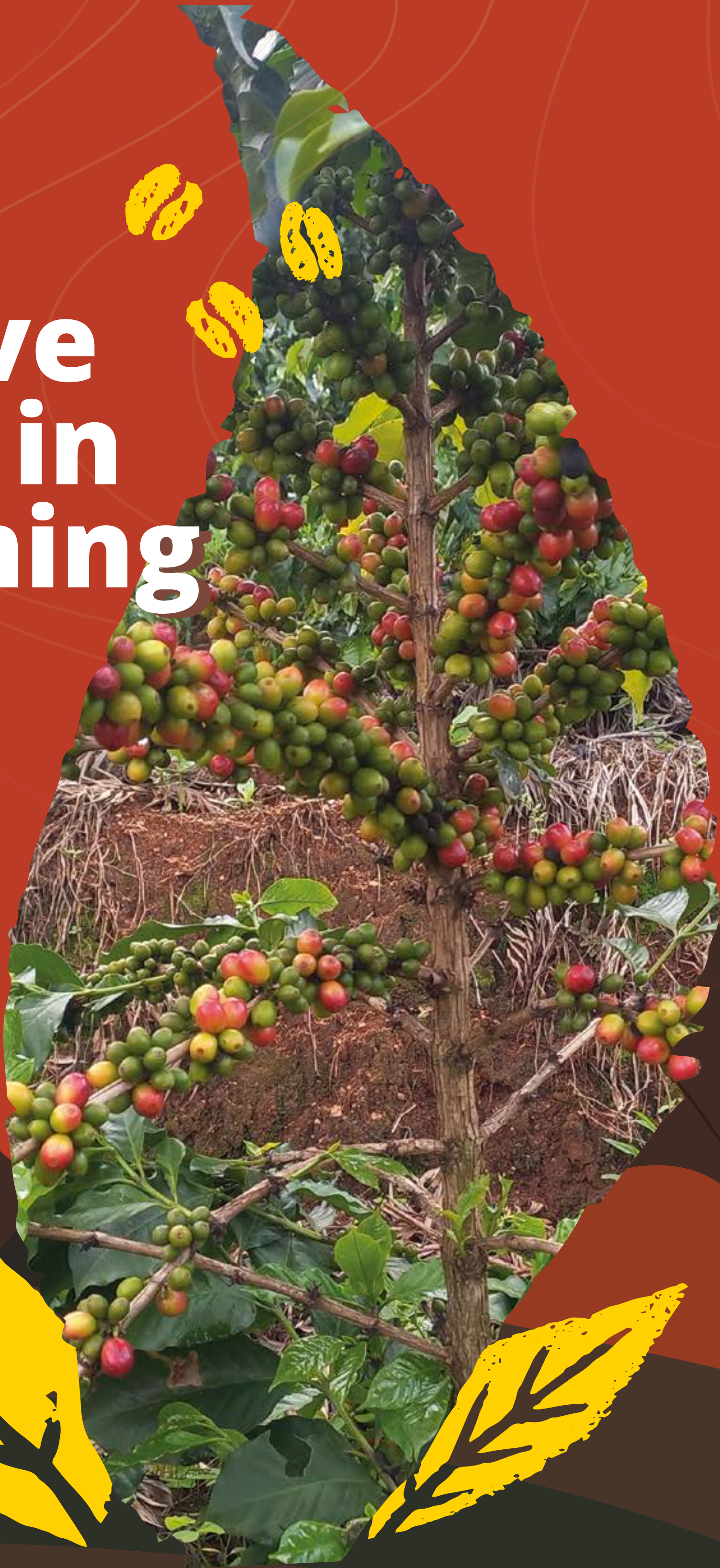
Regenerative Agriculture in Coffee Farming Systems

A handbook for practitioners in Uganda



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Cover image: Ugandan coffee plant ready for harvest. Source: ©2020 CIAT/Trong Chinh

Glossary

Adsorption: when particles of one matter stick to the surface of another matter (as opposed to absorption where particles 'soak into' the other phase).

Agroecological conditions: the relationship between agricultural production systems and ecological processes influenced by the environment such as soil characteristics, topography and climate.

Agroforestry Systems (AFS): tree planting that is deliberately combined with agriculture on the same piece of land.

Belowground Biomass Carbon (BGC): the belowground carbon pool which includes all living biomass of live roots.

Biochar: any organic material that has been carbonised under high temperatures (300-1000°C), in the presence of little, or no oxygen.

Biological control agents (BCA): predators, parasitoids, and pathogens which can be used to control a specific pest and /or disease.

Carbon Sequestration: is the process of storing carbon in a carbon pool (above-/belowground vegetation biomass and soil organic carbon). The process results in a carbon sink, meaning it removes carbon dioxide from the atmosphere.

Contour planting: is a farming practice where farmers plant crops across or perpendicular to slopes to follow the contours of a slope of a field.

Cool Farm Tool (CFT): an online digital tool which calculates greenhous gas, water and biodiversity metrics for farmers. https://coolfarmtool.org/

Cover Crops: plants that are planted to cover the soil rather than for the purpose of being harvested.

Cultural Control Methods: practices that modify the environment to reduce the prevalence of pests, including using resistant varieties, pruning to modify microclimate, disposing infected fruits, etc.

Erosion Barriers: a mound in a shallow trench on the contour to intercept water running down a slope and trap sediment.

Eutrophication: harmful algal blooms and aquatic dead zones which occur when the environment becomes enriched with nutrients, increasing the amount of plant and algae growth to lakes, estuaries and coastal waters.

Evapotranspiration: the sum of water vaporized to the atmosphre from evaporation of the soil and plant surfaces and transpiration through water movement from soil to atmosphere via plants.

F1 hybrids: the term used for the first generation hybrid seed/plant that occurs following the successful cross-pollination of one genetically uniform plant variety with another specific genetically uniform variety.

Green Manure: fast-growing plants sown to cover bare soil and incorporated in the soil after growth.

Greenhouse Gas (GHG): a gas that absorbs and emits radiant energy at thermal infrared wavelengths, causing the greenhouse effect. The primary greenhouse gases in Earth's atmosphere are water vapor (H_2O), carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and ozone (O_3).

Integrated Crop-Livestock Management: a form of sustainable intensification of agriculture relying on synergistic relationships between plant and animal system elements to bolster critical agroecosystem processes.

Integrated Nutrient Management: the maintenance of soil fertility and of plant nutrient supply at an optimum level for sustaining the desired productivity through optimization of the benefits from all possible sources of organic, inorganic and biological components in an integrated manner.

Integrated Pest-Disease Management: a coordinated and planned strategy for the prevention, detection and control of pests, weeds, and diseases.

Integrated weed management: coordinated agronomic practices used to manage weeds, so that the reliance on any one weed control technique is reduced.

Intercropping: the practice of growing two or more crops in association with the goal of producing greater yield on a given piece of land by making use of resources that would otherwise not be utilized by a single crop.

Land equivalent ratio (LER): the area required by sole crops to produce the same yields, relative to the area needed to obtain the same yield obtained through intercropping.

Local Indicators of Soil Quality (LISQ): are soil metrics such as pH, electrical conductivity, nitrate-nitrogen, and phosphorus-phosphates.

Mulch: are loose coverings or sheets of material placed on the surface of soil which can help soils retain moisture and protect soil from erosion.

Niche Differentiation: the process by which competing species use the environment differently in a way that helps them to coexist.

Phytoremediation: the use of plants for the extraction, immobilization, containment, and/ or degradation of contaminants usually in a biological medium (i.e. water or soil).

Regenerative Agriculture: a conservation and rehabilitation approach to food and farming systems.

Renovation (of coffee plants): replacement of old coffee plants with new plants.

Riparian Buffers: an area adjacent to a stream, lake, or wetland that contains a combination of trees, shrubs, and/or other perennial plants and is managed differently from the surrounding landscape, primarily to provide conservation benefits.

Soil Acidification: the buildup of hydrogen cations, which reduces the soil pH.

Soil Conservation: is the prevention of loss of the topmost layer of the soil from erosion or prevention of reduced fertility caused by over usage, acidification, salinization or other chemical soil contamination.

Soil Erosion: a gradual process that occurs when the impact of water or wind detaches and removes soil particles, causing the soil to deteriorate.

Soil Organic Carbon (SOC): the carbon that remains in the soil after partial decomposition of any material produced by living organisms.

Vermicomposting: the process of using earthworms to transform organic materials into rich, organic fertilizers.

Visual Soil Assessment (VSA): a method to asses soil quality in the field, by digging a hole and assess several soil quality indicators visually.

Waste Valorization: the process of reusing, recycling or composting waste materials and converting them into more useful products including materials, chemicals, fuels or other sources of energy.

Water use efficiency: the amount of carbon assimilated as biomass or grain produced per unit of water used by the crop.

Windbreaks: linear plantings of trees and shrubs designed to provide economic, environmental and community benefits.

Zero-/minimum/conservation tillage is a practice in which crops are sown directly into soil, with little to no tilling, in between the harvest of the previous crop.

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CHAPTER 1. INTRODUCTION

i. Purpose of this handbook

ii. Context: Ugandan coffee farming systems

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iv. Reasons for practicing Regenerative Agriculture in coffee farming systems

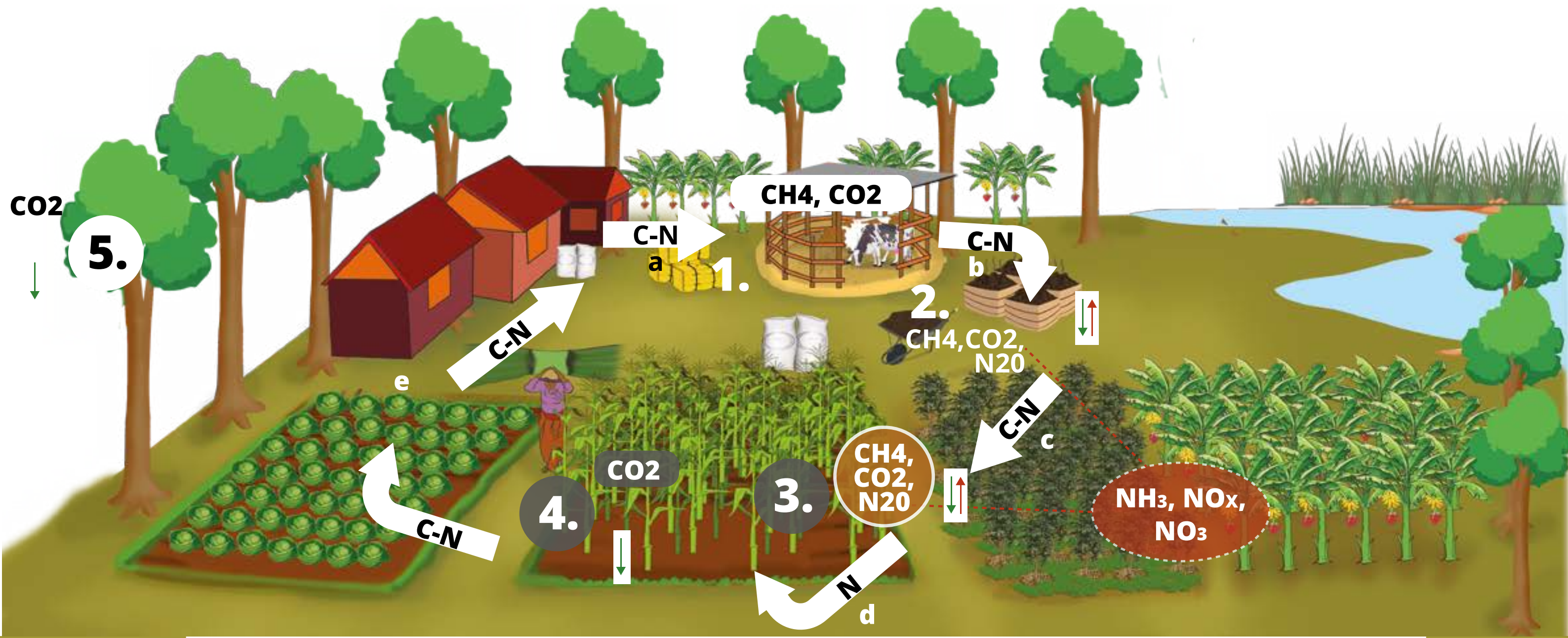
CIAT /Neil Palmer. Coffee and banana intercropping systems in Rwanda.

i. Purpose of the handbook

The purpose of this handbook is to inform the promotion and adoption of Regenerative Coffee Agriculture in Uganda to restore and conserve soil, water and biodiversity in and around farming systems. By using strategies that address multiple environmental and production challenges, Regenerative Agriculture practices can result in both social and economic benefits for farmers. In this context, this handbook has been developed to provide:

- An understanding of Regenerative Agriculture in the context of coffee farming.
- A preliminary framework for deploying Regenerative Coffee Agriculture in Uganda

The handbook is targeted at field agronomists, technicians, lead farmers, village advisors and extensional officers to build their understanding of Regenerative Agriculture so that they can integrate it into project planning and execution. This handbook complements the coffee management manuals and handbooks already in use by the coffee sector such as those provided by the Uganda Coffee Development Authority (https://ugandacoffee.go.ug/index.php/resource-center/manuals).



Farm scale livelihood activities, greenhouse gas emissions (GHG) and carbon (C) sequestration in integrated smallholder crop-livestock system in Uganda. The number (1-5) represent farm components: (1) livestock, (2) manure management systems (MMS), (3) soil, (4) crops and (5) trees. The letters (a-e) are associated with fluxes of C and N: (a) fodder, crop residues and concentrates, (b) dung, urine and bedding materials, (c) inorganic fertilizer, manure and crop residues, (d) nitrogen uptake by crops, (e) the biomass harvested that can follow different pathways: livestock feed, compost heap and mulch.

ii. Context: Ugandan coffee farming

Facts and figures

Agriculture in Uganda accounts for 24% of GDP and employs over 70% of the population. Coffee is the principal cash crop and Uganda's largest agricultural foreign revenue earner. Uganda is the largest exporter and second largest producer of coffee in Africa. Coffee supports over 3.5 million families at all levels of the value chain, especially for income security and contributes to between 20 – 30% of foreign exchange earnings.

