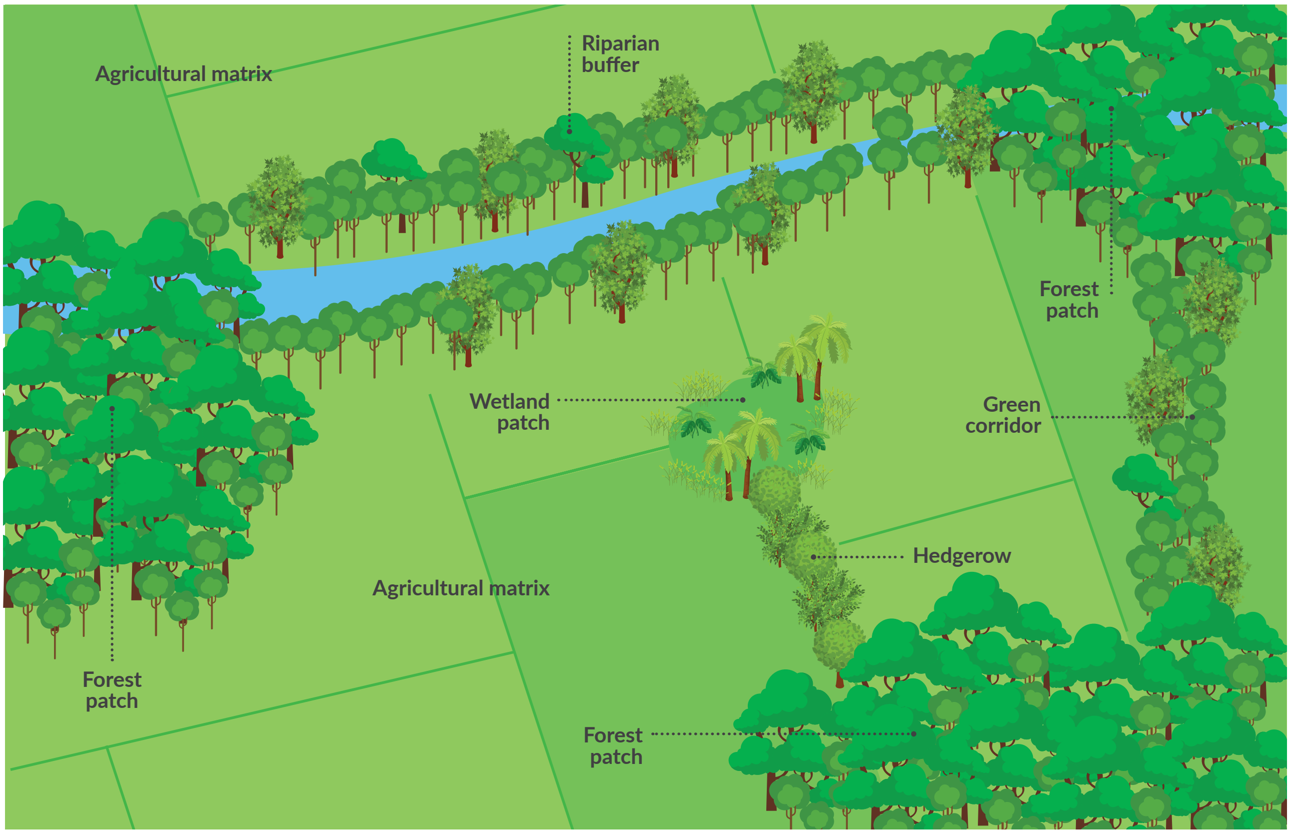

Figure 3.27. A schematic visualization of an agricultural landscape with different forest patches and corridors within the agricultural matrix.

What are the most important benefits?

Regenerative agricultural practices applied on particular fields or farms or across whole communities can have a significant impact on the landscape. Likewise, actions at this higher level can create benefits at lower scales. For example, complex agroforestry systems within individual coffee farms can positively affect dispersal of wild animals across the landscape [183], particularly if connectivity is enabled. Individual farms, in turn, can benefit from surrounding natural habitats that enhance predator diversity and support pollinators. Research has found that coffee pollination by wild bees and fruit setting in Robusta [184] increased with the presence and size of forest patches. Similar findings have been obtained for Arabica, despite this species being largely *self-pollinating* [185]. Complementary interventions at different scales and coordinated action among coffee farmers in a shared landscape also contribute importantly to pest and disease management, as has been shown for coffee beetle borer (CBB) [186] and coffee leaf rust (LR) [187].

Sustainable management of water resources requires an approach that encompasses whole watersheds. Practices that diminish erosion, pesticide use or the improper use of water for irrigation or postharvest processing on coffee farms can create benefits downstream by improving water quality and availability, and by decreasing sedimentation of water reservoirs [188]. Landscape actions such as riparian buffers and erosion control measures can help safeguard water quality and improve water availability while reducing the risk of flooding and landslides, and thus enhance resilience to climate change [189].

IMPACT AREAS	TEN POTENTIAL BENEFITS
Soil health	1 Landscape actions can support control of soil erosion and landslides
Water conservation and quality	2 Decreased sedimentation and contamination of water bodies 3 Landscape actions can improve water retention and storage to diminish flooding risks
Biodiversity and land use	4 Increased habitat quantity, quality and connectivity, which benefit wild biodiversity (fauna and flora) 5 Positive effects on biodiversity functions, such as provision of natural pest enemies, pollinators and seed dispersers
Greenhouse gas mitigation	6 Carbon storage in conserved and restored natural vegetation on farms and across landscapes
Coffee productivity and input use	7 Improved pollination and pest control to enhance coffee productivity 8 Natural pest control, which decreases the need for chemical pesticides
Farm income and livelihoods	9 Decreased vulnerability to extreme events, such as floods, landslides and hurricanes 10 Opportunities for income diversification based on tourism, forest products, honey and payment for ecosystem services

Figure 3.28. Ten potential benefits of landscape actions.

Landscape actions that enhance ecosystem services can create win-win opportunities, both enhancing biodiversity and creating benefits for farmers in terms of sustainable agricultural production. Local communities can further benefit from landscape actions through payment for ecosystem services (PES), and responsible use of forest products (Figure 3.28). Strong partnerships that involve community organizations together with enabling policies and improved market access make it more likely for these landscape management strategies to succeed [190].

Beekeeping in coffee fields | Nestlé.

Where should landscape actions be implemented?

Although landscape actions can benefit any coffee-growing region, they should receive priority in the following situations:

- Homogeneous landscapes with a large proportion of the area under agricultural production
- Large farms or continuous clusters of smallholder farms, especially where these are dedicated to coffee monoculture
- Degraded landscapes with little natural habitat remaining
- Regions that are susceptible to climate change and extreme events, such as hurricanes, flooding and drought
- Landscapes that are sensitive to erosion and landslides
- Landscapes with water scarcity and conflicting demands
- Landscapes with poor water quality due to pollution or sedimentation
- Regions with strong community organizations or with a tradition of participatory decision-making about shared resources
- Areas with Robusta coffee, largely depending on cross-pollination

What should be considered in implementing landscape actions?

Landscape actions can be implemented through three complementary strategies that focus on: (i) conserving or restoring natural vegetation patches on farms and in the surrounding landscape, (ii) improving connectivity between existing patches of natural vegetation through green corridors, and (iii) improving habitat quality within the agricultural matrix (including coffee plots).

Riparian corridors, formed by natural buffer zones around streams and waterways, are especially important target areas for conservation and restoration. They not only protect water bodies but also offer the opportunity to create a network of connected natural habitats, which favor the presence and dispersal of native flora and wildlife.

Habitat quality depends on the availability of resources that wild animals and insects require, such as shelter, nectar and pollen, alternative prey or hosts, and fruits. Since different species move over varying distances and need different resources at different times, it is crucial to enhance habitat complexity. For instance, hollow twigs, rotten logs and leaf litter on the ground can increase CBB predation by ants [[191]]. Regenerative agricultural practices such as agroforestry, integrated weed management and soil conservation (by means of cover cropping or hedges) can enhance these resources on farms. The connected network of natural vegetation patches also provides reservoirs of biodiversity, which is key for species that require less disturbed areas and move over longer distances. For best results, it is important to integrate measures on coffee plots and farms with collective action across the landscape.

There is no simple recipe for planning and implementing landscape actions. Instead, it is important to follow the principles or guidelines listed below, although not necessarily in this order:

- **Assess and understand the landscape baseline.**
  - Map the landscape, including natural vegetation patches (forest cover, protected areas and wetlands) as well as the agricultural matrix (including coffee plantations). Add other land uses, water bodies and streams.
  - Assess habitat quality in different areas based on their size and shape, level of intensification (e.g., canopy cover and plant diversity) and conservation value based on the presence of endangered species or species of high ecological, cultural or economic value.
- **Improve the network of natural vegetation patches.**
  - Identify strategic interventions for improvement, depending on the goals of landscape management and the baseline conditions.
  - Prioritize forest conservation and restoration areas along waterways and streams as well as around springs but especially on hilltops and in areas with steep slopes and unstable soils.
  - When possible, use strategies for natural regeneration of forest trees or habitats through the establishment of naturally dispersed plant species (to decrease costs and labor).
- **Improve habitat quality within the agricultural matrix.**

  For this purpose, apply regenerative practices on farms, such as the use of multi-strata, diverse agroforestry, living fences or windbreaks, preferably including native tree species and those that offer shelter and resources for wildlife.
- **Promote collective decision-making among landscape actors.**
  - Involve the relevant actors at an early stage, including farmers, communities, local government, civil society organizations, NGOs, water and forest management authorities, private companies and others.
  - Keep in mind that different actors have different cultural values, perspectives and power relations, and might also have conflicting goals that need to be managed carefully.
- **Identify ways to finance and incentivize landscape actions.**
  - Identify direct or indirect economic benefits that can be realized from conservation areas – for example, through sustainable use of wild plant species for timber and non-timber forest products (such as fruits, wood and medicine) or through other activities such as ecotourism or beekeeping.
  - Explore opportunities for PES through public policies or market schemes – involving, for example, watershed protection, biodiversity conservation or carbon storage (see Box 3.12).