Uganda produces two coffee types:

- *Coffea arabica* (*aka.* Arabica) which contributes about 20% of the annual national coffee produce. Coffee productivity for Arabica is 2 kg per tree per year of clean green coffee (agronomic potential) with an average baseline productivity of 0.8 kg per tree per year.

- *Coffea canephora* (*aka.* Robusta) which contributes about 80% of the coffee produced in Uganda annually. Coffee productivity for Robusta is 3 kg per tree per year of clean green coffee (agronomic potential) with an average baseline productivity of 1.2 kg per tree per year.

The majority of coffee grown in Uganda is Robusta, which is grown in the low altitude areas of Central, Eastern, Western and Southeastern Uganda up to 900 – 1,200 meters above sea level (**Figure 1**). Arabica coffee is grown in the highland areas on the slopes of Mount Elgon in the East and Mt. Rwenzori and Mt. Muhabura in the Southwestern Region, between 1,500 – 2,300 m above sea level. Arabica coffee beans are more competitive on the international market fetching higher prices because of its superior quality and aroma profile, while Robusta coffee is higher yielding and typically has lower production costs.

Coffea arabica
(aka. Arabica)
contributes about
20%
of the annual National Coffee produce

Coffea canephora
(aka. Robusta)
contributes about
80%
of the Coffee produced in Uganda annually

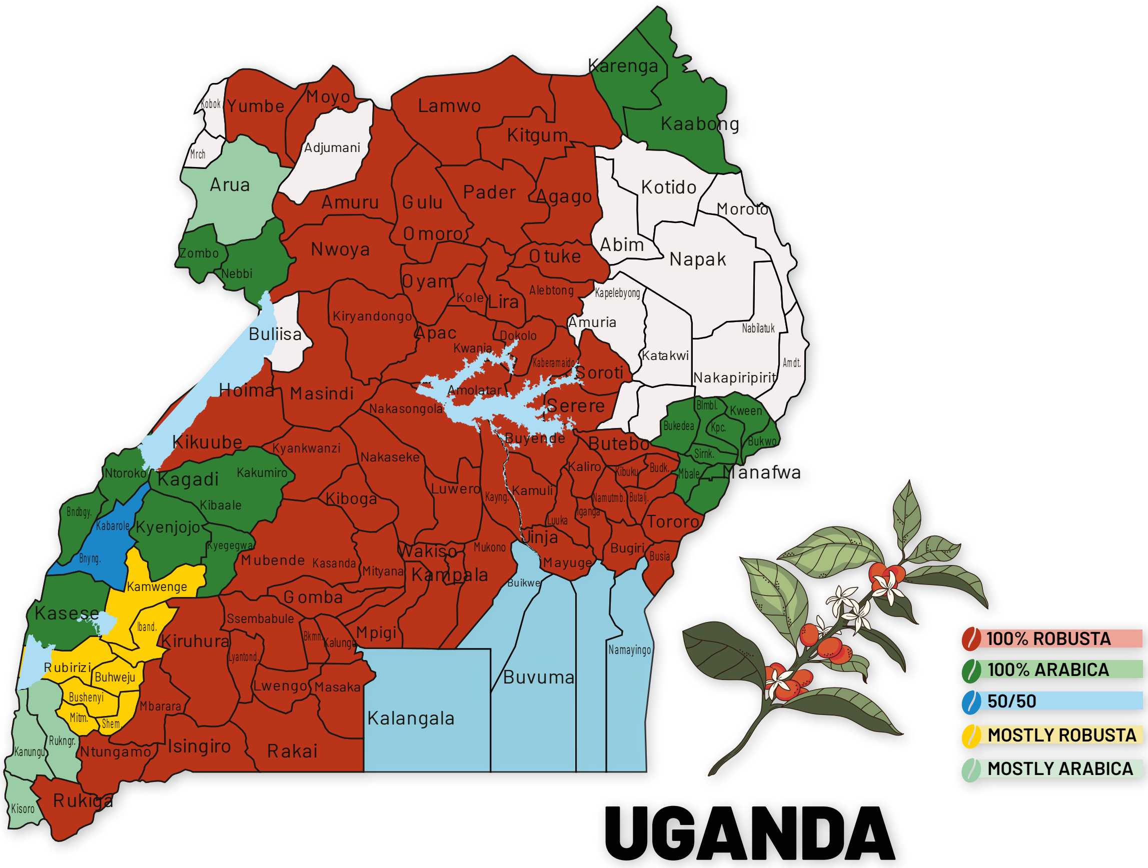


Figure 1. Coffee growing areas of Uganda.

Recent studies have mapped the coffee landscapes of Uganda and described the main farm-household systems across the coffee growing geographies as such (Wang et al., 2015; Mulinde et al., 2019);

In central Uganda:

Most of Ugandan coffee production occurs in the center (approximately 70%). Robusta is the common coffee crop in this region. Poor soil nutrient status (especially potassium) and lack of mulching application found as limiting factors to coffee yields. The following farm-household systems are common to central Uganda:

- ***Coffee-livestock-off-farm:*** with a high proportions of household members with off-farm activities in Central Uganda, and low proportions of land cultivated for crops and values of productions. It has a relatively high proportion of livestock compared to all other systems. This system exists between 1,000 – 1,200 mm-rainfall zones.

- ***Coffee-maize-beans:*** The system is characterized by high proportions of land and value of production for coffee, maize, and beans. It only occurs between 1,000-1,200 mm rainfall zones.

In eastern Ugandan:

Both Robusta and Arabica coffee is grown in eastern Uganda. Excessive numbers of shade trees were found to be the most important yield constraints. The following farm-household systems are common to the east:

- ***Coffee-off-farm:*** with a high number of household members working off-farm, low proportions of land cultivated for banana, and the lowest value of production from coffee. This system is common in the 1,200 mm rainfall zone.

- ***Coffee-banana-maize:*** characterized by the highest proportions of land under coffee, banana and maize and values of production for banana and maize. This system has a low proportion of household members working off-farm and exists in the 1200-1, 400 mm rainfall zones.

- ***Coffee-banana*:** characterized by the low land-crop proportions and values of production for maize and beans; and with the highest values of production for coffee and banana. This system is common in the 1,800 mm-rainfall zone.

Southwest & west-Nile Uganda:

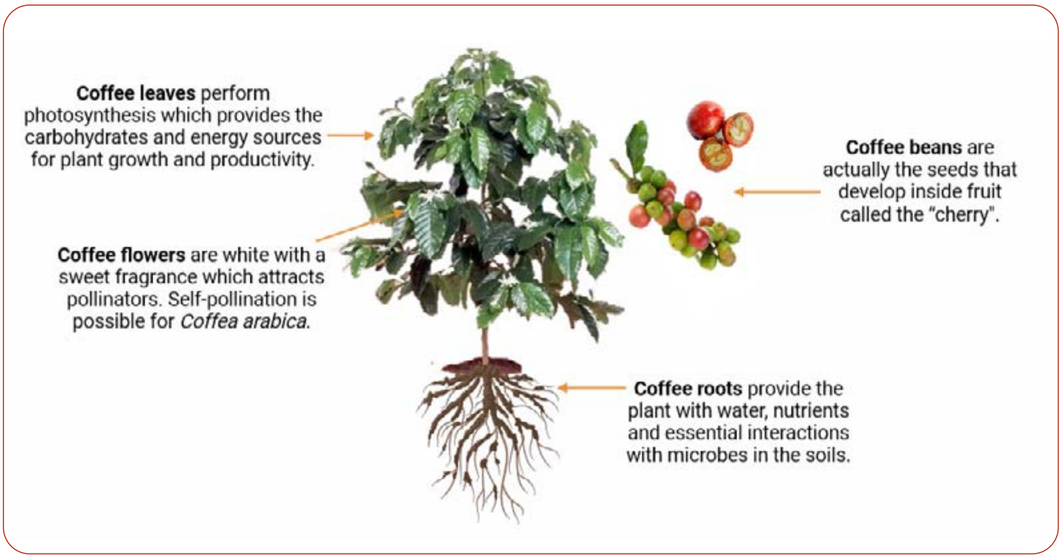
Arabica coffee is the most prominent coffee species growing in the mountain ranges in west-Nile and Mount Rwenzori in southwest Uganda. High soil magnesium concentration and poor mulching limited coffee yield in the Southwest; poor soil nutrient status (especially phosphorus and potassium).

Northwest Uganda:

A mixture of Robusta and Arabica coffee are grown in Northwest Uganda. Low coffee plant density is the most significant factor leading to coffee yield limitations in this region.

At the farm level, different food crops are important for coffee farmer livelihoods and often intercropped with coffee (*e.g.*, beans, taro etc.), while 1-2 livestock units (*e.g.*, cows, pigs, goats) are used as bank accounts. Farming these crops and livestock are critical for food security and provide an important additional income stream for the coffee growing households. More recently, high-value intercrops such as vanilla have gained importance in some cultivation areas of Uganda. Vegetables and other crops are grown on non-coffee fields of the farm for own consumption and the market. Banana species are a common intercrop grown together with coffee in Uganda and are commonly cultivated in the western (44%) and central (36%) regions, while only a small proportion occurs in the eastern (18%) and northern (2%) regions (Ochola et al., 2022).

Smallholder Ugandan coffee farmers may not have access or means to purchase seasonal farm inputs. For this reason, the handbook promotes the use of low-cost, nature-based strategies wherever possible as a first line of defense. By adopting this mindset, Regenerative Agriculture practices can reduce and/or eliminate dependency on purchased inputs which in turn, decreases running costs for coffee farmers. We do, however, not exclude the use of agrochemicals or other inputs if deemed necessary by the farmer.



> Coffee plants utilize light energy, ground water and soil nutrients to produce fruits (called coffee cherries) with seeds which are harvested, processed and roasted to produce coffee beans.

iii. Defining Regenerative Coffee Agriculture

Regenerative Agriculture is a conservation and rehabilitation approach to farming. This method is holistic and designed not only to sustain soils but also to regenerate them, improving soil health as the central foundation for Regenerative Agriculture. By strengthening soil health Regenerative Agriculture helps make agroecosystems more productive and resilient, while also improving farmers' livelihoods. The practices of Regenerative Agriculture also create important opportunities to mitigate greenhouse gas (GHG) emissions.

In the context of coffee systems, this handbook defines Regenerative Coffee Agriculture as a holistic land management practice for coffee production, which builds resilience to address climate change, poverty and ecological degradation. By practicing Regenerative Coffee Agriculture, the whole coffee farm system: the soil; the coffee plant; the people who cultivate it and the surrounding environment benefit from positive effects. Practices are designed to close the nutrient cycle, build better soil health, crop resilience and nutrient density.

> Regenerative Coffee Agriculture is a new coffee farming approach led by restorative principles and practices that are centered around optimizing soil and plant health; reducing greenhouse gas (GHG) emissions; improving waste and water management; and improving livelihoods of coffee farmers. Many of the practices put forward in this handbook are compatible with traditional coffee farming systems across the tropics and can be easily tailored to small-holder farmers' resources and needs.

By considering both the human interests and ecological aspects of farming, Regenerative Coffee Agriculture practices provide a number of benefits to above and belowground plant and animal life, smallholder farmers' livelihoods, and the local ecosystems surrounding coffee growing areas. The key entry points into Regenerative Agriculture are highlighted in **Figure 2** and below.

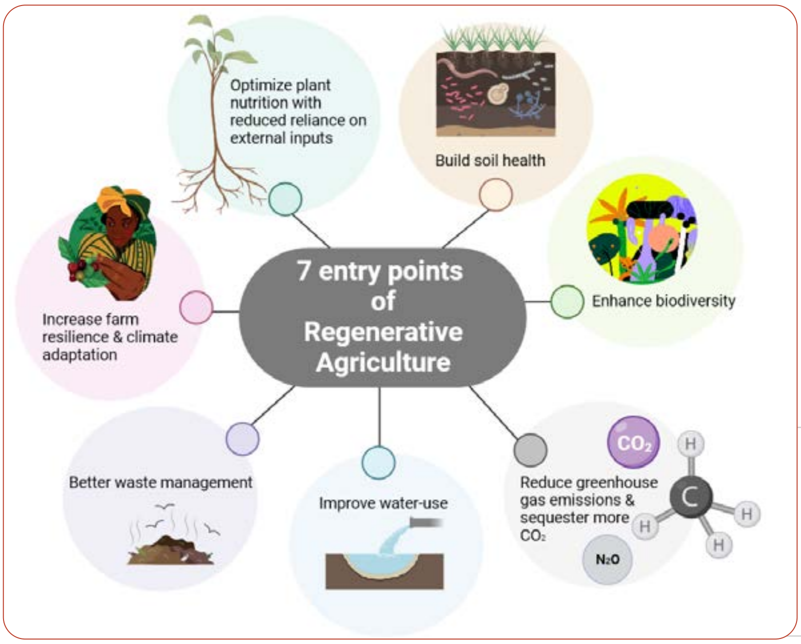


Figure 2. The seven entry points for Regenerative Agriculture serve as the foundation of this handbook. By adopting these, coffee farms can preserve and restore soil, water, biota, and the long-term viability of agriculture.

Seven entry points for Regenerative Agriculture

1. Build soil health

Soils are at the very base of terrestrial life and food production. 95% of our food is produced in soil.

Functions of healthy soils:

- Moderates nutrient cycles (carbon, nitrogen, phosphorus)
- Supplies the nutrients needed for healthy crops, animals and human beings.
- Sustains plant and animal life (biodiversity)
- Regulates water
- Filters potential pollutants
- Supports structures
- Regulates climate through carbon sinks

Soil is finite and takes hundreds of years to form. Over exploitation of soils has intensified due to human activity. This has led to soil erosion, fertility decline, salinization, and compaction; biodiversity loss; climate change and loss of resilience, all ultimately leading to reduced productivity and production capacity of our soils and ecosystems.

Regenerative Agriculture requires active soil management to reduce risk of soil degradation and improve soil health. Soil management is thus critical to securing increased productivity, enhanced ecosystem resilience, supporting biodiversity of animals, plant and microbial life, lowering GHG emissions and enabling soil carbon storage. Soil health can be built using soil cover crops and mulch; maintaining living plant and tree roots; minimizing soil disturbance, and integrating livestock for on-farm nutrient sources.

2. Enhance biodiversity

Biodiversity is essential for the natural processes that support all life on earth. Different organisms perform different functions (supporting, provisioning, regulating, and cultural) in their ecosystem. Pollinators such as birds, bees, other insects and other creatures are estimated to be responsible for generating a third of the world's crop production. Healthy soils are packed with microbes that are vital for liberating nutrients that plants need in order to grow, which are then passed to humans through food. Microbes may also help suppress harmful pathogens. Agriculture is therefore reliant upon invertebrates that help maintain healthy soils for to crops grow in. Soil fauna also condition the soil (*e.g.*, earthworms), and assist decomposition processes.

Trees, bushes, wetlands and wild grasslands naturally slow down water losses by structurally aiding the soil to absorb rainfall. Trees and other plants clean the air and help to tackle the global challenge of climate change by absorbing carbon dioxide. Plants are also a source of useful medicine and extracts for human use. Oversimplification of the ecosystems through cultivation and deforestation, and shifts to monoculture tends to disrupt this natural balance. Further use of harmful agrochemicals also compromises biodiversity.

Regenerative Agriculture calls for adopting farming practices that move away from monoculture and integrate biodiversity conservation practices. In this context, the aim is to leverage functional diversity, which in turn can improve crop production and resource-use efficiency.

3. Reduce greenhouse gas emissions and increase carbon sequestration

Greenhouse gas (GHG) emissions cause warming across various aspects of climate, including surface air and ocean temperatures, changes in precipitation patterns and sea level rise. More than 20% of human-induced net Greenhouse gas (GHG) emissions originates from agriculture (*e.g.* mineral fertilizer use), forestry and land use change (IPCC, 2022). Sustainable production of agricultural goods depends on favorable and stable climatic conditions, as well as on biodiversity and related ecosystem services (i.e., benefits provided by healthy soils and ecosystems, such as nutrient cycling, climate and water regulation, pollination, and natural pest control). Major efforts will be needed in the future to both reduce the contribution of agriculture-related GHG emissions and sequester more GHG (such as CO_2) at the farm level.

Regenerative Agriculture promotes adopting farming practices that enable carbon sequestration and minimize farm-level GHG emissions. This is achieved by better managing organic manures, and relying less on synthetic inputs, as well as avoiding conversion of high- to low-carbon ecosystems.

4. Improve water use

Today the world is undergoing climatic shifts. With this comes the challenge of unreliable rainfall and more frequent flood episodes. Water sources are also at risk of contamination due to soil erosion and runoff. There are concerns of eutrophication of surface waters in many parts of the world. Moreover, conflicts around water are emerging between upstream and downstream users.

Regenerative agriculture calls on farmers to adapt their water-use practices by more efficiently managing floodwaters and drainage and minimizing overuse and water pollution from farm runoff and drift.

5. Better waste management

Globally, large volumes of agricultural waste are being generated each day to meet the increasing demands of the fast-growing population. These are produced from different sources including crop residues, processing, livestock, and aquaculture. Agricultural waste is a global issue since the vast majority is currently burned or buried in soil, causing air and water pollution, and global warming. Limited or improper waste management has created an urgent need to devise strategies for timely and sustainable waste utilization and valorization (recycling, reuse or composting) for human-food and health security.

Waste management is a central theme of regenerative agriculture. By re-using, re-cycling or up-cycling coffee waste materials as close to the source as possible (at the farm level or in the processing facilities), then wastes can be more effectively and safely managed.

6. Increase farm resilience and climate adaptation

Agricultural resilience is about equipping farmers to absorb and recover from environmental or market shocks and stresses to their agricultural production and livelihoods. Some shocks are short-term, others long-term. Some come suddenly while others are predictable. Climate changes, which farmers are currently experiencing today, mean that adaptation strategies must be implemented to ensure crop and farm resilience. Without adaptation, climate-change effects are predicted to reduce global crop yields by between 5 and 30% by 2050. Simultaneously, farms need to increase in efficiency in order to support a growing global population. This means optimizing use of equipment, labor, and inputs, and reducing energy use, waste or by-products.

Regenerative agriculture is a holistic approach that considers the farmers' interests, resources and needs. By implementing a selection of suitable practices, Regenerative Agriculture can increase resilience, adaptability, and efficiency of farms worldwide.

7. Optimize plant health with reduced reliance on external inputs

Inorganic fertilizers and pesticides have been invaluable in meeting global food demand and boosting farmer profits. However, their improper use also leads to negative external environmental and health impacts. Detrimental effects on the environment can degrade the farmers' resource bases. Overreliance on these inputs can put farmers' businesses at risk when prices are too high, or access becomes limited. Increasing fertilizer use efficiency and minimizing toxic pesticide use can be achieved by enhancing nature-based, on-farm resources.

Nutrient depletion is of high concern in East Africa because the exported nutrients in harvested products and nutrient losses through erosion, leaching and volatilization are often not replenished, due to lack of access to mineral fertilizers and low availability of biomass for organic fertilizers resulting from low yields (*i.e.* biomass production) and competing interests (fuel, feed, construction, *etc.*).

Regenerative Agriculture encourages the use of both an integrated nutrient and pest-disease management system. This means that a diverse range of methods are used to bolster plant nutrition and control pests and diseases. By utilizing a wide range of manures, composts, green manures, natural enemies and biological pesticides, reliance on synthetic inputs reduces and soil and plant health is optimized.

Alliance Bioversity-CIAT/ Walter Ocimati

Regenerative Agriculture practices put into play on the Ugandan coffee farm can boost crop productivity and ecosystem vitality.

iv. Reasons for practicing Regenerative Agriculture in coffee farming in Uganda

Agriculture currently faces serious problems of poor soil quality, soil erosion, ecosystem degradation, and poor water and food quality. Some of these threats are a direct result of adopting unsustainable farming practices, or the lack of means to adopt sustainable ones. Many agricultural systems extract resources from the land without adequately replenishing them. They also convert diverse landscapes to homogenous cropland and use agrochemicals in ways that compromise human and ecosystem health. There are growing concerns about the proliferation of weeds, pests, and diseases.

Climate change threatens the livelihoods of millions of people. Increasing temperatures, changing rainfall patterns and more severe and increased frequency of extreme weather events requires substantial efforts to adapting farming to climate change, with smallholder farmers being the most vulnerable, and having low adaptive capacity. Moreover, several agricultural practices contribute significantly to GHG emissions, thus intensifying climate change. Increasing climate instability is negatively impacting agricultural productivity, while the simplifying agricultural landscapes makes them less resilient to climate shocks, as well as pest and disease outbreaks. This puts millions of households at risk of losing their livelihoods.

Agriculture, forestry, and land-use changes account for more than 20% of all global GHG emissions. Deforestation contributes a considerable amount of these GHGs by releasing CO_2 and causing a substantial loss of photosynthetic carbon-sequestration potential.

Coffee farming systems in Uganda face similar challenges. Studies have shown that climate change could dramatically decrease the suitability of most regions for coffee cultivation by 2050, including East Africa. Projected changes in temperature, precipitation, as well as declining soil health impact the coffee crop's growth, phenology, and productivity, as well as the aroma and taste of coffee beans.

Rising global temperature has led to increasing pressures by coffee pests and diseases, leading to increased pesticide dependency. These practices have knock-on health effects on those farmers handling agrochemicals, the environment, and coffee consumers.

Ugandan coffee farmers are dynamic and tend to manage a diverse range of crops, trees and livestock (**Figure 3**). Interactions within these farming systems can influence key ecosystem and social factors such as soil and/or plant nutrient status, greenhouse gas fluxes, carbon stock exchanges, pollination services, household income and food security.

Adopting Regenerative Agriculture promotes cultivating food crops in harmony with livestock and nature, helping the land recover from degradation and conserving healthy agroecosystems and landscapes. Regenerative Agriculture applied to coffee systems therefore increases opportunities to not only improve the productivity and quality of coffee, but the farming systems as well as the health of the ecosystems they rely on, ensuring improved, more sustainable livelihoods for rural households. Additionally, the global coffee market is demanding coffee produced in safe and environmentally sustainable ways. This trend offers an opening for coffee farmers to modify their production systems to benefit from non-commodity markets with higher prices. Overall, Regenerative Agriculture will benefit coffee crop productivity, the environment and the rural communities implementing these practices.

Figure 3. Ugandan coffee farmers can integrate a diverse range of crops, trees and livestock. (*Source:* Boaz Waswa (Alliance Bioversity-CIAT).

CHAPTER 2. PRACTICES OF REGENERATIVE AGRICULTURE

i. Introduction to practices

The main overarching principle of Regenerative Agriculture is to harmonize three P's of agriculture: profit, people and the planet. By striving to close the circle between these three P's, future coffee farming systems stand to be more sustainable (**Figure 4**). A wide range of on-farm practices can be applied to operationalize Regenerative Coffee Agriculture. By implementing these practices, coffee farmers stand to improve soil and plant health, protect and save water bodies, contribute to biodiversity conservation, improve economic resource management, and reduce the carbon footprint specifically linked to coffee farming in Uganda.

Figure 4. Closing the circle between profit, people and planetary needs. (*Source:* Schreefel et al. 2022).

Regenerative Coffee Agriculture principles are guides for on-farm conduct and action. The combination of these principles maximizes the benefits for farmers and the local ecosystems. Note: some principles may not be applicable to all Ugandan coffee farming systems.

In this chapter, a wide range of different practices are firstly introduced (**Figure 5**), and then detailed for application on a Ugandan coffee farm. Combing several of these farming practices maximizes benefits for farmers and local ecosystems. Applying these principles enables coffee farmers to improve soil and plant health, protect and save water bodies, contribute to biodiversity conservation, improve economic resource management, and reduce the carbon footprint linked to coffee farming. A suggestion is made on a stepwise approach for implementing regenerative coffee farming in smallholder farms in Uganda.

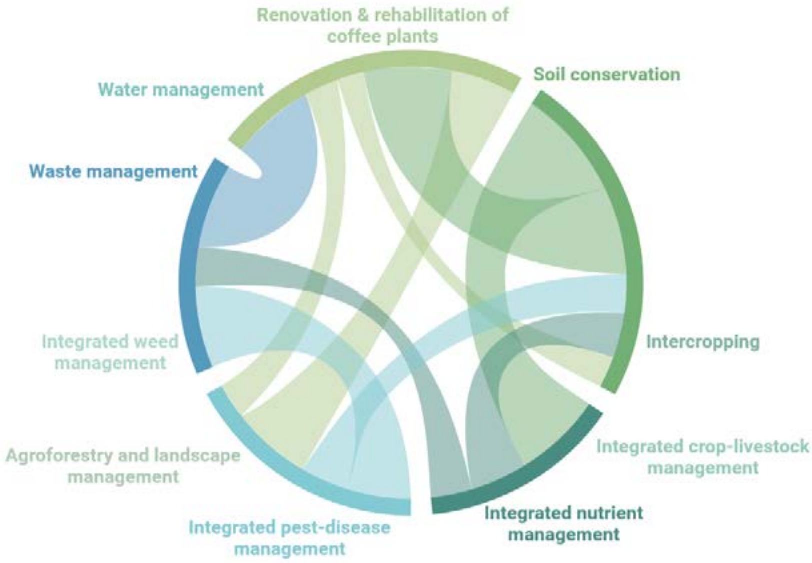


Figure 5. A chord diagram highlighting practices of Regenerative Coffee Agriculture and how they are interconnected.

Optimal soil health is crucial to the vitality and longivity of the perennial coffee plant.

1: Soil conservation

Soil conservation practices aim to protect the soil from water and wind erosion and improve soil health and related functions. This also contributes to protecting water bodies through avoided runoff and sedimentation as well as building the water filtration capacity of healthy soils. Soil conservation practices are always important but need particular attention on steep slopes and close to water bodies. Because coffee is a perennial crop, critical stages of soil exposure are during establishment and rehabilitation/renovation. Hence careful planning is required to avoid exposure of bare soils to water and wind erosion. Soil conservation in coffee Regenerative Agriculture includes:

a. Maintaining soil cover

b. Using deep rooting plant and tree systems

c. Building soil organic matter and thereby its carbon storage capacity.

Practices that contribute to soil conservation are cover cropping, contour planting, erosion barriers, mulching, reduced soil tillage, and terracing. Other practices such as agroforestry, intercropping, organic matter management, and selective weed management, also contribute to soil conservation.

2: Integrated weed management

Integrated weed management aims to keep weed pressure below an economic threshold in a sustainable manner through combining preventive and corrective methods. In the early establishment period, coffee plants are most sensitive to weed competition for water, nutrients, and light. Competition also increases during the dry season when water resources are limiting. Weeds can take up a significant part of the applied fertilizers leading to economic losses. Weed control is most important in systems where more light reaches the soils, such as in full-sun systems, particularly at low planting density and during early establishment when coffee plants are still small. At the same time, if weeds are removed under these conditions, the soil is left bare and prone to erosion. Integrated weed management intends to manage these trade-offs while minimizing the use of chemical herbicides.

Integrated weed management in Regenerative Coffee Agriculture includes:

a. Preventive measures that outcompete weeds through mulching, cover crops, intercrops, agroforestry and appropriate planting densities;

b. Selectively managing beneficial weeds (*e.g.*, low-growing, shallow rooted annuals, nitrogen fixing, habitats for pollinators or natural pest control agents) and non-beneficial weeds;

c. Corrective measures (physical, chemical) once a critical economic threshold has been reached.

Weeds can compete with coffee plants for nutrients, water, and sunlight, reducing crop yields.

Source: https://wikifarmer.com/weed-management-in-a-coffee-plantation/

3: Integrated nutrient management (INM)

Integrated nutrient management combines the use of organic resources and mineral fertilizers. It offers a means to enhance crop productivity by maximizing the agronomic efficiency of applied inputs (*i.e.* application rates that increase yield to a level that makes economic sense where fertilizer costs are considered) (**Figure 6**). It combines practices that include the appropriate use of mineral fertilizers and organic resources, and minimizes negative effects on soil health (*e.g.*, soil acidification), water (*e.g.*, eutrophication aka. increase in algae or plants in water due to excess nutrients), and air (*i.e.* GHG emissions). The right nutrient source, rate, timing, and placement is informed by agroecological conditions (soil conditions, climate), crop genetic yield potential, crop management, and crop stage (establishment, vegetative growth, fruit development).