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- **Develop clear goals and a coordinated action plan for implementation.**
  - Foster consensus around landscape actions that respond to external threats (such as climate change or the spread of a new coffee disease) or to threats from inside the system (such as forest degradation, water pollution caused by pesticide use, water scarcity and frequent flooding).
  - In determining priorities, take into account the culture and perceptions of the actors involved as well as the available resources, relevant policies and technical criteria.
  - Clearly define the responsibilities of each actor, with concrete, achievable objectives and activities as well as methods and indicators to monitor progress and make adjustments when needed.

What challenges does adoption of the practice pose, and how can these be overcome?

Whether or not coffee farmers participate in landscape actions depends on their understanding of how these can affect coffee production and their livelihood as well as on the social and cultural context. Farmers are more likely to engage in actions for which they perceive direct benefits or that respond to an immediate threat, such as the loss of water security. This is why it is important to promote awareness of the ecological value and economic payoffs from landscape actions.

Conflicting land uses or policies as well as *tradeoffs* between environmental and economic goals might hinder landscape actions. For example, setting aside highly productive land for conservation might clash with private economic interests and cultural values. Similarly, the proximity of farms to natural areas might pose risks of wildlife damaging cropping systems.

The larger the scale on which landscape actions are implemented, the more complex they tend to be. Moreover, landscape management is knowledge intensive; designing a long-term strategy requires a good understanding of ecological processes. Landscape actions thus tend to be more successful when strong organizations are present in the territory and can facilitate participatory decision-making and cooperation among stakeholders. NGOs and research institutions can help align different stakeholders and provide local actors with technical guidance in planning and monitoring.

One key challenge is that landscape actions require collective commitment and the investment of resources (such as productive land, labor and money), without offering immediate economic benefits to individual farmers. Financial support from private and public institutions is therefore crucial. PES schemes are a good alternative for providing economic incentives for landscape actions (see Box 3.12).

Box 3.12. Examples of incentive schemes for landscape actions that create economic benefits for farmers

Economic compensation schemes, such as payment for ecosystem services (PES) or direct payments from governments or the private sector, can provide incentives to farmers that engage in landscape actions. Farmers can also seek certifications that promote forest conservation and add value to their products (e.g., Rainforest Alliance and 4C) or participate in environmental markets such as that for carbon credits. Described below are three examples of these strategies.

PES scheme

The SAF program, a government-promoted PES scheme for farmers in Costa Rica, has proved successful in providing smallholders with incentives to plant trees on their farms. Paying up to US$1.30 per tree planted, the program resulted in more than 1.2 million trees being planted between 2004 and 2007 [192]. PES schemes can also be local, small-scale initiatives, such as that created by the water council in the Cumes River basin of Honduras. The council collects a small monthly fee of US$ 0.06 per household to compensate coffee farmers upstream for adopting waste management practices and forest protection [193].

Certification

According to studies in Ethiopia, Rainforest Alliance certification of forest coffee has successfully promoted conservation by offering farmers a premium price. In the five years following certification, the probability of forest conservation was 19% higher in certified forest coffee areas than in non-certified ones [194]. Rainforest-certified coffee farms in Brazil showed similar results over 10 years, decreasing deforestation rates and improving the conservation of native species and wildlife corridors, compared to the surrounding landscape [195].

Carbon credits

The Hiniduma Bio-link Project, promoted by the Conservation Carbon Company in Sri Lanka, aims to conserve patches of pristine forest while restoring biological corridors to connect natural areas within the agricultural landscape. The program is financed through the sale of certificates for carbon sequestration. For this purpose, native trees were selected on the basis of their ecological value and potential service provision (e.g., non-timber forest products) and distributed to farmers. As a result of direct payments from this program, farmers increased their monthly income by 10%, or 25% when the sale of non-timber forest products from planted trees was included [196].

Further reading and useful tools

Participatory mapping tool:

- Braslow J et al. 2016. A guide for participatory mapping of ecosystem services in multiuse agricultural landscapes: How to conduct a rapid spatial assessment of ecosystem services. CIAT, Cali, Colombia. 96 p. https://hdl.handle.net/10568/77762

A social mapping tool that can be applied for the diagnosis of landscapes integrating cultural and biophysical analyses to define landscape actions, and is freely available in multiple languages:

- Buckingham K et al. 2018. Mapping social landscapes: A guide to identifying the networks, priorities, and values of restoration actors. World Resources Institute. 96 p. https://www.folur.org/sites/default/files/2022-03/18_Guide_SocialMapping_FINAL3.pdf

3.5. References

1. Bunn C; Läderach P; Pérez Jimenez JG; Montagnon C; Schilling T. 2015. Multiclass Classification of Agro-Ecological Zones for Arabica Coffee: An Improved Understanding of the Impacts of Climate Change. *PLOS ONE* 10. http://doi.org/10.1371/journal.pone.0140490

2. Solymosi K; Techel G. 2019. Brewing up climate resilience in the coffee sector. Adaptation strategies for farmers, plantations and producers. https://bit.ly/3QeB2xR (Accessed on 11 March 2023).

3. IDH. 2019. Coffee production in the face of climate change: Country profiles. https://bit.ly/44sKXnI (Accessed on 11 March 2023).

4. Piato K; Lefort F; Subía C; Caicedo C; Calderón D; Pico J; et al. 2020. Effects of shade trees on robusta coffee growth, yield and quality. A meta-analysis. *Agronomy for Sustainable Development* 40. https://doi.org/10.1007/s13593-020-00642-3

5. Harvey CA; Pritts AA; Zwetsloot MJ; Jansen K; Pulleman MM; Armbrecht I; et al. 2021. Transformation of coffee-growing landscapes across Latin America. A review. *Agronomy for Sustainable Development* 41. http://doi.org/10.1007/s13593-021-00712-0

6. Bunn C; Läderach P; Ovalle Rivera O; Kirschke D. 2015. A bitter cup: climate change profile of global production of Arabica and Robusta coffee. *Climatic Change* 129. http://doi.org/10.1007/s10584-014-1306-x

7. Ovalle-Rivera O; Läderach P; Bunn C; Obersteiner M; Schroth G. 2015. Projected shifts in *Coffea arabica* suitability among major global producing regions due to climate change. *PLOS ONE* 10. http://doi.org/10.1371/journal.pone.0124155

8. Browning D; Moayyad S. 2017. Social Sustainability-Community, Livelihood, and Tradition. In: The Craft and Science of Coffee. Elsevier Inc., 31. http://doi.org/10.1016/B978-0-12-803520-7.00005-0

9. Enviritas. 2000. Bringing Smallholder Coffee Farmers out of Poverty. https://carto.com/blog/enveritas-coffee-poverty-visualization (Accessed on 21 April 2023).

10. Pal Singh V; Bhushan Sinha R; Nayak D; Neufeldt H; Van Noordwijk M; Rizvi J. 2016. The national agroforestry policy of India: experiential learning in development and delivery phases. New Delhi. http://doi.org/10.5716/WP16143.PDF

11. Rigal C; Vaast P; Xu J. 2018. Using farmers' local knowledge of tree provision of ecosystem services to strengthen the emergence of coffee-agroforestry landscapes in southwest China. *PLOS ONE* 13. http://doi.org/10.1371/journal.pone.0204046

12. ICO. 2014. World Coffee Trade: A Review of the Markets, Challenges and Opportunities Facing the Sector. http://www.ico.org/news/icc-111-5-r1e-world-coffee-outlook.pdf (Accessed on 29 November 2022).

13. Giller KE; Hijbeek R; Andersson JA; Sumberg J. 2021. Regenerative Agriculture: An agronomic perspective. Outlook on Agriculture 50. http://doi.org/10.1177/0030727021998063

14. USAID. 2017. Renovation & Rehabilitation for Resilient Coffee Farms: A Guidebook for Roasters, Traders and Supply Chain Partners. https://bit.ly/3DgX3Ep (Accessed on 1 December 2022).

15. Van Rikxoort H; Schroth G; Läderach P; Rodríguez-Sánchez B. 2014. Carbon footprints and carbon stocks reveal climate-friendly coffee production. *Agronomy for Sustainable Development* 34. http://doi.org/10.1007/s13593-014-0223-8

16. Netsere A; Kufa T; Shimber T. 2015. Review of Arabica coffee management research in Ethiopia. *Journal of Biology, Agriculture and Healthcare* 5. ISSN 2225-093X. https://bit.ly/3QkEQ0i

17. Cenicafé. 1992. La renovación de los cafetales por zoca. Avances Técnicos 0174. https://www.cenicafe.org/es/publications/avt0174.pdf

18. Campuzano-Duque LF; Blair MW. 2022. Strategies for Robusta Coffee (*Coffea canephora*) Improvement as a New Crop in Colombia. *Agriculture* 12. http://doi.org/10.3390/agriculture12101576

19. Etienne H; Breton D; Breitler JC; Bertrand B; Déchamp E; Awada R; et al. 2018. Coffee somatic embryogenesis: How did research, experience gained and innovations promote the commercial propagation of elite clones from the two cultivated species? *Frontiers in Plant Science* 871. http://doi.org/10.3389/fpls.2018.01630

20. Andrade Jr. S de; Sobreira Alexandre R; Romais Schmildt E; Partelli FL; Ferrão MAG; Luiz Mauri A. 2013. Comparison between grafting and cutting as vegetative propagation methods for Conilon coffee plants. *Acta Scientiarum Agronomy* 35. http://doi.org/10.4025/actasciagron.v35i4.16917

21. Evizal R; Sugiatno S; Dwi Utomo S; Pujisiswanto H; Widagdo S; Erry Prasmatiwi F; et al. 2018. Growth Performance of Mature Trees Resulted from Intra and Inter-specific Grafting on Robusta Coffee. *Planta Tropika: Journal of Agro Science* 6. http://doi.org/10.18196/pt.2018.083.77-83

22. Marie L; Abdallah C; Campa C; Courtel P; Bordeaux M; Navarini L; et al. 2020. G × E interactions on yield and quality in *Coffea arabica*: new F1 hybrids outperform American cultivars. *Euphytica* 216. http://doi.org/10.1007/s10681-020-02608-8

23. Breitler J-C; Etienne H; Léran S; Marie L; Bertrand B. 2022. Description of an Arabica Coffee Ideotype for Agroforestry Cropping Systems: A Guideline for Breeding More Resilient New Varieties. *Plants* 11. http://doi.org/10.3390/plants11162133

24. Damatta F; Rodríguez N. 2007. Sustainable production of coffee in agroforestry systems in the Neotropics: an agronomic and ecophysiological approach. *Agronomía Colombiana* 25. http://www.scielo.org.co/pdf/agc/v25n1/v25n1a13.pdf

25. Gassner A; Dobie P. 2022. Agroforestry: a primer. Design and management principles for people and the environment. Bogor. http://doi.org/10.5716/cifor-icraf/BK.25114

26. Damatta FM; Ronchi CP; Maestri M; Barros RS. 2007. Ecophysiology of coffee growth and production. *Brazilian Journal of Plant Physiology* 19. https://doi.org/10.1590/S1677-04202007000400014

27. Farfán F. 2014. Agroforestería y Sistemas Agroforestales con Café. Cenicafé, Manizales, Caldas (Colombia). 342 p. ISBN 978-958-8490-16-8.

28. Ehrenbergerová L; Cienciala E; Kučera A; Guy L; Habrová H. 2016. Carbon stock in agroforestry coffee plantations with different shade trees in Villa Rica, Peru. *Agroforestry Systems* 90. http://doi.org/10.1007/s10457-015-9865-z

29. Zaro GC; Caramori PH; Yada Junior GM; Sanquetta CR; Filho AA; Nunes ALP; et al. 2020. Carbon sequestration in an agroforestry system of coffee with rubber trees compared to open-grown coffee in southern Brazil. *Agroforestry Systems* 94. http://doi.org/10.1007/s10457-019-00450-z

30. Negash M; Starr M. 2015. Biomass and soil carbon stocks of indigenous agroforestry systems on the south-eastern Rift Valley escarpment, Ethiopia. *Plant and Soil* 393. http://doi.org/10.1007/s11104-015-2469-6

31. Noponen MRA; Healey JR; Soto G; Haggar JP. 2013. Sink or source – The potential of coffee agroforestry systems to sequester atmospheric CO_2 into soil organic carbon. *Agriculture, Ecosystems & Environment* 175. http://doi.org/10.1016/j.agee.2013.04.012

32. Tumwebaze SB; Byakagaba P. 2016. Soil organic carbon stocks under coffee agroforestry systems and coffee monoculture in Uganda. *Agriculture, Ecosystems & Environment* 216. http://doi.org/10.1016/j.agee.2015.09.037

33. Rezende MQ; Venzon M; Santos PS dos; Cardoso IM; Janssen A. 2021. Extrafloral nectary-bearing leguminous trees enhance pest control and increase fruit weight in associated coffee plants. *Agriculture, Ecosystems & Environment* 319. http://doi.org/10.1016/J.AGEE.2021.107538

34. Tumwebaze SB; Byakagaba P. 2016. Soil organic carbon stocks under coffee agroforestry systems and coffee monoculture in Uganda. *Agriculture, Ecosystems & Environment* 216. http://doi.org/10.1016/J.AGEE.2015.09.037

35. Farfán F. 2007. Producción de café en sistemas agroforestales. In: Ospina H; Marín S, eds. Sistemas de producción de café en Colombia. Cenicafé. https://bit.ly/3Yjq4Jm

36. Mesquita CM. 2016. Manual do café: Implantação de cafezais. Belo Horizonte, 2016.

37. Padovan MP; Brook RM; Barrios M; Cruz-Castillo JB; Vilchez-Mendoza SJ; Costa AN; et al. 2018. Water loss by transpiration and soil evaporation in coffee shaded by *Tabebuia rosea Bertol.* and *Simarouba glauca* dc. compared to unshaded coffee in sub-optimal environmental conditions. *Agricultural and Forest Meteorology* 248. http://doi.org/10.1016/j.agrformet.2017.08.036

38. Orwa C; Mutua A; Kindt r; Simons A; Jamnadass RH. 2009. Agroforestree database: a tree reference and selection guide, version 4.0. https://apps.worldagroforestry.org/treedb/ (Accessed on 12 December 2022).

39. Somarriba E; Zamora R; Barrantes J; Sinclair FL; Quesada F. 2023. ShadeMotion: tree shade patterns in coffee and cocoa agroforestry systems. *Agroforestry Systems* 97. http://doi.org/10.1007/s10457-022-00784-1

40. Souza HN de; Graaff J de; Pulleman MM. 2012. Strategies and economics of farming systems with coffee in the Atlantic Rainforest Biome. *Agroforestry Systems* 84. http://doi.org/10.1007/s10457-011-9452-x

41. Van Asten PJA; Wairegi LWI; Mukasa D; Uringi NO. 2011. Agronomic and economic benefits of coffee–banana intercropping in Uganda's smallholder farming systems. *Agricultural Systems* 104. http://doi.org/10.1016/j.agsy.2010.12.004

42. Thi Duong Nga N, Thuy PT. 2017. Economic performance of coffee and pepper intercropping in Quang Hiep commune, Cumgar district, Dak Lak province. *Journal des Sciences et Technologies Agricoles* 15. https://hdl.handle.net/2268/235821

43. Mekonnen B; Temteme S; Getachew Seyum E; Netsere A; Hailemichael G. 2020. Intercropping Coffee and Korarima at Tepi, Southwest Ethiopia. *American Journal of Agriculture and Forestry* 8. http://doi.org/10.11648/j.ajaf.20200804.20

44. Malézieux E; Crozat Y; Dupraz C; Laurans M; Makowski D; Ozier-Lafontaine H; et al. 2009. Mixing plant species in cropping systems: concepts, tools and models. A review. *Agronomy for Sustainable Development* 29. http://doi.org/10.1051/agro:2007057

45. Harelimana A; Goff G le; Ntirushwa Rukazambuga DT; Hance T. 2018. Coffee Production Systems: Evaluation of Intercropping System in Coffee Plantations in Rwanda. *Journal of Agricultural Science* 10. http://doi.org/10.5539/jas.v10n9p17

46. Rapidel B; Coq J-F le; Beer J. 2011. Ecosystem Services from Agriculture and Agroforestry: measurement and payment. (DeClerk F, Coq JF le, Rapidel B, Beer J, eds.). Routledge. http://doi.org/10.4324/9781849775656

47. Avelino J; Hoopen GM ten; DeClerck FAJ. 2012. Ecological mechanisms for pest and disease control in coffee and cacao agroecosystems of the Neotropics. In: Ecosystem services from agriculture and agroforestry. Routledge.

48. Landis DA; Wratten SD; Gurr GM. 2000. Habitat Management to Conserve Natural Enemies of Arthropod Pests in Agriculture. *Annual Review of Entomology* 45. http://doi.org/10.1146/annurev.ento.45.1.175

49. Opoku-Ameyaw K; Oppong F; Ofori-Frimpong K; Amoah F; Osei-Bonsu K. 2005. Intercropping robusta coffee with some edible crops in Ghana: Agronomic performance and economic returns. *Ghana Journal of Agricultural Science* 36. http://doi.org/10.4314/gjas.v36i1.2059

50. Moreno A; Sánchez P. 2012. Reduzca los costos en el establecimiento del café: Intercale cultivos transitorios. Manizales.

51. Pacheco Bustos A; Pohlan HAJ; Schulz M. 2008. Interaction between Coffee (*Coffea arabica* L.) and intercropped herbs under field conditions in the Sierra Norte of Puebla, Mexico. *Journal of Agriculture and Rural Development in the Tropics and Subtropics* 109. https://bit.ly/3OTYAa0

52. Dávila-Solarte P; Sanginés-García L; Amezcua T; Solano L. 2019. Productive performance and economic evaluation of sheep grazing on weeds in coffee plantations compared to pastures with or without supplementation. *Agroforestry Systems* 93. http://doi.org/10.1007/s10457-017-0165-7

53. Torres JA. 2005. Effect of sheep grazing on coffee quality. In: Silvopastoralism and sustainable land management. Proceedings of an international congress on silvopastoralism and sustainable management held in Lugo, Spain, April 2004. UK: CABI Publishing. http://doi.org/10.1079/9781845930011.0204

54. Van Asten P; Ochola D; Wairegi L; Nibasumba A; Jassogne L; Mukasa D. 2015. Coffee-Banana Intercropping: Implementation guidance for policymakers and investors. https://hdl.handle.net/10568/69017

55. Verbist B; Poesen J; Van Noordwijk M; Widianto; Suprayogo D; Agus F; et al. 2010. Factors affecting soil loss at plot scale and sediment yield at catchment scale in a tropical volcanic agroforestry landscape. *CATENA* 80. http://doi.org/10.1016/j.catena.2009.08.007

56. Iijima M; Izumi Y; Yuliadi E; Sunyoto; Afandi; Utomo M. 2003. Erosion Control on a Steep Sloped Coffee Field in Indonesia with Alley Cropping, Intercropped Vegetables, and No-Tillage. *Plant Production Science* 6. http://doi.org/10.1626/pps.6.224

57. Silva RF da; Severiano E da C; Oliveira GC de; Barbosa SM; Peixoto DS; Tassinari D; et al. 2021. Changes in soil profile hydraulic properties and porosity as affected by deep tillage soil preparation and *Brachiaria* grass intercropping in a recent coffee plantation on a naturally dense Inceptisol. *Soil and Tillage Research* 213. http://doi.org/10.1016/j.still.2021.105127

58. Concenço G; Motta I de S; Melo T; Silva L; Mariani A. 2015. Ocorrência de plantas espontâneas em café solteiro ou consorciado com braquiária. In: IX Congresso Brasileiro de Agroecologia. Belem.

59. Woods Pedrosa A; Favarin JL; Ocheuze PC; Soares AL; Vasconcelos B; Carvalho PP. 2013. Balanço do nitrogênio no consórcio entre cafeeiro e brachiaria. In: VIII Simpósio de Pesquisa dos Cafés do Brasil. Salvador.