Unbalanced plant nutrition is one of the main causes of low coffee yields. For example, nitrogen (N) is the most indispensable nutrient for coffee production. Yield losses of up to 60% have been reported to occur when no N fertilizer is applied during the early reproductive stages of coffee plant development. However, yield responses from mineral fertilizer application are reduced in soils with a low soil organic matter content, due to the higher levels of nutrient losses through leaching and volatilization, while inadequate soil pH levels can make nutrients unavailable to plants. Although many Ugandan coffee farmers use both organic and mineral fertilizers, insufficient nutrient inputs (volume and sources) and soil fertility tend to limit yields. Given this, there is a high need for INM on Ugandan coffee farms.

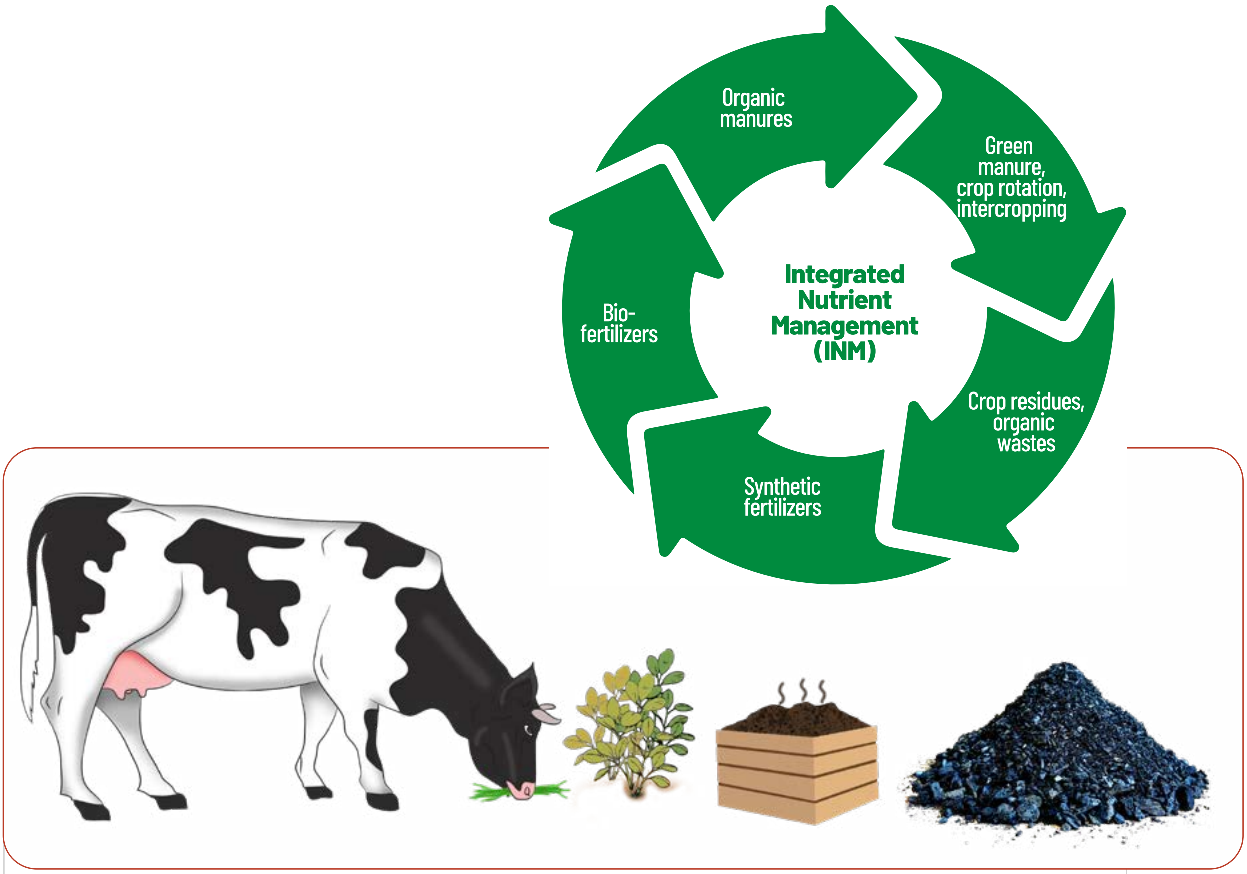


Figure 6. *Top:* An Integrated Nutrient Management plan utilizes multiple approaches to plant and soil nutrition. *Bottom:* combined use of animal manure, cover crops, compost (including vermicompost and coffee waste compost) and biochar make up an Integrated Nutrient Management plan.

Integrated nutrient management in coffee Regenerative Agriculture includes:

a. Alleviating local soil constraints including soil pH and competition (*e.g.*, weeds, insufficient pruning, excessive shading in agroforestry systems) or plant productive capacity (*e.g.*, old plants, low yielding varieties) which can limit crop response to nutrient inputs.

b. Combining organic resources of nutrients with the judicious use of mineral fertilizers to deliver essential nutrients to the coffee plants and associated crops.

c. Prioritizing on-farm nutrient cycling (also linked to integrated crop-livestock management practices) as a means of achieving circularity and reducing dependency on external resources (**Figure 7**).

d. Appropriate use of organic and mineral fertilizer (right nutrient source, timing, rate and placement) to avoid nutrient losses through runoff, leaching or volatilization thus reducing GHG emissions (N_2O, CO_2).

e. Using high quality organic inputs as nutrient sources for intercrops and coffee plants, whilst protecting beneficial soil biota.

f. Avoiding soil and nutrient loss through erosion.

g. Monitoring nutrient balances through regular soil testing.

Figure 7. The use of livestock manure is a way of achieving on-farm nutrient cycling and circularity.

4: Integrated crop-livestock management (ICLM)

An integrated crop-livestock farming system approach enables cross-linkages between many on-farm practices, to improve the efficiency of land, labor, finance, and nutrient investments, while providing more diversified income sources (**Figure 8**). Integrated crop-livestock management (ICLM) is a core aspect of regenerative agriculture in Uganda, as it can contribute substantially to farm profits and to sustaining production levels, while minimizing the dependency on external nutrient sources. Furthermore, ICLM can buffer the economic impacts of bi-annual yield variation and cash shortages between harvests in coffee, and thereby improve farmers' livelihoods. Many Ugandan coffee farmers keep livestock on their farm, and milk production is an important income source. The majority of Uganda's dairy cattle are kept by smallholders in crop-livestock systems with an average of 1-2 dairy cows. Local horned breeds along with Ayrshire, Friesian, Guernsey, Holstein, and Jersey are the main dairy cow breeds; however, goats and buffaloes also contribute to dairy production in East Africa. ntegrating coffee and livestock farming can provide valuable on-farm nutrient sources (*i.e.*, animal manure) and alternative income and/or human foodstuffs (*i.e.*, dairy products) for smallholder coffee farmers. However, in many cases, there is substantial opportunity to improve land-use efficiency, nutrient cycling, and income, while reducing GHG emissions.

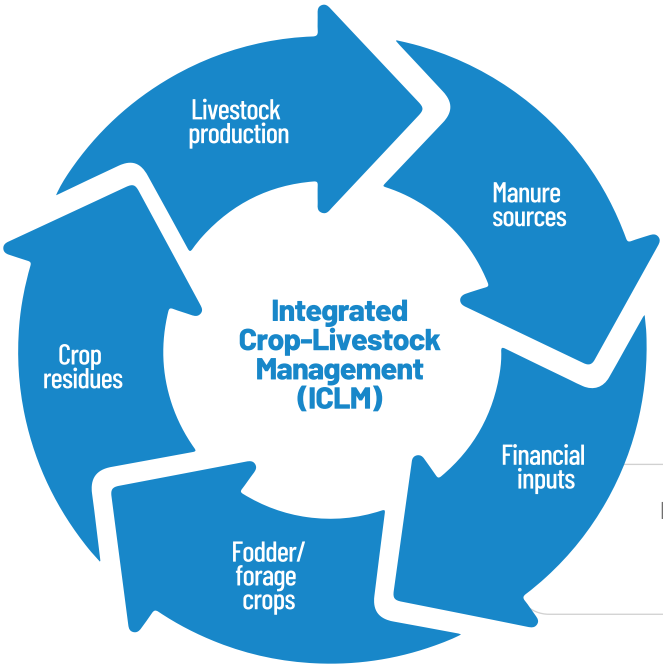


Figure 8. An integrated crop-livestock management (ICLM) approach ensures circularity of critical farm inputs and use of valuable outputs.

Integrated crop-livestock management in Regenerative Coffee Agriculture includes:

a. Responsibly utilizing animal manures (*i.e.* manure collection and handling, storage, and application).

b. Integrating soil conservation practices by sowing forages as intercrops.

c. Optimizing farm-level resource allocation to improve animal feed, manure production and livestock related income sources.

d. Promoting on-farm circularity and waste management by re-using coffee pulp and husks as fodder for livestock (e.g., coffee pulp and husks in addition to other organic waste as feedstock to black soldier flies, which provides protein-rich animal feed).

e. Reducing GHG emissions (N_2O, CO_2) associated with animal agriculture.

5: Integrated pest and disease management (IPDM

The primary objective of this key area is to bolster soil and plant health, particularly through integrated nutrient management and the use of resistant varieties. Secondly, IPDM uses cultural control to avoid favorable pest microclimates and to create habitats for beneficial insects. Thirdly, where preventive measures are not sufficient, IPDM applies physical and biological control, and judicious use of insecticides and fungicides where necessary. Good knowledge of pest life cycles and monitoring is a prerequisite. In doing so, terrestrial and aquatic biodiversity can be better protected, including beneficial organisms for pest control and pollination.

Some prominent coffee pests and diseases found in East Africa include coffee berry borer, white coffee stem borer, green scale insect, coffee root mealybug, nematodes, coffee leaf rust, coffee berry disease, coffee wilt disease and brown eye spot disease.

IPDM in Regenerative Coffee Agriculture includes:

- Prioritizing preventive measures and making use of cultural control
- Monitoring pests and diseases
- Continuously evaluating pest-disease pressures and adjusting corrective measures
- Sensible use of chemical control (as a last measure).

6: Intercropping

The practice of 'intercropping' refers to growing two or more crops on the same field at the same time. Intercropping and cover cropping have distinctive objectives (food production vs. soil conservation, respectively) and therefore make use of different plant species. The harvested products of intercrops are exported from the field resulting in nutrient loss, while cover crops are not exported and nutrients are recycled and even added in the case of legumes. Intercropping is different to agroforestry, as intercrops are non-woody species that typically provide harvests in a short time after planting, while agroforestry refers to integrating woody trees, which take several years before they can be harvested (e.g., fruits, timber). Most intercrops are smaller than coffee (except for banana and plantains) and therefore do not modify microclimate at the coffee tree layer (but they do so at soil level), which is another important difference to agroforestry.

Intercropping in Regenerative Coffee Agriculture includes:

- Preferring intercrops, which are complementary with the allometry of coffee plants (*i.e.*, architecture of branches and root systems) and in nutrient and water use and in turn, provide a high land equivalent ratio and niche differentiation.
- Using intercrop varieties that contribute to food security (*i.e.*, they provide for household nutrition), household income, or animal feed for ICLM.

Traditionally, Ugandan coffee farming features the use of intercropping. These systems combine agroforestry, banana, beans, coffee (**Figure 9**), perennial fruit trees (avocados, macadamia, *etc.*), maize, sweet potato and vegetables. Vegetables as intercrops were a common feature to almost all identified systems, for the primary reason that they mature and sell quickly, generating a fast household income. Vegetable cultivation was also identified as providing labor opportunities for women and youth (vulnerable groups typically not involved in coffee farming).

Figure 9. *A:* Banana plants are a complementary intercrop with coffee. ***B***: Intercropping the cash-crop (coffee) with the staple-crop (beans) is a common practice in Uganda and East African coffee farming. (*Sources:* Alinde Mulinde and An Notenbaert).

7: Agroforestry and landscape actions

Agroforestry systems (AFS) are defined as "agriculture with trees". As some Coffea species originated from forests of the Congo basin and West Africa as well as Uganda (*C. canephora*) and the Afromontane forested regions of southwestern Ethiopia and South Sudan (*C. arabica*), a certain level of shade tolerance is inherent to its genetic resources. Therefore, growing coffee together with timber, fruit, fuel biomass, or for other services (*e.g.*, nitrogen fixation, shade) trees have been part of a viable agricultural system since the origin of coffee domestication. Trees within a coffee AFS may be planted within coffee plots, as living fences, garden zones, riparian buffers or as woodlots (**Figure 10**). Trees are either remnants, naturally regenerated or purposively planted. High quality planting material can ensure higher economic benefits of timber and fruit trees but requires more investment costs than naturally regenerated trees. The former, however, are limited to the seeds available in the soil. Forest-derived coffee agroforestry systems (*i.e.*, planting coffee in forests and selectively removing trees) is not part of Regenerative Agriculture due to the associated loss in biodiversity and carbon stocks from deforestation.

Agroforestry and landscape actions in Regenerative Coffee Agriculture includes:

a. Creating habitat to bolster biodiversity (including pollination and pest control ecosystem services)

b. Protecting water bodies (*e.g.*, riparian buffers)

c. On-farm nutrient cycling including nitrogen fixation

d. Protecting soil from erosion or nutrient leaching and/or run-off

e. Microclimate regulation for the coffee plant

f. Diversifying income with high-value tree biomass and /or products

g. Increasing on-farm carbon sequestration (above- and belowground biomass and soil carbon).

Figure 10. Agroforestry systems consist of multiple plant and tree species which grow at different strata.