60. Rocha O; Guerra A; Gerosa ML; Veiga A; Ferreira G; Costa G; et al. 2015. Relação solo-água em função da brachiaria nas entrelinhas do café no cerrado. In: IX Simpósio de Pesquisa dos Cafés do Brasil. Curitiba.

61. Nzeyimana I; Hartemink AE; Ritsema C; Stroosnijder L; Lwanga EH; Geissen V. 2017. Mulching as a strategy to improve soil properties and reduce soil erodibility in coffee farming systems of Rwanda. *CATENA* 149. http://doi.org/10.1016/j.catena.2016.08.034

62. Delgado JA; Barrera Mosquera VH; Alwang JR; Villacis-Aveiga A; Cartagena Ayala YE; Neer D; et al. 2021. Potential use of cover crops for soil and water conservation, nutrient management, and climate change adaptation across the tropics. *Advances in Agronomy* 165. http://doi.org/10.1016/bs.agron.2020.09.003

63. Rose TJ; Kearney LJ; Morris S; Van Zwieten L; Erler DV. 2019. Pinto peanut cover crop nitrogen contributions and potential to mitigate nitrous oxide emissions in subtropical coffee plantations. *Science of The Total Environment* 656. http://doi.org/10.1016/j.scitotenv.2018.11.291

64. Rosado M da C; Araújo GJ de; Pallini A; Venzon M. 2021. Cover crop intercropping increases biological control in coffee crops. *Biological Control* 160. http://doi.org/10.1016/j.biocontrol.2021.104675

65. Meylan L; Merot A; Gary C; Rapidel B. 2013. Combining a typology and a conceptual model of cropping system to explore the diversity of relationships between ecosystem services: The case of erosion control in coffee-based agroforestry systems in Costa Rica. *Agricultural Systems* 118. http://doi.org/10.1016/j.agsy.2013.02.002

66. Paningbatan EP; Ciesiolka CA; Coughlan KJ; Rose CW. 1995. Alley cropping for managing soil erosion of hilly lands in the Philippines. *Soil Technology* 8. http://doi.org/10.1016/0933-3630(95)00019-4

67. Bekele Jiru E. 2019. Review: Role of Vetiver Grass for Soil and Water Conservation in Ethiopia. *International Journal of Agricultural Economics* 4. http://doi.org/10.11648/j.ijae.20190403.11

68. Sotomayor-Ramírez D; Ramírez-Ávila J; Más E; Martínez GA. 2008. Erosion and nutrient loss reduction with an alternative planting method for coffee (*Coffea arabica*). *The Journal of Agriculture of the University of Puerto Rico* 92. http://doi.org/10.46429/jaupr.v92i3-4.2633

69. Raizada M. 2018. Encyclopedia of subsistence farming solutions: SAKpedia. 2018 ed. Guelph: University of Guelph. http://hdl.handle.net/10625/57144

70. Mota RP da; Almeida RF de; Lemes EM; Buiatti C; Alvarenga L; Magela MLM; et al. 2018. Soil attributes in conventional tillage of *Coffea arabica* L.: A Case Study. *Coffee Science* 13. http://doi.org/10.25186/cs.v13i2.1411

71. Ajayi AE; Tassinari D; Araujo-Junior CF; Faloye OT; Abayomi F; Dias Junior M de souza; et al. 2021. Long-term no tillage management impact on soil hydro-physical properties in coffee cultivation. *Geoderma* 404. http://doi.org/10.1016/j.geoderma.2021.115306

72. Bucagu C; Vanlauwe B; Giller KE. 2013. Managing *Tephrosia* mulch and fertilizer to enhance coffee productivity on smallholder farms in the Eastern African Highlands. *European Journal of Agronomy* 48. http://doi.org/10.1016/j.eja.2013.02.005

73. Mayerly A; Suárez F; Valencia F; Morales-Londoño C. 2005. Biomasa seca y contenido de nutrientes de *Cajanus cajan*, *Crotalaria juncea* y *Tephrosia candida* empleadas como abonos verdes en cafetales. Cenicafé 56. https://bit.ly/44RwLow

74. Ronchi CP; Silva AA. 2006. Effects of weed species competition on the growth of young coffee plants. *Planta Daninha* 24. http://doi.org/10.1590/S0100-83582006000300001

75. Lopes SA; Marcussi S; Torres SCZ; Souza V; Fagan C; França SC; et al. 2003. Weeds as Alternative Hosts of the Citrus, Coffee, and Plum Strains *Xylella fastidiosa* in Brazil. *Plant Disease* 87. http://doi.org/10.1094/PDIS.2003.87.5.544

76. Granados-Montero M; Avelino J; Arauz-Cavallini F; Castro S; Ureña N. 2017. IX Congreso Latinoamericano de Micología. In: Patogenicidad de cepas de *Mycena citricolor* (Berk. & M.A. Curtis) Sacc provenientes de vegetación acompañante en cafeto. Lima, 2017.

77. Murphy CE; Lemerle D. 2006. Continuous cropping systems and weed selection. *Euphytica* 148. http://doi.org/10.1007/s10681-006-5941-9

78. Staver C; Juventia S; Navarrete E; Navarrete L; Sepulveda N; Barrios M. 2020. Long-term response of groundcover components to organic and conventional weed control in shaded and open-sun coffee in Nicaragua. *Crop Protection* 133. http://doi.org/10.1016/j.cropro.2020.105150

79. García-Pérez JA; Alarcón-Gutiérrez E; Perroni Y; Barois I. 2014. Earthworm communities and soil properties in shaded coffee plantations with and without application of glyphosate. *Applied Soil Ecology* 83. http://doi.org/10.1016/j.apsoil.2013.09.006

80. Knezevic SZ; Jhala A; Datta A. 2017. Integrated Weed Management. In: Encyclopedia of Applied Plant Sciences. Elsevier. http://doi.org/10.1016/B978-0-12-394807-6.00231-8

81. Hauggaard-Nielsen H; Jensen ES. 2005. Facilitative root interactions in intercrops. In: Lambers H; Colmer TD. (eds). Root Physiology: from Gene to Function. Plant Ecophysiology, vol 4. Springer, Dordrecht. https://doi.org/10.1007/1-4020-4099-7_13

82. Staver C; Guharay F; Monterroso D; Muschler RG. 2001. Designing pest-suppressive multistrata perennial crop systems: shade-grown coffee in Central America. *Agroforestry Systems* 53. http://doi.org/10.1023/A:1013372403359

83. Caamal-Maldonado JA; Jiménez-Osornio JJ; Torres-Barragán A; Anaya AL. 2001. The Use of Allelopathic Legume Cover and Mulch Species for Weed Control in Cropping Systems. *Agronomy Journal* 93. http://doi.org/10.2134/agronj2001.93127x

84. Aguilar V; Staver C; Milberg P. 2003. Weed vegetation response to chemical and manual selective ground cover management in a shaded coffee plantation. *Weed Research* 43. http://doi.org/10.1046/j.1365-3180.2003.00318.x

85. Bradshaw L; Lanini WT. 1995. Use of perennial cover crops to suppress weeds in Nicaraguan coffee orchards. *International Journal of Pest Management* 41. http://doi.org/10.1080/09670879509371947

86. Renz MJ; DiTomaso JM. 2004. Mechanism for the enhanced effect of mowing followed by glyphosate application to resprouts of perennial pepperweed *Lepidium latifolium*. *Weed Science* 52. http://doi.org/10.1614/WS-03-024R

87. Motisi N; Ribeyre F; Poggi S. 2019. Coffee tree architecture and its interactions with microclimates drive the dynamics of coffee berry disease in coffee trees. *Scientific Reports* 9. http://doi.org/10.1038/s41598-019-38775-5

88. Agegnehu E; Thakur A; Mulualem T. 2015. Potential Impact of Climate Change on Dynamics of Coffee Berry Borer (*Hypothenemus hampi* Ferrari) in Ethiopia. *Open Access Library Journal* 2. http://doi.org/10.4236/oalib.1101127

89. Aristizábal L; Bustillo A; Arthurs S. 2016. Integrated Pest Management of Coffee Berry Borer: Strategies from Latin America that Could Be Useful for Coffee Farmers in Hawaii. *Insects* 7. http://doi.org/10.3390/insects7010006

90. Avelino J; Willocquet L; Savary S. 2004. Effects of crop management patterns on coffee rust epidemics. *Plant Pathology* 53. http://doi.org/10.1111/j.1365-3059.2004.01067.x

91. Assis GA; Assis FA; Scalco MS; Parolin FJT; Fidelis I; Moraes JC; et al. 2012. Leaf miner incidence in coffee plants under different drip irrigation regimes and planting densities. *Pesquisa Agropecuária Brasileira* 47. http://doi.org/10.1590/S0100-204X2012000200002

92. Perfecto I; Hajian-Forooshani Z; White A; Vandermeer J. 2021. Ecological complexity and contingency: Ants and lizards affect biological control of the coffee leaf miner in Puerto Rico. *Agriculture, Ecosystems & Environment* 305. http://doi.org/10.1016/j.agee.2020.107104

93. Venzon M. 2021. Agro-Ecological Management of Coffee Pests in Brazil. *Frontiers in Sustainable Food Systems* 5. http://doi.org/10.3389/fsufs.2021.721117

94. Peñalver-Cruz A; Alvarez-Baca JK; Alfaro-Tapia A; Gontijo L; Lavandero B. 2019. Manipulation of Agricultural Habitats to Improve Conservation Biological Control in South America. *Neotropical Entomology* 48. http://doi.org/10.1007/s13744-019-00725-1

95. Armbrecht I; Gallego MC. 2007. Testing ant predation on the coffee berry borer in shaded and sun coffee plantations in Colombia. *Entomologia Experimentalis et Applicata* 124. http://doi.org/10.1111/j.1570-7458.2007.00574.x

96. Moreira CC; Celestino D; Guerra Sobrinho T; Cardoso IM; Elliot SL. 2019. Agroforestry coffee soils increase the insect-suppressive potential offered by entomopathogenic fungi over full-sun soils: A case proposing a "bait survival technique." *Ecology and Evolution* 9. http://doi.org/10.1002/ece3.5598

97. Gontijo LM. 2019. Engineering natural enemy shelters to enhance conservation biological control in field crops. *Biological Control* 130. http://doi.org/10.1016/j.biocontrol.2018.10.014