8: Renovation and rehabilitation of existing coffee farms

Rehabilitation and renovation are strategies for ensuring long-term productivity of healthy coffee plants through pruning, stumping and/or replacing old or sick plants with new improved and adapted varieties. The main objective of this practice is to maintain coffee productivity over time, which can increase time-averaged annual yields. In doing so, renovation or rehabilitation of old coffee farms can positively contribute to land use efficiency by avoiding expansion of coffee areas into areas of higher ecological importance.

Renovation and rehabilitation of coffee farms in Regenerative Coffee Agriculture includes:

a. Renovating and / or rehabilitating coffee plants as a means of managing age-density-yield relationships.

b. Establishing new plantations to include intercropping and agroforestry designs (*i.e.* re-design of coffee systems).

c. Selecting locally-adapted and/or improved varieties, cultivars, or hybrids.

9: Waste management

Waste management is the process of reusing, recycling or composting waste materials from a particular process and transforming them into alternative products and/or services. Coffee production generates waste from the coffee berries amounting to more than 50% of the fruit mass. This waste product can be routinely converted into high-value by-products for both the coffee farm itself and/or alternative industries.

Waste management in Regenerative Coffee Agriculture includes:

a. Reducing material or loss residues (*i.e.* bad coffee berries collected during harvest).

b. Re-using coffee pulp, husk, silver skin and leaves for alternative purposes or sources of income.

10: Wastewater treatment

De-pulping, fermentation and washing steps in the 'wet' coffee processing system uses large volumes of water (15–20 L for 1 kg of coffee bean) and generates polluted effluent water (containing tannins, phenolic and alkaloids), which are traditionally discharged into nearby water sources such as streams or rivers. Additionally, synthetic inputs such as fertilizers or pesticides can also run-off into water sources close to coffee farms (**Figure 11**).

Wastewater treatment in Regenerative Coffee Agriculture includes:

a. On-farm recycling of wastewater.

b. Decontaminating of wastewater which is re-directed into nearby water bodies

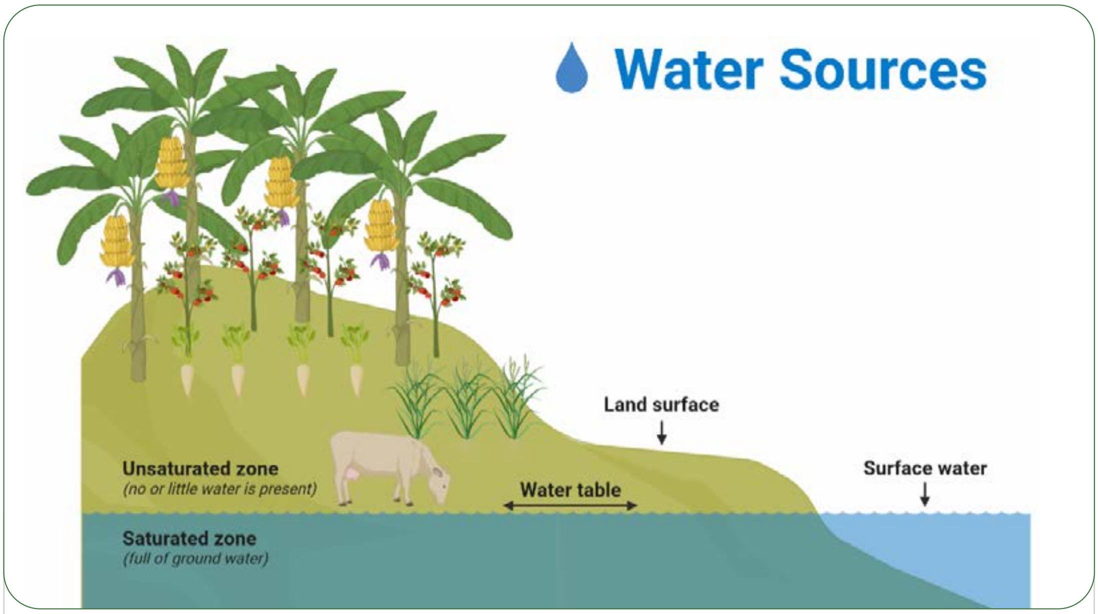


Figure 11. Water sources surrounding coffee farms are vulnerable to contamination.

ii. Application of practices

The following section will detail a number of different methods which can put Regenerative Agriculture into practice in the coffee farm. These methods are not specific to the coffee crop but are highly compatible with the farming system and the resources available to Ugandan coffee farmers. **Table 1** provides an overview of the practices and how they can serve as more than one of the entry points into Regenerative Coffee Agriculture.

Table 1. Overview of the 7 entry points into Regenerative Agriculture matched with specific practices that can be implemented on a Ugandan coffee farm. +, ++, +++ indicate relevance of the practice to the entry point.

	7 entry points Regenerative Agriculture						
	1. Build soil health	**2. Enhance biodiversity**	**3. Reduce greenhouse gas emissions and increase carbon sequestration**	**4. Improved water use**	**5. Better waste management**	**6. Improved farm resilience and climate adaptation**	**7. Optimization of plant health with reduced reliance on external inputs**
Practices							
1. Soil conservation							
1.1 Mulching	+++	++	+	+++	+	+++	+
1.2 Cover crops	+++	+	+++	+		+++	++
1.3 Zero-/minimum/ conservation tillage	+++	++	++	+++		+++	
1.4 Erosion terraces	+++	+		++		++	+
1.5 Contour planting	+++			+		++	
2. Integrated weed management							
2.1 Cultural control methods	++	+++		++		+	+++
3. Integrated nutrient management							
3.1 Using livestock manure	+++	++	++	+++	+++	+++	+++

	7 entry points Regenerative Agriculture						
	1. Build soil health	2. Enhance biodiversity	3. Reduce greenhouse gas emissions and increase carbon sequestration	4. Improved water use	5. Better waste management	6. Improved farm resilience and climate adaptation	7. Optimization of plant health with reduced reliance on external inputs
3.2 Compost	+++	++	++	+++	+++	+++	+++
3.3 Green manures	+++	++	++	+++		+++	+++
3.4 Vermicomposting	+++	++	+++		+++	++	+++
3.5 Coffee waste manure compost	+++	+	++	+++	+++	+++	+++
3.6 Biochar	+++	+	+++	+++	++	+++	+++
3.7 Covering manure sources	+++		+++		++		+
4. Integrated crop-livestock management							
4.1 Covering manure sources	+++		+++		++	+	+
Resource cycling	+++				+++		++
5. Integrated pest and disease management							
5.1 Plant and natural predators		+++	+			++	+++
5.2 Pest and disease resistant coffee plant varieties						+++	+++
5.3 Natural forest barriers (e.g., forest corridors or islands) to trap pests/pathogens	+++	+++	+++			+++	+++

	7 entry points Regenerative Agriculture						
	1. Build soil health	2. Enhance biodiversity	3. Reduce greenhouse gas emissions and increase carbon sequestration	4. Improved water use	5. Better waste management	6. Improved farm resilience and climate adaptation	7. Optimization of plant health with reduced reliance on external inputs
5.4 Pest and disease monitor and surveillance	+	+	++			++	+++
5.5 Biological control agents	++	++	++			++	++
6. Intercropping							
6.1 Legumes intercrops	+++	+				+++	++
6.2 Banana/ plantains intercrop	+	+	++			++	+
7. Agroforestry and landscape actions							
7.1 Multipurpose trees (Fruit/ Shade trees)	+++	+++	+++	++		+++	+++
7.2 Windbreaks		+++	+++			+++	+++
8. Renovation and rehabilitation of existing coffee farms							
8.1a Pruning				++		++	+++
8.b Stumping				+		++	+++
8.2 Improved coffee varieties				++		+++	+++
9. Waste management							
9.1 Re-use coffee waste (pulp, husks and leaves)	++				+++	+++	
10. Water management							
10.1 Plant remediation or 10.2 Adsorption		++		+++	++		

1:Practices to achieve soil conservation

Figure 12. Mulching coffee using Gravillea leaves in Uganda. (*Source*: Boaz Waswa/Allaince Bioversity-CIAT).

1.1 Mulching

Mulching is the placement of any organic material over the top of a soil surface to protect it. Regenerative Agriculture circularity can be achieved by using organic, on-farm sources of mulching materials (*e.g.*, shade tree leaf litter, banana leaves or fibers, well-decomposed coffee husks and local grasses such as *Cymbopogon* spp. and *Panicum* spp.). The mulching material improves soil moisture, moderates soil temperature, reduces evaporation, suppresses weed growth, reduces soil losses and improves soil fertility.

If organic materials are limited, mulch can be applied as a ring 10 to 30 cm from the coffee stem (**Figure 12**). To maximize the known benefits of mulching on coffee yields, it is recommended that a mixture of organic materials is applied to the coffee farm soil system at regular intervals. It must be noted that mulching alone is not a sufficient substitute for exported nutrients in the context of coffee production (see **Integrated Nutrient Management**).

In its natural environment coffee grows in a bed of forest litter. Its superficial root system is therefore adapted to function most efficiently under such conditions. On commercial coffee farms we attempt to simulate these conditions by keeping the bare soil permanently covered with a layer of organic mulch material. Mulch is most beneficial when done to trap soil moisture and to keep soil cool during the hot seasons and months. Mulching at 10 – 30 cm away from the coffee plant stem (*e.g.*, ring mulching) allows for covering of the feeder roots; avoids shallow rooting of the coffee plant and/or prevents seasonal termites from feeding too close to the plant stem.

Mulch can be applied in strips in between the rows (inter-row mulching) of coffee trees. The approach can be considered more economical because it requires considerably less mulching material and the results are almost as good. Timing of applying the mulch is important to minimize splash erosion and encourage infiltration in the exposed area between the coffee trees. Mulch can also be applied as a ring placed in a 0.5m circle around the main stem soon after planting out and each year for the next three to four years. Mulch must be at least 10-20 cm deep).

1.2 Cover crops

Cover crops are annual or perennial plants grown in fields intended to cover exposed soil in between primary crop harvest periods and/or for nitrogen fixing purposes (**Figure 13**).

Cover crops are non-cash crops that are grown specifically to protect the soil and improve soil health. In Ugandan coffee systems,, annual and perennial cover crops are commonly used to prevent soil erosion, suppress weeds, and enhance soil fertility. Unlike green manure crops, cover crops are not primarily grown for the purpose of being incorporated into the soil to improve soil fertility, but rather to provide cover and other benefits to the soil and cash crop. Farmers may grow leguminous cover crops intercropped with coffee plants. These crops fix nitrogen from the atmosphere, which, when incorporated to the soil, release nitrogen that can be used by the coffee plants.

Examples of cover crops reported in the Ugandan coffee system are *Canavalia ensiformis* (jack bean), *Crotalaria*, *Desmodium*, *Dolichos*, *Lablab and Mucuna* species. These species have been found to be beneficial in terms of coffee yield increases, biomass accumulation, ground cover and weed suppression. *Mucuna* and *desmodium* can be grown in between the coffee trees to serve as permanent cover. Care should be taken with the use of *Desmodium as it* is a climbing plant which may require frequent pruning to ensure it doesn't interfere with the coffee plant growth. It is a slow-growth intercrop but once established has been shown to be effective in weed control.

Cover crops may be incorporated while still green into the soil (*i.e.* as green manure), converted into mulch or used as fodder to support livestock integration. Green manure refers to the practice of growing crops that are specifically intended to be incorporated into the soil to improve its fertility. When they have matured, they are cut down and tilled into the soil. As they decompose, the plants release nutrients back into the soil, which can help to improve soil health and fertility.

In mature systems, cover crops are more common in Robusta coffee as there is more open space between coffee rows, while the smaller Arabica coffee is usually planted at higher density with little space between rows. During establishment, when coffee trees are still small, there is more space for cover crops and/or intercrops. Selective weed management is another form of cover cropping where naturally occurring herbaceous vegetation is used (see **Integrated Weed Management**).

Example of spacing of cover crops in coffee systems

Crop	Distance from the coffee trees (m)		Spacing (cm)	
	Year 1	Year 2	Between rows	Within rows
Mucuna sp.	1	1.5	40-50	30
Desmodium sp.	1	1	30-40	30

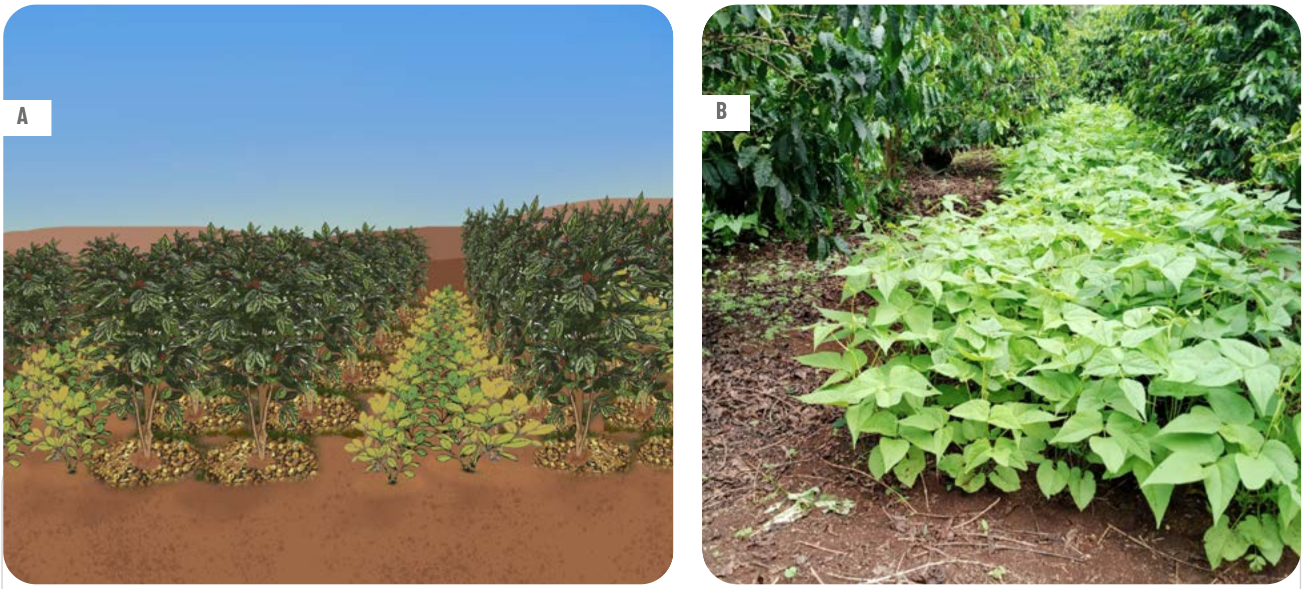


Figure 13. ***A:*** Cover crops can be used to cover any exposed soil in the coffee field and help fix nitrogen. ***B:*** This is common beans in coffee systems. (*Source:* Peter Ndambiri, Sustainable Management Services Limited).