98. Bedimo JAM; Njiayouom I; Bieysse D; Nkeng MN; Cilas C; Nottéghem JL. 2008. Effect of Shade on Arabica Coffee Berry Disease Development: Toward an Agroforestry System to Reduce Disease Impact. *Phytopathology®* 98. http://doi.org/10.1094/PHYTO-98-12-1320

99. Avelino J; Gagliardi S; Perfecto I; Isaac M; Liebig T; Vandermeer J; et al. 2022. Tree effects on coffee leaf rust at field and landscape scales. *Plant Disease* 107. http://doi.org/10.1094/PDIS-08-21-1804-FE

100. Haddad F; Maffia LA; Mizubuti ESG; Teixeira H. 2009. Biological control of coffee rust by antagonistic bacteria under field conditions in Brazil. *Biological Control* 49. http://doi.org/10.1016/j.biocontrol.2009.02.004

101. Mamani-Huayhua G; Leon-Ttacca B; Palao-Iturregui LA; Borja-Loza YR. 2021. Biocontrol of coffee yellow rust (*Hemileia vastatrix* Berk. & Br.) with *Trichoderma* sp. endophyte strains. *Cultivos Tropicales* 42. http://scielo.sld.cu/scielo.php?pid=S0258-59362021000400001&script=sci_arttext&tlng=en

102. Suu BT; Giảng VQ; Liên VP; Huy DTN; Lan HT. 2021. The Auto-infection Trap with the Native Entomopathogenic Fungus, *Beauveria bassiana* for Management of Coffee Berry Borer (*Stephanoderes hampei* Ferrari) in the Northwest Region of Vietnam. *Alinteri Journal of Agriculture Sciences* 36. https://dinhtranngochuy.com/AJAS21028-4.pdf

103. Celestino FN; Pratissoli D; Machado LC; Santos Junior HJG dos; Queiroz VT de; Mardgan L. 2016. Control of coffee berry borer, *Hypothenemus hampei* (Ferrari) (Coleoptera: Curculionidae: Scolytinae) with botanical insecticides and mineral oils. *Acta Scientiarum Agronomy* 38. http://doi.org/10.4025/actasciagron.v38i1.27430

104. Castro AM; Benavides P; Góngora C. 2018. Push-pull strategy for handling the coffee berry borer. *Trends in Entomology* 14. https://www.cabdirect.org/cabdirect/abstract/20203382658

105. Njihia TN; Jaramillo J; Murungi L; Mwenda D; Orindi B; Poehling H-M; et al. 2014. Spiroacetals in the Colonization Behaviour of the Coffee Berry Borer: A 'Push-Pull' System. *PLOS ONE* 9. http://doi.org/10.1371/journal.pone.0111316

106. Aristizábal LF; Johnson M; Shriner S; Hollingsworth R; Manoukis NC; Myers R; et al. 2017. Integrated pest management of coffee berry borer in Hawaii and Puerto Rico: Current status and prospects. *Insects* 8. http://doi.org/10.3390/insects8040123

107. Leite SA; Guedes RNC; Santos MP dos; Costa DR da; Moreira AA; Matsumoto SN; et al. 2020. Profile of Coffee Crops and Management of the Neotropical Coffee Leaf Miner, *Leucoptera coffeella*. *Sustainability* 12. http://doi.org/10.3390/su12198011

108. Dantas J; Motta IO; Vidal LA; Nascimento EFMB; Bilio J; Pupe JM; et al. 2021. A Comprehensive Review of the Coffee Leaf Miner *Leucoptera coffeella* (Lepidoptera: Lyonetiidae) – A Major Pest for the Coffee Crop in Brazil and Others Neotropical Countries. *Insects* 12. http://doi.org/10.3390/insects12121130

109. Gichuru E; Alwora G; Gimase J; Kathurima C. 2021. Coffee Leaf Rust (*Hemileia vastatrix*) in Kenya – A Review. *Agronomy* 11. http://doi.org/10.3390/agronomy11122590

110. Lemma D; Abewoy D. 2021. Review on Integrated Pest Management of Coffee Berry Disease and Coffee Berry Borer. *International Journal of Plant Breeding and Crop Science* 8. https://www.researchgate.net/publication/349312510

111. Belachew K; Teferi D. 2015. Climatic Variables and Impact of Coffee Berry Diseases (*Colletotrichum kahawae*) in Ethiopian Coffee Production. *Journal of Biology, Agriculture and Healthcare* 5. ISSN 2225-093X. https://core.ac.uk/download/pdf/234660863.pdf

112. Souza RM, ed. 2008. Plant-Parasitic Nematodes of Coffee. 1st ed. Dordrecht: Springer, 2008.

113. Schoeman PS; Van Hamburg H; Pasques BP. 1998. The morphology and phenology of the white coffee stem borer, *Monochamus leuconotus* (Pascoe) (*Coleoptera: Cerambycidae*), a pest of Arabica coffee. *African Entomology* 6. https://hdl.handle.net/10520/AJA10213589_260

114. Kutywayo D; Chemura A; Kusena W; Chidoko P; Mahoya C. 2013. The Impact of Climate Change on the Potential Distribution of Agricultural Pests: The Case of the Coffee White Stem Borer (*Monochamus leuconotus* P.) in Zimbabwe. *PLOS ONE* 8. http://doi.org/10.1371/journal.pone.0073432

115. Liebig T; Babin R; Ribeyre F; Läderach P; Van Asten P; Poehling H-M; et al. 2018. Local and regional drivers of the African coffee white stem borer (*Monochamus leuconotus*) in Uganda. *Agricultural and Forest Entomology* 20. http://doi.org/10.1111/afe.12284

116. Espinoza JC; Infante F; Castillo A; Pérez J; Nieto G; Pinson EP; et al. 2009. The biology of *Phymastichus coffea* LaSalle (Hymenoptera: Eulophidae) under field conditions. *Biological Control* 49. http://doi.org/10.1016/J.BIOCONTROL.2009.01.021

117. Escobar-Ramírez S; Grass I; Armbrecht I; Tscharntke T. 2019. Biological control of the coffee berry borer: Main natural enemies, control success, and landscape influence. *Biological Control* 136. http://doi.org/10.1016/J.BIOCONTROL.2019.05.011

118. Motisi N; Bommel P; Leclerc G; Robin MH; Aubertot JN; Butron AA; et al. 2022. Improved forecasting of coffee leaf rust by qualitative modeling: Design and expert validation of the ExpeRoya model. *Agricultural Systems* 197. http://doi.org/10.1016/J.AGSY.2021.103352

119. Johnston AM; Bruulsema TW. 2014. 4R Nutrient Stewardship for Improved Nutrient Use Efficiency. *Procedia Engineering* 83. http://doi.org/10.1016/J.PROENG.2014.09.029

120. Noponen MRA; Edwards-Jones G; Haggar JP; Soto G; Attarzadeh N; Healey JR. 2012. Greenhouse gas emissions in coffee grown with differing input levels under conventional and organic management. *Agriculture, Ecosystems & Environment* 151. http://doi.org/10.1016/j.agee.2012.01.019

121. Van der Vossen H. 2005. A critical analysis of the agronomic and economic sustainability of organic coffee production. *Experimental Agriculture* 41. http://doi.org/10.1017/S0014479705002863

122. Bernoux M; Volkoff B; Carvalho M da CS; Cerri CC. 2003. CO_2 emissions from liming of agricultural soils in Brazil. *Global Biogeochemical Cycles* 17. http://doi.org/10.1029/2001GB001848

123. Sadeghian S. 2022. Nutrición del café. Consideraciones para el manejo de la fertilidad del suelo. Cenicafé. http://doi.org/10.38141/cenbook-0017

124. Sadeghian S; Alarcón VF; Díaz-Poveda V; Lince-Salazar LA; Rey-Sandoval JC. 2019. Fertilidad del suelo y manejo de la nutrición. In: Aplicación de ciencia tecnología e innovación en el cultivo del café ajustado a las condiciones particulares del Huila. Cenicafé. http://doi.org/10.38141/10791/0005_4

125. Wairegi IWIi; Van Asten PJA. 2012. Norms for multivariate diagnosis of nutrient imbalance in Arabica and Robusta coffee in the East African highlands. *Experimental Agriculture* 48. http://doi.org/10.1017/S0014479712000142

126. Viscarra Rossel RA; Behrens T; Ben-Dor E; Chabrillat S; Demattê JAM; Ge Y; et al. 2022. Diffuse reflectance spectroscopy for estimating soil properties: A technology for the 21st century. *European Journal of Soil Science* 73. http://doi.org/10.1111/ejss.13271

127. Carlisle L. 2016. Factors influencing farmer adoption of soil health practices in the United States: a narrative review. *Agroecology and Sustainable Food Systems* 40. http://doi.org/10.1080/21683565.2016.1156596

128. Vanlauwe B; Bationo A; Chianu J; Giller KE; Merckx R; Mokwunye U; et al. 2010. Integrated Soil Fertility Management. *Outlook on Agriculture* 39. http://doi.org/10.5367/000000010791169998

129. Palm CA; Gachengo CN; Delve RJ; Cadisch G; Giller KE. 2001. Organic inputs for soil fertility management in tropical agroecosystems: application of an organic resource database. *Agriculture, Ecosystems & Environment* 83. http://doi.org/10.1016/S0167-8809(00)00267-X

130. Van der Sloot M; Kleijn D; Deyn GB De; Limpens J. 2022. Carbon to nitrogen ratio and quantity of organic amendment interactively affect crop growth and soil mineral N retention. *Crop and Environment* 1. http://doi.org/10.1016/j.crope.2022.08.001

131. Munroe JW; Isaac ME. 2014. N_2-fixing trees and the transfer of fixed-N for sustainable agroforestry: A review. *Agronomy for Sustainable Development* 34. http://doi.org/10.1007/s13593-013-0190-5

132. Mendonça E de S; Lima PC De; Guimarães GP; Moura W de M; Andrade FV. 2017. Biological nitrogen fixation by legumes and N uptake by coffee plants. *Revista Brasileira de Ciencia do Solo* 41. http://doi.org/10.1590/18069657rbcs20160178

133. Hall H; Li Y; Comerford N; Arévalo Gardini E; Zuniga Cernades L; et al. 2010. Cover crops alter phosphorus soil fractions and organic matter accumulation in a Peruvian cacao agroforestry system. *Agroforestry Systems* 80. https://doi.org/10.1007/s10457-010-9333-8

134. Beer J; Muschler R; Kass D; Somarriba E. 1998. Shade management in coffee and cacao plantations. In: Nair PKR; Latt CR. (eds). Directions in Tropical Agroforestry Research. Forestry Sciences, vol 53. Springer, Dordrecht. https://doi.org/10.1007/978-94-015-9008-2_6

135. Beer J. 1988. Litter production and nutrient cycling in coffee (*Coffea arabica*) or cacao (*Theobroma cacao*) plantations with shade trees. *Agroforestry Systems* 7. https://doi.org/10.1007/BF00046846

136. Janzen HH; McGinn SM. 1991. Volatile loss of nitrogen during decomposition of legume green manure. *Soil Biology and Biochemistry* 23. http://doi.org/10.1016/0038-0717(91)90066-S

137. Marinho EB; Oliveira AL de; Zandonadi DB; Benedito LEC; Souza RB de; Figueiredo CC de; et al. 2014. Organic matter pools and nutrient cycling in different coffee production systems in the Brazilian Cerrado. *Agroforestry Systems* 88. http://doi.org/10.1007/s10457-014-9723-4

138. Urgiles-Gómez N; Avila-Salem ME; Loján P; Encalada M; Hurtado L; Araujo S; et al. 2021. Plant Growth-Promoting Microorganisms in Coffee Production: From Isolation to Field Application. *Agronomy* 11. http://doi.org/10.3390/agronomy11081531

139. Pulleman MM; Boer W de; Giller KE; Kuyper TW. 2022. Soil biodiversity and nature-mimicry in agriculture; the power of metaphor? *Outlook on Agriculture* 51. http://doi.org/10.1177/00307270221080180

140. Sato T. 2014. Effects of Rhizobium Inoculation on Nitrogen Fixation and Growth of Leguminous Green Manure Crop Hairy Vetch (*Vicia villosa* Roth). In: Advances in Biology and Ecology of Nitrogen Fixation. InTech. http://doi.org/10.5772/56992

141. Carvalho MEA; de Camargo e Castro PR. 2019. Seaweeds as Plant Biostimulants. In: Seaweeds as Plant Fertilizer, Agricultural Biostimulants and Animal Fodder. Boca Raton, FL: CRC Press, 2019: CRC Press. http://doi.org/10.1201/9780429487156-5

142. Mayer J; Scheid S; Widmer F; Fließbach A; Oberholzer HR. 2010. How effective are 'Effective microorganisms® (EM)'? Results from a field study in temperate climate. *Applied Soil Ecology* 46. http://doi.org/10.1016/J.APSOIL.2010.08.007

143. Gómez-Delgado F; Roupsard O; Maire G le; Taugourdeau S; Pérez A; Van Oijen M; et al. 2011. Modelling the hydrological behaviour of a coffee agroforestry basin in Costa Rica. *Hydrology and Earth System Sciences* 15. http://doi.org/10.5194/hess-15-369-2011

144. Silva BM; Oliveira GC; Serafim ME; Silva ÉA; Guimarães PTG; Melo LBB; et al. 2019. Soil moisture associated with least limiting water range, leaf water potential, initial growth and yield of coffee as affected by soil management system. *Soil and Tillage Research* 189. http://doi.org/10.1016/J.STILL.2018.12.016

145. Amarasinghe UA; Hoanh CT; D'haeze D; Hung TQ. 2015. Toward sustainable coffee production in Vietnam: More coffee with less water. *Agricultural Systems* 136. http://doi.org/10.1016/j.agsy.2015.02.008

146. Almeida WV. 2010. Eficiência da irrigação localizada e do consumo de energia na cafeicultura na região do Alto Jequitinhonha. Dissertação (Mestrado) – Programa de Pós-Graduação em Produção Vegetal, Universidade Federal dos Vales do Jequitinhonha e Mucuri, 2010. http://acervo.ufvjm.edu.br/jspui/handle/1/535

147. Van der Vossen H; Bertrand B; Charrier A. 2015. Next generation variety development for sustainable production of arabica coffee (*Coffea arabica* L.): a review. *Euphytica* 204. http://doi.org/10.1007/s10681-015-1398-z

148. Tran DNL; Nguyen TD; Pham TT; Rañola RF; Nguyen TA. 2021. Improving Irrigation Water Use Efficiency of Robusta Coffee (*Coffea canephora*) Production in Lam Dong Province, Vietnam. *Sustainability* 13. http://doi.org/10.3390/su13126603

149. D'haeze D; Deckers J; Raes D; Phong TA; Chanh NDM. 2003. Over-irrigation of *Coffea canephora* in the Central Highlands of Vietnam revisited: Simulation of soil moisture dynamics in Rhodic Ferralsols. *Agricultural Water Management* 63. http://doi.org/10.1016/S0378-3774(03)00181-1

150. Carr MKV. 2001. The water relations and irrigation requirements of coffee. *Experimental Agriculture* 37. http://doi.org/10.1017/s0014479701001090

151. Martini E; Riyandoko; Roshetko JM. 2017. Guidelines for Establishing Coffee-Agroforestry Systems. World Agroforestry Centre. https://bit.ly/3QDiSpn

152. Rodríguez Valencia N; Sanz Uribe JR; Oliveros Tascón CE; Ramírez Gómez CA. 2015. Beneficio del café en Colombia. Prácticas y estrategias para el ahorro, uso efficiente del agua y el control de la contaminación hídrica en el proceso de beneficio húmedo del café. https://biblioteca.cenicafe.org/handle/10778/659 (Accessed on 25 June 2023).

153. Rojas Acosta JM; Rodríguez N; Romero MA; García Á de M; Montes MA; Quintero L. 2019. Guía para la evaluación de la huella hídrica del café en Colombia. Chinchiná. https://bit.ly/3DzB23D

154. Ijanu EM; Kamaruddin MA; Norashiddin FA. 2020. Coffee processing wastewater treatment: a critical review on current treatment technologies with a proposed alternative. *Applied Water Science* 10. http://doi.org/10.1007/s13201-019-1091-9

155. Banti M; Abraham E. 2021. Coffee Processing Methods, Coffee Quality and Related Environmental Issues. *Journal of Food and Nutrition Sciences* 9. http://doi.org/10.11648/j.jfns.20210906.12

156. Poltronieri P; Rossi F. 2016. Challenges in Specialty Coffee Processing and Quality Assurance. *Challenges* 7. http://doi.org/10.3390/challe7020019

157. Rueda X; Lambin EF. 2013. Responding to Globalization: Impacts of Certification on Colombian Small-Scale Coffee Growers. *Ecology and Society* 18. http://doi.org/10.5751/ES-05595-180321

158. Birkenberg A; Birner R. 2018. The world's first carbon neutral coffee: Lessons on certification and innovation from a pioneer case in Costa Rica. *Journal of Cleaner Production* 189. http://doi.org/10.1016/j.jclepro.2018.03.226

159. Abubakar Y; Hasni D; Muzaifa M; Sulaiman; Mahdi; Widayat HP. 2019. Effect of varieties and processing practices on the physical and sensory characteristics of Gayo Arabica specialty coffee. *IOP Conference Series: Materials Science and Engineering* 523. http://doi.org/10.1088/1757-899X/523/1/012027

160. Chanakya HN; Alwis AAP de. 2004. Environmental Issues and Management in Primary Coffee Processing. *Process Safety and Environmental Protection* 82. http://doi.org/10.1205/095758204323162319

161. Technoserve. Coffee Wet Mill Processing Guide Background Wet Mill Processing Stages. https://www.technoserve.org/resources/technoserves-coffee-wet-mill-processing-guide/

162. Beyene A; Yemane D; Addis T; Assayie AA; Triest L. 2014. Experimental evaluation of anaerobic digestion for coffee wastewater treatment and its biomethane recovery potential. *International Journal of Environmental Science and Technology* 11. http://doi.org/10.1007/s13762-013-0339-4

163. Alemayehu YA; Asfaw SL; Tirfie TA. 2020. Management options for coffee processing wastewater. A review. *Journal of Material Cycles and Waste Management* 22. http://doi.org/10.1007/s10163-019-00953-y

164. Muthukumar H; Shanmugam MK; Dash SS; Gummadi SN. 2021. Chapter 18. Comparison of Biological and Physicochemical Techniques for Treatment of Coffee Wastewater – A Comprehensive Review. http://doi.org/10.1039/9781839165399-00391

165. Hernández-Sarabia M; Sierra-Silva J; Delgadillo-Mirquez L; Ávila-Navarro J; Carranza L. 2021. The potential of the biodigester as a useful tool in coffee farms. *Applied Sciences (Switzerland)* 11. http://doi.org/10.3390/app11156884

166. Sanz-Uribe JR; Yusianto; Menon SN; Peñuela A; Oliveros C; Husson J; et al. 2017. Postharvest Processing—Revealing the Green Bean. In: The Craft and Science of Coffee. Elsevier. http://doi.org/10.1016/B978-0-12-803520-7.00003-7

167. Pandey A; Soccol CR; Nigam P; Brand D; Mohan R; Roussos S. 2000. Biotechnological potential of coffee pulp and coffee husk for bioprocesses. *Biochemical Engineering Journal* 6. http://doi.org/10.1016/S1369-703X(00)00084-X

168. Corato U De. 2020. Disease-suppressive compost enhances natural soil suppressiveness against soil-borne plant pathogens: A critical review. *Rhizosphere* 13. http://doi.org/10.1016/J.RHISPH.2020.100192

169. Rahn E; Läderach P; Baca M; Cressy C; Schroth G; Malin D; et al. 2014. Climate change adaptation, mitigation and livelihood benefits in coffee production: where are the synergies? *Mitigation and Adaptation Strategies for Global Change* 19. http://doi.org/10.1007/s11027-013-9467-x

170. Chandler JV; Bonet, E; Abruña F; Figarella J. 1969. Effects of Clean and Strip Cultivation, and of Mulching with Grass, Coffee Pulp, and Black Plastic, on Yields of Intensively Managed Coffee in Puerto Rico. *The Journal of Agriculture of the University of Puerto Rico* 53. http://doi.org/10.46429/jaupr.v53i2.11168

171. Dadi D; Daba G; Beyene A; Luis P; Van der Bruggen B. 2019. Composting and co-composting of coffee husk and pulp with source-separated municipal solid waste: a breakthrough in valorization of coffee waste. *International Journal of Recycling of Organic Waste in Agriculture* 8. http://doi.org/10.1007/s40093-019-0256-8

172. Dávila A; Ramirez G. 1996. C.A. Lombricultura en pulpa de café. Avances Técnicos Cenicafé 225. https://biblioteca.cenicafe.org/bitstream/10778/4248/1/avt0225.pdf

173. Martí Herrero J. 2019. Biodigestores Tubulares: Guía de Diseño y Manual de Instalación. Redbiolac. Ecuador. ISBN: 978-9942-36-276-6. https://bit.ly/3PSi4wM

174. Quansah E. 2021. The quality of cocoa pod husk biochar produced with the "Kon-tiki" kiln technology, and its effect as a soil enhancer on the growth rate of cocoa seedlings. Norwegian University of Life Sciences, Ås.