1.3 Zero-/minimum/conservation tillage

Zero-/minimum/conservation tillage is a practice in which crops are sown directly into soil, with little to no tilling, after the harvest of the previous crop. Conventional soil tillage comprises all the physical, mechanical, chemical or biological actions conducted to prepare the land for planting and establishing a crop. Prolonged ploughing using disc harrows has been associated with widespread soil degradation and loss of soil fertility. Minimum/conservation tillage embraces one principle of conservation agriculture that is minimum soil disturbance. Minimum tillage should be used in combination with other practices such as mulching and cover crops, and crop rotation using legumes in conservation agriculture systems. Minimum tillage slows mineralization of soil organic matter through less exposure to climatic elements and soil micro and macro fauna. It reduces the release of GHG from the soil. Minimal tillage also minimizes water evaporation from the soil and can contribute to saving labor for weeding coffee systems.

1.4 Erosion terraces

Coffee cultivation on sloping land in tropical highlands of East Africa is highly prone to soil erosion. This is especially the case for Arabica coffee which is grown at high altitudes. The associated financial losses of soil erosion rise with increasing land slope. Given this, steep slopes should not be used for new coffee farms in Uganda. Erosion barriers which are locally sourced or made from low- or no-cost materials should be used as a best practice for existing Ugandan coffee farms positioned on steep slopes.

Erosion terraces can be constructed with natural materials such as rock, land contouring (*e.g.*, bunds and trenches), or vegetation (*e.g.*, use of trees or shrubs along slopes) (**Figure 14 *top***). The *fanya chini* and *fanya ju* methods for land contouring (with deep rooted grasses to hold the soil bands) are already common practice in East Africa and the current recommended approaches for erosion terraces in slopy terrains (**Figure 14 *bottom*).**

Fanya chini means "do it down", while ***Fanya juu*** means "throw the soil up" in Kiswahili. The terraces are formed in similar ways by digging holes and then placing soil as a barrier for the terrace embarkment. Often the terraces are reinforced by planting grass strips on the soil bunds that are harvested regularly and used to feed livestock. Nitrogen fixing trees and shrub species can also be planted to hold the soil bunds. These terraces are thus ideal for fodder grasses in addition to soil erosion control and water conservation. Cultivation becomes easier as the terraces spread out to make the land more level and when combined with manure/ fertilizer yields increase.

Figure 14. *A*: Erosion barriers should be used on sloping terrains and can be constructed with natural materials such as rock and vegetation. *B*: Grass strips can be used as vegetative erosion barriers. (*Source:* Boaz Waswa/Alliance Bioversity-CIAT).

Construction of erosion terraces can often be too costly for farmers to invest in on an individual scale. Government incentives (as previously conducted in the Kigezi region of Uganda) could be used to facilitate the implementation of terracing in mountainous coffee producing landscapes with steep slopes.

1.5 Contour planting

When a coffee plantation is on land with a slope of more than 5%, the coffee trees should be planted along the contour (coffee rows should follow a line at constant elevation). To manage rainfall run-off use anti-erosion measures such as contour ridges, contour bunds, and contour ditches, and vegetative measures of erosion control that also run along the contour between the coffee rows. Contour planting is recommended for conservation and other management considerations such as energy use when spraying and more even application of water via irrigation systems. Contour planting offers high potential for Regenerative Agriculture especially for hilly and sloping farmlands.

Coffee is commonly cultivated on steep slopes making the crop system prone to soil erosion.

2: Practices to achieve integrated weed management

Specific Regenerative Agriculture practices and advice for the Ugandan coffee farmers include the combined use of the following:

1. Identifying the weed species with the highest on-farm pressure (**Figure 15**).
2. Identifying life-history traits for example::
   i. Are the weeds perennial or annual?
   ii. Can the weeds be of benefit at the farm-level (*e.g.*, fodder source, cover crops between coffee rows, attract pollinators)?
   iii. Do the weeds' root architecture compete with the coffee plants?
   iv. What are the interactions with pests, diseases, beneficial species, allelopathic effects?
3. Understanding the weed life cycle and its response to environmental conditions and crop phenology.
4. Monitoring environmental conditions and weed populations.
5. Preventing or providing early response to control weeds (when it reaches a certain economic threshold).
6. Using recommended herbicide dose rates for control of perennial weeds.

Figure 15. Prominent weeds on Ugandan coffee farms *(left to right)* include Bermuda grass (*Cynodon dactylon)*, East African couch grass (*Digitaria abyssinica* and/or *D. scalarum)*, Nut grass (*Cyperus rotundus)*, Kikuyu grass (*Pennisetum clandestinum)* and Buttercup oxalis, Wood sorrel or Sourgrass (*Oxalis* spp.) Photos ©: Harry Rose, Forest and Kim Starr, Joseph DiTomaso, James H. Miller & Ted Bodner.

2.1 Cultural control methods

Cultural control methods for weed suppression include routine slashing in the dry and wet seasons, selective weed management (*i.e.* strip weeding) or "clean" weeding with hand tools or by use of small machinery such as single-axle tractor (which do not heavily compact the soil), if available to the farmer. Agroforestry, cover crops (to displace weeds) and mulching can be preventative measures for weed control. Beneficial weeds with shallow root systems and low growth not disturbing the coffee branches can be left as groundcover between coffee rows.

3: Practices to achieve integrated nutrient management

3.1 Livestock Manure

Livestock Manure used in coffee-based systems offers many benefits. Livestock manure is known to provide valuable nutrients to the soil. Manure can also provide additional benefits by improving the soil's biological, chemical, and physical properties. A well-composed manure consists of four main components: carbon, nutrients, microbial life, and water. Carbon from manure improves many soil health indicators, such as water holding capacity, nutrient cycling, and raising and/or buffering soil pH. Manure in the soil increases the cation exchange capacity, which affects the soil's ability to hold onto available nutrients and improves nutrient use efficiency. Manure also improves soil biodiversity. Manure is an important part of recycling nutrients. Manure application increases soil biological activity by food to microorganisms and introducing new and important microorganisms. Nutrients from manure can also mean coffee farmers divert financial resources away from commercial fertilizers and in turn use less of inorganic forms of fertilization. Manure provides part of the required nutrients, and it can also increase the efficiency of mineral fertilizer use. Efficient handling of livestock manure is outlined in the next section below (**in Integrated crop-livestock managemen**t). Using high-quality livestock manure increases these benefits, whereby quality mainly depends on manure type, storage and treatment methods.

3.2 Compost

Compost is an organic fertilizer source which adds nutrients to the soil and helps in maintaining the soil structure. Adding compost to the soil contributes to both soil biota and plant growth. It also helps to prevent erosion, and increases the water retention capacity of sandy soils, amongst other benefits. The basic requirements for composting include organic waste materials (manure, grass or hay, sawdust, food waste among other things) found on the farms. Compost has similar benefits to livestock manure. Compost can be made by piling organic materials in layers and covering to enable these to decay. An initial addition of urine can fast-track composting processes. It can also be produced in composting pits where the materials are moved and mixed from first pit to the fourth pit. The compost should be ready after 6 – 9 weeks depending on the type of material used for the compost. Around this time the well decomposed compost should have a rich brown color and crumbles easily into small particles in the hand.

3.3 Green manure

Green manures *are* fast-growing plants, typically legumes that fix nitrogen, sown to cover bare soil and later incorporated or ploughed into the soil, and provide an additional source of nitrogen and soil carbon (C). *Canavalia ensiformis*, *Mucuna pruriens*, *Crotalaria ochroleuca* and *Lablab purpureus* have been tested in Eastern Africa and elsewhere.. Green manure application was shown to improve maize yields; however, this was dependent on the site, season and species of plant used as green manure. Care should be taken in the species selection of the green manure used. For example, *Mucuna pruriens* can become highly invasive and smother whole forest canopies, if left unmanaged.

3.4 Vermicomposting

Agricultural practices generate diverse wastes from crops and livestock which can be turned into useful fertilizers for application on coffee or other crops. Improper handling of such waste can cause a very unhygienic environment. Vermicomposting is one way to turn the organic waste on the farm into useful and high-quality inputs.

Vermicomposting is the process of using earthworms to transform organic materials into rich, organic fertilizers (**Figure 16**). The growth of earthworms in organic waste is termed **vermiculture**. The final product of this process produces vermicompost. Vermicomposting also produces **vermicast** (also called **worm castings**, **worm humus**, **worm faeces,** worm manure). It is the end-product of the breakdown of organic matter by earthworms.

Vermicomposting uses epigeic earthworms that live in and consume surface litter. These worms can be domesticated and used to produce high quality vermicompost.

Figure 16. Vermicomposting of coffee pulp (*Source: Sustainable Management Services Limited*).

Vermicompost is superior in a number of important ways:

Vermicompost is a high-quality fertilizer for crop production. A typical nutrient content of the compost is 1.9% nitrogen, 0.3% phosphorus and 2.7% potassium. Vermicompost acts as an inoculant during compost production. Worms have several other possible uses on farms, including value as a high-quality animal feed for poultry and fishery. Vermicomposting supports supplemental income as it does not require farmers to invest highly in commercial fertilizers. It is hygienic with little or no odor compared to normal manure. It requires no external energy inputs for aeration. It is a waste recycling and management practice.

It generates an efficient vermicompost byproduct that can be used on the farm or sold to make income. The worms themselves can be sold to earn income.

3.5 Coffee waste compost

Coffee waste compost can be produced by composting the coffee pulp and husks (see also **Waste management**). Coffee processing produces of huge volumes of coffee pulp as waste, either locally on the farm or centrally on a processing facility. Often this is burnt and produces smoke that pollutes the air. Coffee pulp, however, can be used to produce high quality compost that can be applied back on the coffee farms to supply nutrients. Coffee pulp organic compost can be made by mixing coffee husk, manure, and water and composting it at a temperature of about 60°C. This compost will mature and be ready to use in 4 months.

The compost from coffee pulp and manure is rich in potassium and nitrogen, making it suitable for soil improvement in coffee systems. Between 6 and 12 kg per plant (25-50 tons per hectare per year for densities < 5000 plants per hectare) can provide similar results as when using the recommended amount of mineral fertilizers. About 2500 kg pulp are produced with a yield of 1250 kg parchment coffee. Hence, this would allow fertilizing 104-208 plants with sufficient nutrients. Applying and incorporating this organic compost can result in an increase in stable soil organic matter. Other benefits include improvement in soil properties such as reduced soil erosion, improved water infiltration and soil aeration, accelerated decomposition of soil minerals over time, and enhanced soil microbial biodiversity, which can help suppress diseases and pests.

3.6 Biochar

Biochar is a charcoal-like substance obtained by the burning of organic waste under oxygen-restricted conditions (**Figure 17**). This can be produced from coffee pulp. Biochar can be applied on the surface of the soil as a soil amendment to improve soil functions (*e.g.*, by increasing pH and soil fertility), enhancing water holding capacity and reducing land degradation. Because of its high levels of potassium, biochar is used as an organic substitute, replacing chemical fertilizers used to provide the soil and coffee plant with sufficient potassium. Biochar can also be added to organic compost to increase the levels of carbon in the mixture. The quality of the biochar strongly depends on the feedstock (*i.e.*, organic inputs used) and pyrolysis protocol (*i.e.*, temperature profile to produce biochar), which has led to difficulties in comparing effects on soil fertility and the amount required for intended effects in the research literature. However, the positive effects on soil carbon storage are well evidenced, and there is an indication that biochar can act as a nitrification inhibitor, therefore reducing GHG emissions. Therefore, biochar contributes to climate-change mitigation and adaptation; however, there is a lack of knowledge on costs, site-specific benefits, and practical guidelines for high-quality biochar production. When produced in large amounts, biochar can have impressive carbon sequestration properties. By being applied and stored in the soil for hundreds of years, it stores carbon dioxide from the atmosphere.

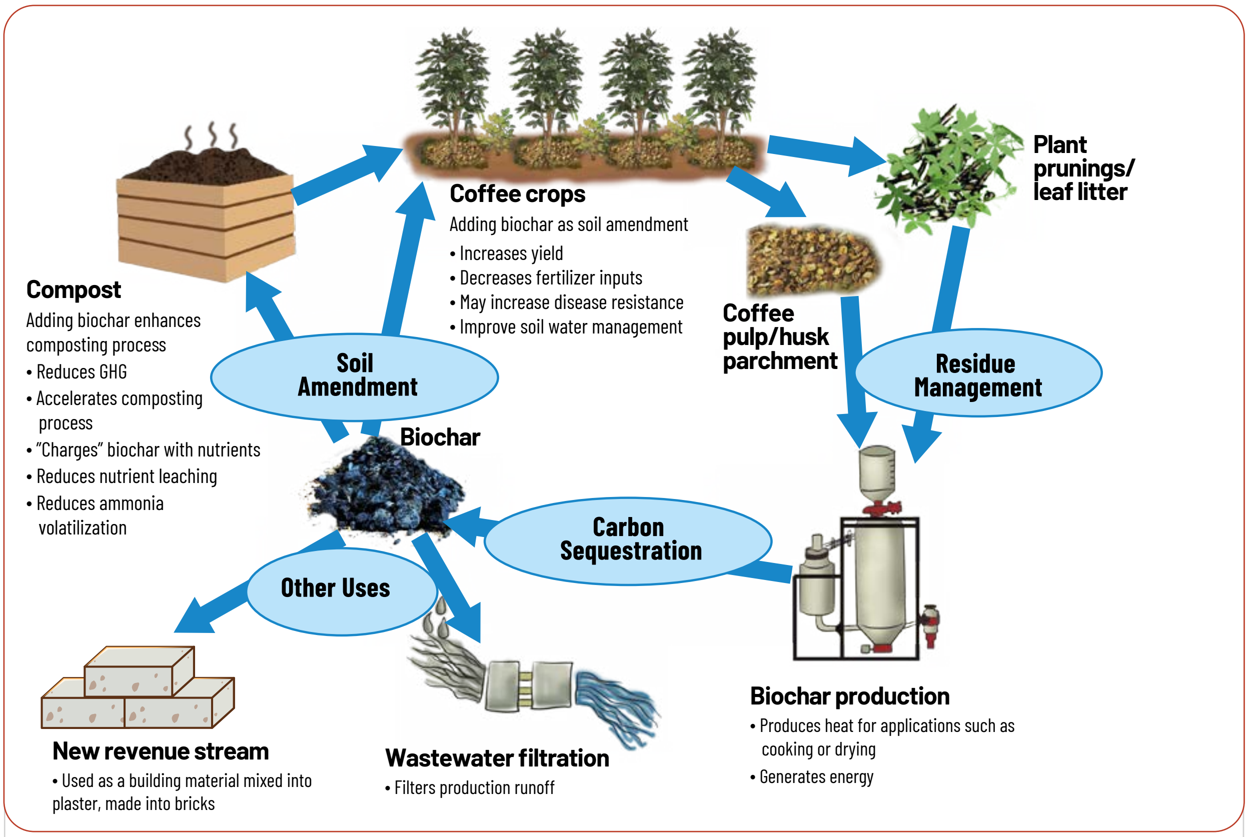


Figure 17. Biochar production and application in coffee farming.