175. Joseph S; Cowie AL; Van Zwieten L; Bolan N; Budai A; Buss W; et al. 2021. How biochar works, and when it doesn't: A review of mechanisms controlling soil and plant responses to biochar. GCB *Bioenergy* 13. http://doi.org/10.1111/gcbb.12885

176. Rodríguez VN; Jaramillo LC. 2005. Cultivo de hongos comestibles del género *Pleurotus* en residuos agrícolas de la zona cafetera. *Boletín Técnico Cenicafé*. https://biblioteca.cenicafe.org/handle/10778/583

177. Londoño-Hernández L; Ruiz HA; Cristina Ramírez T; Ascacio JA; Rodríguez-Herrera R; Aguilar CN. 2020. Fungal detoxification of coffee pulp by solid-state fermentation. *Biocatalysis and Agricultural Biotechnology* 23. http://doi.org/10.1016/j.bcab.2019.101467

178. Webb C. 2017. Design Aspects of Solid State Fermentation as Applied to Microbial Bioprocessing. *Journal of Applied Biotechnology & Bioengineering* 4. http://doi.org/10.15406/jabb.2017.04.00094

179. Porres C; Alvarez D; Calzada J. 1993. Caffeine reduction in coffee pulp through silage. *Biotechnology Advances* 11. http://doi.org/10.1016/0734-9750(93)90020-N

180. Rosmiati M; Nurjanah K; Suantika G; Putra R. 2017. Application of Compost Produced by Bioconversion of Coffee Husk by Black Soldier Fly Larvae (*Hermetia illucens*) as Solid Fertilizer to Lettuce (*Lactuca sativa* var. Crispa): Impact to Growth. P*roceedings of the International Conference on Green Technology* 8.

181. Barragán-Fonseca KY; Nurfikari A; Van de Zande EM; Wantulla M; Van Loon JJA; Boer W de; et al. 2022. Insect frass and exuviae to promote plant growth and health. *Trends in Plant Science* 27. http://doi.org/10.1016/j.tplants.2022.01.007

182. Limousy L; Jeguirim M; Labaki M. 2017. Chapter 11 - Energy applications of coffee processing by-products. *Handbook of Coffee Processing By-Products: Sustainable Applications*. http://doi.org/10.1016/B978-0-12-811290-8.00011-6

183. Otero Jiménez B; Li K; Tucker PK. 2020. Landscape drivers of connectivity for a forest rodent in a coffee agroecosystem. *Landscape Ecology* 35. http://doi.org/10.1007/s10980-020-00999-6

184. Krishnan S; Kushalappa CheppudiraG; Shaanker RU; Ghazoul J. 2012. Status of pollinators and their efficiency in coffee fruit set in a fragmented landscape mosaic in South India. *Basic and Applied Ecology* 13. http://doi.org/10.1016/j.baae.2012.03.007

185. González-Chaves A; Jaffé R; Metzger JP; M. P. Kleinert A de. 2020. Forest proximity rather than local forest cover affects bee diversity and coffee pollination services. *Landscape Ecology* 35. http://doi.org/10.1007/s10980-020-01061-1

186. Vilchez-Mendoza S; Romero-Gurdián A; Avelino J; DeClerck F; Bommel P; Betbeder J; et al. 2022. Assessing the joint effects of landscape, farm features and crop management practices on berry damage in coffee plantations. *Agriculture, Ecosystems & Environment* 330. http://doi.org/10.1016/j.agee.2022.107903

187. Beasley EM; Aristizábal N; Bueno EM; White ER. 2022. Spatially explicit models predict coffee rust spread in fragmented landscapes. *Landscape Ecology* 37. http://doi.org/10.1007/s10980-022-01473-1

188. Ramos-Scharrón CE; Figueroa-Sánchez Y. 2017. Plot-, farm-, and watershed-scale effects of coffee cultivation in runoff and sediment production in western Puerto Rico. *Journal of Environmental Management* 202. http://doi.org/10.1016/j.jenvman.2017.07.020

189. Mander Ü; Hayakawa Y; Kuusemets V. 2005. Purification processes, ecological functions, planning and design of riparian buffer zones in agricultural watersheds. *Ecological Engineering* 24. http://doi.org/10.1016/j.ecoleng.2005.01.015

190. Schroth G; Laderach P; Dempewolf J; Philpott S; Haggar J; Eakin H; et al. 2009. Towards a climate change adaptation strategy for coffee communities and ecosystems in the Sierra Madre de Chiapas, Mexico. *Mitigation and Adaptation Strategies for Global Change* 14. http://doi.org/10.1007/s11027-009-9186-5

191. Mora A de la; García-Ballinas JA; Philpott SM. 2015. Local, landscape, and diversity drivers of predation services provided by ants in a coffee landscape in Chiapas, Mexico. *Agriculture, Ecosystems & Environment* 201. http://doi.org/10.1016/j.agee.2014.11.006

192. Cole R. 2010. Social and environmental impacts of payments for environmental services for agroforestry on small-scale farms in southern Costa Rica. *International Journal of Sustainable Development & World Ecology* 17. http://doi.org/10.1080/13504501003729085

193. Williams-Guillén K; Otterstrom S. 2014. Market-Based Incentives for the Conservation of Ecosystem Services in Agricultural Landscapes: Examples from Coffee Cultivation in Latin America. In: Encyclopedia of Agriculture and Food Systems. Elsevier. http://doi.org/10.1016/B978-0-444-52512-3.00011-5

194. Takahashi R; Todo Y. 2014. The impact of a shade coffee certification program on forest conservation using remote sensing and household data. *Environmental Impact Assessment Review* 44. http://doi.org/10.1016/j.eiar.2013.10.002

195. Hardt E; Borgomeo E; Santos RF dos; Pinto LFG; Metzger JP; Sparovek G. 2015. Does certification improve biodiversity conservation in Brazilian coffee farms? *Forest Ecology and Management* 357. http://doi.org/10.1016/j.foreco.2015.08.021

196. Senadheera DKL; Wahala WMPSB; Weragoda S. 2019. Livelihood and ecosystem benefits of carbon credits through rainforests: A case study of Hiniduma Bio-link, Sri Lanka. *Ecosystem Services* 37. http://doi.org/10.1016/j.ecoser.2019.100933

197. Jardin P du. 2015. Plant biostimulants: Definition, concept, main categories and regulation. *Scientia Horticulturae* 196. http://doi.org/10.1016/J.SCIENTA.2015.09.021

198. Pretty J; Bharucha ZP. 2014. Sustainable intensification in agricultural systems. *Annals of Botany* 114. http://doi.org/10.1093/aob/mcu205

Glossary

TERM	DEFINITION
Agroecological zone	A geographic area possessing a well-defined combination of soil characteristics, topography, climatic conditions and natural biodiversity, which influence agricultural production constraints and potential.
Agroforestry	A production system that combines trees with crops, livestock or both on the same land. In this guidebook, agroforestry refers to the practice of growing trees and coffee plants (and sometimes other crops) in the same plot, thereby creating multiple vegetation layers. Trees can have multiple functions in the system, such as shade provision, microclimate regulation, nutrient cycling and production of additional products for consumption or commercialization.
Allelopathy	The positive or negative influence that one plant exerts on another plant's growth, survival, development and reproduction through the release of biochemical compounds (allelochemicals) into the environment (atmosphere or rhizosphere).
Bio-based technologies	Technologies used to generate products (goods, services or energy) that are derived from renewable materials of biological origin.
Biochar	A recalcitrant high-carbon material produced by pyrolysis of biomass under controlled conditions is a more stable form of organic matter than compost and has a larger surface area and cation exchange capacity.
Biofertilizers	A subcategory of *biostimulants* intended to improve plant productivity by increasing nutrient-use efficiency or opening new routes of nutrient acquisition by plants. Biofertilizers include mycorrhizal and non-mycorrhizal fungi, bacterial endosymbionts (such as *Rhizobium*) and plant growth-promoting rhizobacteria [[181]].
Biological oxygen demand	The amount of oxygen that bacteria and other microorganisms consume during the decomposition of a specific organic substrate under aerobic conditions at a determined time and temperature.
Carbon footprint	An environmental indicator that measures the impact that a certain production system or product has on global warming. The footprint is calculated as the total amount of the greenhouse gases (CO_2, CH_4 and N_2O), expressed in terms of *CO_2 equivalents*, that are emitted due to the production or supply of an agricultural product (see also Chapter 1, Box 1.2).

TERM	DEFINITION
Carbon removal	The capture of CO_2 from the atmosphere for long-term storage in soils, oceans, rocks, saline aquifers, depleted oil wells, and long-lived plant and mineral products, such as hardwood, biochar and limestone. It includes increasing carbon stocks in standing biomass through reforestation or afforestation.
Cation exchange capacity	A soil chemical property, normally abbreviated as CEC, that reflects the total negative charges on soil surfaces and hence the soil's capacity to absorb, retain and provide plants with important nutrient cations, such as calcium, magnesium and potassium.
Circular agriculture	A concept that focuses on the efficient use of resources (nutrients, water) and energy to reduce the pressure of agriculture on the environment, nature and climate. This is achieved by maximizing the use of renewable resources, minimizing losses and reusing and reincorporating residues and waste into production.
Climate change adaptation	Adjusting to the actual or expected future climate, with the goal of reducing the harmful effects of climate change, such as sea-level rise, more extreme weather events and food insecurity. This also involves harnessing the potential benefits and opportunities offered by climate change, such as longer growing seasons and increased yields in some regions.
Climate-smart agriculture	An integrated approach to transform agri-food systems towards low-emission and climate-resilient practices. Climate-smart agriculture (CSA) aims to tackle three main objectives: sustainably increasing agricultural productivity; adapting and building *resilience* to climate change; and reducing and/or removing greenhouse gas emissions, where possible. Based on FAO definition. https://www.fao.org/climate-smart-agriculture/en/
CO_2 equivalents	The mass of CO_2 (expressed in kilograms or tons) needed to produce the same global warming effect as another greenhouse gas. Since gases vary in their radiative efficiency and lifetime in the atmosphere, they also vary in terms of *global warming potential*. This expresses how much energy the emissions of 1 ton of a gas will absorb over a given period (generally 100 years) relative to the emission of 1 ton of CO_2, providing a common unit of measurement for adding up emission estimates of the three different gases to calculate the total carbon footprint of a farm or product (see Chapter 1, Figure 1.1). IPCC definition.

TERM	DEFINITION
Coffee variety	A genetically distinct subset of a crop species possessing a set of specific traits. Cultivars are varieties that result of breeding and selection for desired agronomic traits.
Complementarity	The ability of two or more species to coexist in a community without competing for resources. For instance, plant roots may exploit different soil layers or use different soil nutrient forms.
Compost	A carbon-rich soil amendment produced by microbial decomposition of organic residues or waste, which has reached a level of maturity or stability that allows to supply nutrients to plant and improve *soil health*.
Conservation agriculture	A farming approach that minimizes soil disturbance (especially tillage), promotes permanent soil cover and diversifies plant species.
Cover crops	Plants used mainly for soil protection and *soil fertility* improvement. Such crops also help maintain optimal soil temperature, conserve soil moisture and suppress weed growth. Cover crops are not removed from the field but may be cut to provide biomass for incorporation into the soil or for use as mulch.
Ecological functions	Processes that control the flow of energy and matter (e.g., nutrients and organic matter) within an ecosystem, thus creating a base for the provision of *ecosystem services*.
Ecological intensification	The enhancement of agricultural productivity and plant health through practices that harness the benefits of natural ecological processes by promoting and conserving biodiversity.
Ecosystem engineers	Species that have a disproportionate impact on the whole ecosystem by modifying the environment physically or chemically. They may do this by creating or significantly modifying habitats and resources available to other species.
Ecosystem services	Benefits that humans derive from ecosystems. These services are of several types: supporting (such as nutrient cycling and pollination), regulating (such as erosion control and climate regulation), provisioning (such as food, fuel, water) and cultural services (e.g., recreation, spiritual values). See Chapter 2, Figure 2.5.
F1 hybrid	First-generation offspring from a cross between two different pure-bred varieties; the offspring tend to express hybrid vigor (i.e., improved quality or other characteristics, often yield) in comparison with either parent variety.

TERM	DEFINITION
Facilitation	Positive interaction between different coexisting species, whereby the presence of one species has a beneficial effect on the other's survival, growth, reproduction or activity, while remaining unaffected itself.
Functional biodiversity	A component of biodiversity that concerns the number of different ecological functional traits present in a biological community or system. This is not the same as genetic diversity, since different species in a community are often functionally similar, so that removing one species will not alter the functioning of the ecosystem.
Global warming potential	A means of comparing the impacts of different greenhouse gases (GHGs) based on two factors: their "radiative efficiency" (or ability to absorb energy) and their "lifetime" (i.e., the amount of time they remain in the atmosphere). The global warming potential of a GHG is used to calculate *CO_2 equivalents*. See Chapter 1, Figure 1.1.
Hydraulic lift	Passive redistribution of water by a plant root system from deep soil layers to the upper layer.
Intercropping	Growing non-woody crops simultaneously with coffee in the same plot, so that farmers can diversify and intensify production. This practice enhances the *resilience* of farm households and coffee-farming communities by providing a wider variety of food and income-generating products. Intercropping can be permanent or practiced temporarily to provide income during coffee establishment or renovation.
Land equivalent ratio (LER)	A computed value used to compare total yields from crops grown in *intercropping* systems with yields from sole cropping.
Microbial inoculants	Agricultural amendments composed primarily of living microorganisms (i.e., fungi and bacteria) with the aim of improving plant health and productivity through different mechanisms, including *biofertilizer, biostimulant* or biocontrol effects.
Mitigation	Reducing the risk or negative impact of any undesirable event. With respect to climate change, this involves a reduction in the net flow of heat-trapping GHGs into the atmosphere, either by lowering emissions from particular sources (e.g., the burning of fossil fuels) or by enhancing the capture and storage of GHGs into stable pools (e.g., the storage of CO_2 in tree biomass or *soil organic matter*).

TERM	DEFINITION
Monetary equivalent ratio (MER)	A computed value used to compare total returns from crops grown in *intercropping* systems with the returns from sole cropping.
Nutrient balance	The estimated difference between the total input of a nutrient (the sum of fertilizer applications, organic inputs, nitrogen fixation and deposition) and the output of that same nutrient from the system through harvested products, as well as from losses due to leaching, volatilization and erosion.
Nutrient pump effect	The transfer of plant nutrients absorbed by plant roots from deep soil layers to the upper layer as a result of litter accumulation.
Plant phenology	Features that are related to the timing and various stages of a plant's growth cycle, for example germination, flowering or leaf senescence.
Resilience	The ability of a social (e.g., a household or a community) or ecological system (e.g., a plant community or a cropping system to cope with shocks and disturbances by adapting to environmental change, while retaining its original structure and functionality.
Resource competition	Negative interaction between organisms, which diminishes growth, survival or fecundity by reducing the availability of shared resources, such as light, nutrients and space.
Resource-use efficiency	Crop output expressed as yield gained in response to the addition of a fixed unit of input, such as liters of water, kilograms of fertilizer or hours of manual labour.
Root-knot nematodes	Microscopic parasitic worms of the genus *Meloidogyne*, which in their adult stage infect plant roots, inducing root deformation (root-knot galls) and reducing plant health by feeding on plant photosynthates.
Scion	The bud or stem of a desired variety that is grafted on to the rootstock (root system) of another plant.
Self-pollination	Fertilization of a plant's flowers with pollen from the same flower or plant. This mechanism is convenient, since it does not rely on pollen vectors, such as animals or wind, but it results in low genetic diversity in the offspring. For this reason, many species, such as Robusta coffee, have developed self-incompatibility mechanisms.
Soil carbon sequestration	The removal of CO_2 from the atmosphere through practices that increase the amount of organic matter stored in the soil.

TERM	DEFINITION
Soil degradation	The gradual loss of *soil health* and functions, which undermines the land's ability to sustain plant productivity. This may result from climate change as well as from soil pollution, erosion or compaction and nutrient exhaustion due to agriculture.
Soil fertility	The soil's ability to sustain agricultural plant production, by providing the different plant nutrients in adequate amounts and supporting their efficient uptake by plant roots, according to the requirements of the crop(s).
Soil health	The capacity of soil to perform its ecological functions, i.e., sustaining plant productivity and biodiversity, providing a habitat for soil biota, regulating water, cycling and provision of nutrients, buffering pollutants, and regulating pest and disease populations.
Soil organic matter (SOM)	A mixture of carbon-based compounds derived from living organisms, such as plants, animals and fungi. This includes decaying matter at different stages of degradation, for example, plant residues and exudates, animal droppings as well as charcoal.
Soil structure	The way in which soil particles – including mineral (sand, silt and clay) and organic components – are assembled by physical, chemical and biological processes into aggregates (i.e., porous compounds with different sizes, shapes and arrangements). This affects important soil properties, for instance, porosity, density and water retention capacity.
Soil texture	The proportions of primary soil particles of different sizes, including clay (<2 µm), silt (2–50 µm) and sand (50 µm–2 mm).
Sustainable intensification	The introduction of innovative practices and techniques that rely on natural processes to improve agricultural production and profitability, while also conserving and enhancing natural ecosystems and boosting *resilience* to climate change.
Symbiosis	A relationship between two organisms, that coexist and interact in a natural environment, sometimes obligately. This relationship can be beneficial for both organisms (mutualism) or for only one (parasitism and commensalism). Such is the case with nitrogen-fixing bacteria, for example, rhizobia, or arbuscular mycorrhizal fungi, which live inside the roots of leguminous plants and depend on them to obtain energy for their growth.

TERM	DEFINITION
Trade-off	A situation implying decisions about different ends, in which gains for one end are partially or completely offset by losses for another.
Vapour pressure deficit	The difference between the actual amount of moisture in the air and the amount of moisture the air can hold when saturated. Air is saturated when water starts to condense to form clouds, dew or films of water over leaves.
Water footprint	An environmental indicator that measures the volume of fresh water (in litres or cubic metres) used throughout the entire production or supply chain of a consumer good or service. Water use is measured in water volume consumed and/or polluted per unit of time or volume of product (e.g., a kilogram of dry coffee beans). A distinction is made between the usage of blue water (surface- or groundwater, e.g., for irrigation of crops); green water (rainfall that has been stored in the root zone of the soil and that is lost by evapotranspiration or incorporated into plants); and grey water (water required for dilution of pollutants in order to meet water quality standards).
Watershed	A land area that drains water and rainfall into a waterbody, such as a river, lake or ocean.


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The Alliance of Bioversity International and the International Center for Tropical Agriculture (CIAT) delivers research-based solutions that harness agricultural biodiversity and sustainably transform food systems to improve people's lives. Alliance solutions address the global crises of malnutrition, climate change, biodiversity loss, and environmental degradation.

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