Any management practice that results in greater carbon return to the soil, increases stabilization of soil C, or reduces C losses may lead to soil organic carbon (SOC) storage in soil. Given this, the use of livestock and other manure forms, compost, biochar, mulching, intercropping and recycled use of coffee residues are on-farm practices that can increase carbon sequestration in soils. Biochar has a particularly high potential for soil carbon sequestration. If biochar is produced using a pyrolysis system rather than made artisanal, the quality can be standardized and the produced heat can be used to dry the coffee beans.

3.7 Fertilizer application

Coffee requires an adequate and timely supply of both macro- and micronutrients. The nutrients can be supplied from various sources such as fertilizers, manure, or compost. Fertilizer programs are based on established inherent soil fertility characteristics and expected production levels. Soil testing is critical to know the status of the soil and determine which nutrients to apply.

The essential macronutrients – elements required in large quantities – include primary macronutrients such as nitrogen (N), phosphorous (P), and potassium (K), and the secondary macronutrients required in moderately-high quantities such as calcium (Ca), magnesium (Mg), and sulphur (S). Micronutrients are required in very small quantities but are essential for plant growth. They include zinc (Zn), copper (Cu), boron (B), iron (Fe), manganese (Mn), molybdenum (Mo), and chlorine (Cl). Lack of any of the nutrients in the soil is manifested through nutrient-deficiency symptoms, poor coffee health and reduced productivity.

Conventional fertilizers provide plants with three main nutrients, nitrogen, potassium, and phosphorus, but soils are often deficient in secondary or micronutrients such as zinc or boron. Examples of compound fertilizers with primary nutrients NPK are 17:17:17 and 20:10:10, and are applied at a rate of approximately 250g per tree six months before flowering based on the soil analysis report.

For new coffee plants, soil-applied inorganic fertilizers should be applied at the rate of 50g/tree/application. This can be conducted with up to four applications per year. For mature coffee, inorganic fertilizers are applied alternatively at the rate of 100g/tree/application or as per soil analysis recommendation. Four applications can be made in a year in the months of March, May, August and November. The use of blended fertilizers that contain both macro and micronutrients will ensure that the coffee trees receive all the required nutrients for healthy growth and higher yields. Spreading varied compost sources and biochar on the farms around the coffee trees seasonally can bolster plant health and coffee yields.

Figure 18. Granular fertilizer can be applied as a ring around the coffee tree just before the cropping season. (*Source*: Boaz Waswa /Alliance Bioversity-CIAT).

Fertilizer program and placement

Appropriate fertilizer types and application rates depend on overall soil fertility status, coffee plant age, planting density, and yield objectives, and can be determined through soil analysis.

- There are various coffee nutrition programs depending on the developmental stage of the plant.
- Fertilizers can be granular or in liquid form. Granular fertilizer can be applied and mixed with soil at planting, or as a ring around the coffee tree just before the cropping season (**Figure 18**).
- Liquid fertilizers are formulations of soluble fertilizers often applied to the coffee tree foliage to supplement soil-applied fertilizers, correcting nutrient deficiency and supplementing nutrient availability where soil nutrient uptake is impeded during dry weather, cold spells or other nutrient lockup.

4: Practices for achieving integrated crop-livestock management (ICLM)

When utilizing manure from on-farm livestock, its storage and application must be considered. A step-by-step approach to this is provided below:

1. Manure should be collected directly within animal housing/enclosures (to prevent loss of any dung or urine) using a waterproof floor and a cover against rain. Loss of urine should be prevented as it is a valuable source of nitrogen and potassium fertilizer.
2. Manure should be stored and left undisturbed until the first mixing of compost piles approximately four weeks after collection.
3. Major losses in ammonia released from animal manure can be avoided by covering the manure with an inexpensive plastic cover and changing the distribution method of manure from surface application to rapid below-ground incorporation (**Figure 19**).
4. Apply well-rotted manure to the coffee and other crops at the time when crops need the nutrients.
5. Manure can be placed on soils around the coffee trees seasonally.
6. Cover or plough the manure into the soil and cover with mulch.

If family-sized digesters are accessible for Ugandan coffee farmers, generating biogas from manure in these digesters is another valid option for mitigating GHG emissions. Importing purchased animal feeds is also costly and boosts GHG emissions. Thus, using intercrops (such as leguminous fodder) and coffee waste by-products (*i.e.* coffee pulp and husks) as alternative animal-feed sources is a crucial element of ICLM in Regenerative Coffee Agriculture.

Figure 19. Covering manure prevents nitrogen loss through leaching, run-of and volatilization. (*Source:* adapted from ILRI).

5: Practices to achieve Integrated Pest and Disease Management (IPDM)

The main working practices which contribute to integrated pest-disease management in Regenerative Coffee Agriculture are summarized and detailed below (**Figure 20**). Many of the listed approaches are common farming practices which can be guided by the official coffee growing manuals.

5.1 Possible approaches for achieving IPDM:

5.1.1 Increase plant and natural predator biodiversity to facilitate natural pest and disease control by enabling appropriate habitats and avoiding the use of broad-spectrum pesticides.

5.1.2 Avoid microclimates that are favorable for pests and diseases (e.g., high intra-canopy humidity) through cultural practices such as appropriate planting designs, regular pruning, and shade management.

5.1.3 Use pest and disease-resistant varieties, and rehabilitate/renovate aging coffee trees.

5.1.4 Improve soil health and plant nutrition to enhance the plants' natural defenses.

5.1.5 Create natural barriers and/or make use of traps to prevent the spread of pests and diseases across the farm and region.

5.1.6 Anticipate and monitor the early onset of key pests and/or diseases using early warning systems or weather data *e.g.*, ExpeRoya for monitoring of coffee leaf rust. Keep good records of annual pests and disease prevalence and control practices as well as any noticeable links to weather patterns.

5.1.7 Moderate the coffee field micro-climate through cultural practices such as pruning of coffee plants and nearby shade trees. This can help to increase rainfall wash-off, lower the intra-canopy humidity levels and allow for better air circulation which can reduce favorable conditions for fungal pathogens.

5.1.8 Favor the use of biological pesticides and control agents, as well as selective pesticides at low dosages, only when pest/disease populations reach an economic threshold.

5.1.9 Establish new coffee plantations using plantlets from healthy, pest-disease-free sources.

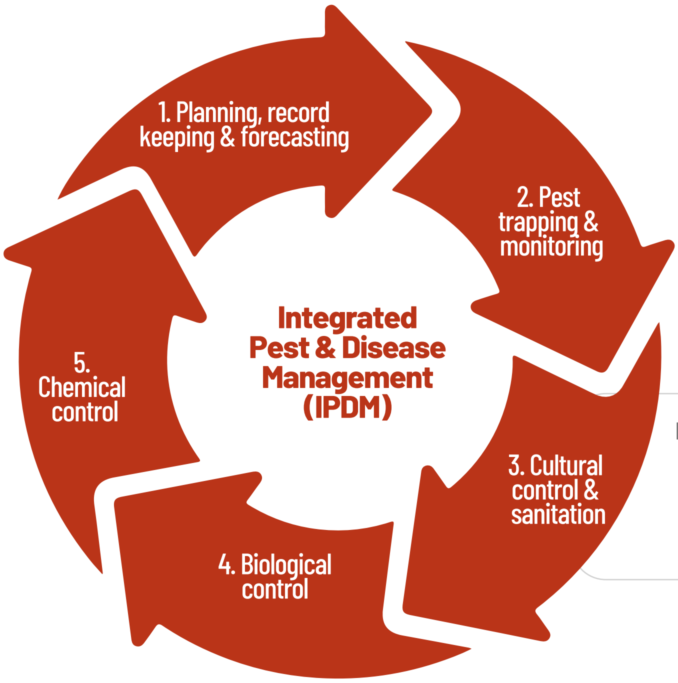


Figure 20. The basis of an Integrated Pest and Disease Management system is to use a variety of approaches. Priority should be placed on forecasting, prevention, monitoring and then control of the outbreak of a pest or pathogen in the coffee field.

5.2 Agroforestry as a pest and disease management tool

With increasing habitat complexity comes an improvement in ecological pest-disease control and overall plant health. Therefore, the biodiversity which exists within a coffee Agroforestry System (AFS) can become a part of a coffee Regenerative Agriculture IPDM by helping to reduce dependency on pesticides in coffee farming. This is achieved through the shaded environment and plant species abundance which provide habitats for antagonists and natural native enemies of coffee pests and diseases. The context of agroforestry within the landscape matrix can further improve ecological pest-disease control through enabling ecological connectivity with forest remnants and other land uses of high ecological value.

A word of caution concerning the use of shade trees and coffee pest-disease interactions:

AFS can also act as an environmental buffer to the very pests and diseases which a coffee farmer is attempting to control. Given this, on-farm management practices (such as timely pruning of shade trees) can be used to avoid favorable microclimate modifications for the pests or pathogens. High humidity with coffee AFS was repeatedly found to promote the severity of foliar coffee fungal pathogens such as *Hemileia vastatrix* (causal agent of CLR), *Colletotrichum kahawae* and *Mycena citricolor*. Given this finding, densely shaded coffee AFS must be avoided if leaf diseases are of concern.

Another example of how AFS should be used with caution in coffee Regenerative Agriculture is found in the case of Black Coffee Twig Borer (BCTB). Infestation by this beetle is suppressed when dense canopies of sap-exuding shade trees are grown together with coffee. ,On the other hand, some research including farmer surveys have highlighted the potential of *Ficus* spp. and *Albizia chinensis* as an alternative host to the BCTB. However, it is not certain that the benefits of using these species outweigh the costs associated with BCTB. Other plant species such as *Almeidea rubra, Alseis floribunda, Plinia grandifolia* and *Casearia sylvestris* may also serve as alternate hosts for BCTB. Farmers who are confronted with BCTB should weigh up the costs-benefits of using these particular species together with coffee production especially when planning conversion to Regenerative Agricultural practices.

5.3 Biological control agents (BCA)

Biological control agents (BCA) include the use of predators, parasitoids, and pathogens to control a specific pest and /or disease (**Figure 21**). BCA are compatible with coffee Regenerative Agriculture as they offer an alternative to the use of chemical pesticides (*i.e.* insecticides and fungicides). Several known and trialed BCA are available for use on coffee farms (**Table 2**); however efficacy varies according to environmental demands of the BCA, handling and timing of applications. Given this, many BCA still require further in-field testing for some of the major coffee pests and diseases.

Cephalonomia stephanoderis (*Source:* Wikipedia). Natural enemy of Coffee Berry Borer (CBB)

Prorops nasuta (*Source:* Jaramillo & Vega, 2009) (*Source:* Wikipedia). *Natural enemy of Coffee Berry Borer*

Cathartus quadricollis, (*Source:* SNSB, Zoologische Staatssammlung Muenchen). Natural enemy of CBB and Black Coffee Twig Borer

Leptophloeus sp., Natural enemy of CBB and Black Coffee Twig Borer

Vespidae spp (*Source*: Wikipedia). Natural enemy of Coffee Leaf Miner (CLM)

Anoline lizards (*Source:* Wikipedia). Natural enemy of CLM

Ceraeochrysa cubana (*Credit:* Zimlich, 2011). Natural enemy of CLM

Mirax insularis (*Source:* Gallardo et al 2008). Natural enemy of CLM

Diomus spp. (*Source*: Wikipedia). Natural enemy of Green Coffee Scale

Coccinellids (*Source:* Wikipedia). Natural enemy of Green Coffee Scale

Coccophagus rusti (*Source:* Wikipedia). Natural enemy of Green Coffee Scale

Female Phymastichus coffea. (*Source: Dr Georg Goergen*). Natural enemy of Coffee Berry Borer.

Figure 21. Natural enemies of coffee pests and diseases can be used in the field as a form of biological control.

Table 2. Summary of coffee pest and disease interactions with predators and biological control agents. *Source:* Koutouleas et al., 2022

Pest/Disease name	Causal organism	Known BCA	Trialed BCA
Black Coffee Twig Borer	**Beetle:** *Xylosandrus compactus* (Eichhoff))	**Fungus:** *Beauveria bassiana* **Beetles:** *Cathartus quadricollis* and *Leptophloeus sp.*	N/A
Coffee Berry Borer	**Beetle:** *Hypothenemus hampei* (Ferrari)	**Parasitic wasps:** *Cephalonomia stephanoderis, Cephalonomia hyalinipennis and Prorops nasuta* **Nematodes:** *Heterorhabditis sp.* and *Steinernema sp.* **Fungus:** *Beauveria bassiana* **Beetles:** *Cathartus quadricollis* and *Leptophloeus sp.*	**TVC:** Terpene-volatile compounds from *Lantana camara e.g.*, caryophyllene
Coffee Berry Disease	**Fungus:** *Colletotrichum kahawae* (Waller & Bridge)	**Fungus:** *Beauveria bassiana*	**Bacterial isolates:** *Actinomycetes* (especially *Streptomyces spp.)*
Coffee Leaf Miner	**Insect:** *Leucoptera coffeella* (Guérin-Méneville)	**Wa***sps: Vespidae spp.* **Reptile:** Anoline lizards **Insect:** *Achrysonocharoides sp., Ceraeochrysa cubana* and *Mirax insularis*	**Extracts:** Neem seed extract (NeemAzal™) *Plantago lanceolata and Momordica charantia extracts* Methanolic extract Trypsin inhibitor in castor bean leaf
Coffee Leaf Rust	**Fungus:** *Hemileia vastatrix* (Broom & Berkley)	**Fungus:** *Calonectria hemileiae, Lecanicillium lecanii, Mycodiplosis hemileiae* and *Trichoderma harzianum* **Insect:** *Ricoseius loxocheles* **Gastropod:** *Bradybaena similaris*	**Bacterial isolates:** *Bacillus cereus, Bacillus lentimorbus, Bacillus megaterium, Bacillus subtilis, Brevibacillus choshinensis, Cedecea davisae, Microbacterium testaceum Pectobacterium carotovorum, Pseudomonas sp. and Salmonella enterica* **Fungal isolates:** *Acremonium sp, Aspergillus sp, Cladosporium sp., Fusarium spp.* and *Penicillium sp.* **Natural Polymer:** Chitosan
Coffee Wilt Disease	**Fungus:** *Fusarium xylarioides* (Steyaert) **Teleomorph name:** *Gibberella xylarioides* (Heim and Sacc.))	N/A	**Bacterial isolate:** *Bacillus subtilis* (AUBB20)
Green Coffee Scale	**Insect:** *Coccus viridis* (Green)	**Beetles:** *Coccinellids* and *Diomus spp.* incl. *Diomus lupusapudoves* **Fungus:** *Lecanicillium lecanii* **Insect:** *Coccophagus rusti*	N/A

6: Practices to achieve intercropping

Figure 22. Uprooted coffee plants offer insights into the root architecture. (*Source:* Ferreira et al., 2019).

Fine coffee roots tend to be less than 1 mm in diameter and are concentrated in the first few centimeters of the soil (**Figure 22)**. Therefore, the roots of intercrops in a coffee Regenerative Agriculture system must be deeper than the coffee roots to avoid competition for water and nutrients. A comprehensive Ugandan study evaluated the cost-benefits of intercropping various crops together with young *Coffea arabica* and *C. canephora* plants. Overall, dry beans, cabbages, carrots, potatoes, soyabeans, and tomatoes were found to be economically viable when grown together with young coffee plants (although results varied from farm to farm). However, sweet potatoes, groundnuts, cowpeas, garden peas, and cassava were not advised as intercrops due to obstructions with coffee plant growth and / or seed costs.

6.1 Using legumes as intercrops

The use of legumes as an intercrop reduces the risk of nitrogen competition. Because most of the fixed nitrogen in leguminous crops is allocated to the harvested parts and are therefore exported, they do not add additional nitrogen to the soil. This is different in the case of leguminous trees, where much of the fixed nitrogen is recycled through leaf litter. Bush bean varieties "Nyota (KAD02), KAT B1 are also highly suitable as a cover crop to integrate with coffee due to their tolerance of drought; heat and shade cover. Growing beans as a cover crop can provide smallholder Ugandan farmers with a dense nutrition source especially zinc and iron which are important minerals for pregnant woman, infants and children.

6.2 Using Banana/plantains as an intercrop

Banana (*Musa spp.*) plants can provide substantial biomass back to the soil if leaves, pseudostems, and banana peels are used as mulch (however, substantial potassium is exported with the fruits). Soil-borne pests (*e.g.*, nematodes) and diseases are often an issue when intercropping coffee with banana and other crops. However, this can be avoided by careful nursery management, as the source is typically-contaminated growing medium at nursery stage. Permanent intercrops could include banana in the inter-row.

6.3 Using other types of intercrops

Other temporary intercrop options have been thought to have an adverse effect on coffee growth. These include plants such as beans, cassava, cowpeas, potatoes, and soya. This may be minimized if intercrop distances are observed. Given this, suggested spacing for some of these crops are provided.

Example of spacing of intercrops in a coffee system

Crop	Distance from coffee plants (m)		Spacing (cm)	
	Year 1	Year 2	Between rows	Within rows
Dwarf beans	0.5	0.8	25-30	20
Runner beans	1	1.5	40-50	15
Soybean	0.6	1.0	30	15
Maize	0.6 (2 rows)	1.0 (1 row)	0.75	30

7: Practices to achieve agroforestry and landscape actions

7.1 Planting coffee together with trees and other plants

Trees can compete or provide complementary services to coffee. While the benefits obtained from tree products such as timber, fruits, firewood, etc. are more straightforward to define, required knowledge to manage competition is less established. Nonetheless, the competitive and beneficial effects of trees can be assessed based on their plant functional traits, referring to specific tree characteristics such as height, basal area, crown diameter, leaf shedding pattern, chemical content of leaves (decomposition rate and nutrient release), and rooting depth. These variables are used to inform how trees affect coffee yield, nutrient cycling, carbon storage or water competition, and other ecosystem services. For example, tall trees with smaller leaves increase humidity levels to a lesser extent than short trees with larger leaves due to differences in air circulation and shade level, directly impacting the prevalence of diseases. Trees with complementary rooting and leaf shedding patterns compete less for water during the dry season. Understanding these characteristics can guide tree species selection. Additionally, the market value or the value given by farmers of tree products is an important criterion to consider (provisioning, supporting, or regulating ecosystem services), as well as when these products are available and the required establishment costs. Surveys show that the most abundant AFS tree species on Ugandan coffee farms is *Grevillea robusta* (Silky Oak) (**Table 3**).

Table 3. Agroforestry trees ranked by Ugandan coffee farmers based on ecosystem services and suitable for all rainfall zones. *Source:* Bukomeko et al., 2019.

Ecosystem service		Tree species
Amount of litter		Jackfruit - *Artocarpus heterophyllus* Mango - *Mangifera indica* Mugavu - *Albizia coriaria*

Ecosystem service		Tree species
Firewood		Umbrella tree - *Maesopsis eminii* Mugavu - *Albizia coriaria* Natal fig - *Ficus natalensis* African teak - *Milicia excelsa* Nile tulip - *Markhamea lutea*
Food		Banana - *Musa paradisiaca* Jackfruit - *Artocarpus heterophyllus* Papaya - *Carica papaya* Mango - *Mangifera indica* Avocado - *Persea americana*
Growth rate		Banana - *Musa paradisiaca* Papaya - *Carica papaya* Spiked Powder Puff - *Calliandra calothyrsus* Umbrella tree - *Maesopsis eminii* Natal fig - *Ficus natalensis*
Temperature		Natal fig - *Ficus natalensis* Mugavu - *Albizia coriaria* Mango - *Mangifera indica*
Quick leaf decomposition		Spiked Powder Puff - *Calliandra calothyrsus* Mugavu - *Albizia coriaria* Natal fig - *Ficus natalensis* Papaya - *Carica papaya*
Shade quality		Mugavu - *Albizia coriaria* Natal fig - *Ficus natalensis* Umbrella tree -*Maesopsis eminii* Cilemba - *Ficus ovata*

Another valuable resource for coffee farmers wishing to implement AFS is the shade tree advice online tool (https://www.shadetreeadvice.org/). The most suitable tree species score the highest based on the selected geography and desired ecosystem services. This tool is available for two areas of Uganda and in the Kilimanjaro national park region (bordering on Kenya).

Selected shade trees for coffee systems should:

- Provide a homogenous canopy with few gaps and no undue leaf density.
- Intercept 20-40% of total light on the plantation.
- Be deeply rooted, wind resistant, long living and fast-growing.
- Be well adapted to local conditions.
- Preferably provide consistent coverage year-round.
- Be able to withstand intensive pruning to provide organic mulch material.
- Not be a host to coffee pests and diseases.

Note: Arabica coffee requires more dense shade coverage as compared to Robusta coffee. Shade trees should be planted at least one year before the coffee is planted, if possible.

Common species that are used as shade trees in Ugandan coffee systems include:

- *Grevillea*: very good for timber and firewood, wind break on boundaries (12m × 12m)
- *Leucaena*: fast-growing, nitrogen-fixing, rich animal feed, good biomass (4m × 4m)
- *Albizia:* improves soil fertility, nitrogen-fixing, biomass
- *Calliandra:* fast-growing, good firewood and fodder, nitrogen-fixing, heavy leaf litter
- *Gliricidia:* fast-growing, nitrogen fixing, and biomass
- *Croton:* fast growing and supplies a lot of litter for mulch

Table 4 shows coffee yields and grade "A" percentage of coffee beans when intercropped with various fruit trees. Short-term coffee yields tend to be higher when coffee is grown as the sole crop. However, bean quality has been shown to increase when coffee is grown together with intercrops.

Table 4. Coffee yields and grade "A" quality percentage from mixed-cropping systems versus coffee grown alone (adapted from Mithamo, 2013). Different alphabetical letters indicate significant differences.

Intercrop	Coffee Yields (kg per hectare)	Percentage Grade "A"
Avocadoes	707.67d	89.70abc
Bananas	755.00cd	86.70c
Coffee alone	1127.67a	86.80c
Guavas	522.00e	81.70d
Loquats	563.33e	91.13ab
Macadamia	785.67bc	88.70bc
Mangoes	839.67b	92.40a

Figure 23. The landscapes around a coffee farm can be fragmented for different agricultural and forestry purposes using trees as windbreaks where high winds occur. (*Source:* www.flickr.com).

7.2 Windbreaks

Coffee trees can be harmed by consistent exposure to strong winds and therefore it is important to shield the trees using windbreaks in wind-prone areas (**Figure 23**). If breaks are not naturally provided by vegetation, trees may need to be planted intentionally. The windbreaks must be planted at least 15 meters away from the coffee and should be grown in a row that is planted across the slope and perpendicular to the prevailing wind direction. They should be planted in the few years prior to planting coffee and should be allowed to grow higher than shade trees. Considering the length of time it takes for windbreak trees to grow to full maturity, it may be sensible to plant alternative intermediary solutions (fast growing biennials or perennials in the meantime). The selected trees could include a mixture of short and tall trees to ensure a successful barrier is achieved. Pine trees, gum trees and cypress trees tend to deplete the fertility and water of the soil and are therefore not advised for use in close proximity to coffee plants. There are many advantages to the use of windbreaks which go beyond wind protection. These include climate buffering (temperature and humidity), a reduction in evapotranspiration losses by the coffee plants and spore catchment (for airborne fungal diseases).

8: Practices for renovating and rehabilitating existing coffee farms

8.1 Rehabilitation

Rehabilitation consists of removing unproductive branches through pruning or rejuvenation through stumping (cutting the main stems) and does not result in a re-design of the system. Rehabilitation is performed frequently (*e.g.*, every 5 years of production or when yields start to drop or in case of severe die-back). Rehabilitation might involve different forms of pruning (*e.g.*, topping, bending pruning or high pruning) or stumping (low stumping, partial or full) (**Figure 24**). In both cases, pruning and stumping are intended to encourage productivity and help extend coffee plants' production as they age.

Figure 24. Pruning and stamping to improve productivity. (Source: wikifarmer.com).

8.2 Renovation

Renovation typically occurs on old farms (e.g., after 20 years) where plants are aging, diseased or poorly managed with low or declining yields. Renovation allows for an improvement to the system design with respect to coffee and associated crops and trees. Both rehabilitation and renovation can be performed selectively or partially to avoid complete production losses and given the high investment costs to meet financial needs.

Renovation allows for the management of coffee planting densities by replacing unproductive trees or filling existing gaps and ensures that the newly planted varieties are well adapted to the local agroecological conditions as well as production objectives. A general requirement of improved varieties is resistance or tolerance to pests and diseases. Depending on agro-ecological conditions, drought tolerance and temperature sensitivities also be an important consideration. Production objectives define what quality characteristics are of interest and whether the variety should grow well in agroforestry systems or under extensive or intensive management. It is important to note that although past breeding programs have mainly focused on yield and disease resistance under full sun conditions, new breeding efforts are looking at coffee quality and performance within agroforestry settings.

Recent coffee breeding efforts using American cultivars crossed with Ethiopian accessions have been geared toward productivity under shaded environments (Marie et al., 2020). New F1 Arabica hybrids are now developed with demonstrated "hybrid" vigor in terms of yield when compared to their parental lines and cultivated under agroforestry-like conditions. Using locally adapted F1 hybrids or the most suitable varieties available in the region should be prioritized for renovating existing Ugandan coffee farms. Dominant Arabica coffee varieties in Uganda are SL14, Catimor, Ruiru11 and SL28 among other varieties.

9: Practices to achieve waste management

9.1 Avoid cherry losses

To reduce coffee cherry losses early in the post-harvest processing chain, it is critical to avoid precipitation, high humidity, night dew and/or rewetting of partially dried cherries.

9.2 Re-using coffee waste material

Both **coffee pulp and husk** have potential uses directly on the coffee farm as sources of manure, biological control of *Hemileia vastatrix* and *Hypothenemus hampei*; livestock feed for chickens, sheep, goats, and fish. Similarly, coffee husk can be re-purposed for citric acid, gibberellic and tannase production, while the **silver skin** is useful in providing dietary fiber and phenolic compounds. **Coffee leaves** have various pharmaceutical and cultural applications including ethnomedicine, coffee leaf tea, therapeutic agent, packaging material, tobacco substitute, organic fungicide, personal hygienic products, and animal feed. As a niche´ product, European companies have begun processing waste coffee leaves into alcoholic and non-alcoholic, high-end beverages[1].

9.3 Coffee waste as a substrate

Coffee pulp can also be used as a growing medium for mushrooms, biosorbents, and on a commercial scale be used for anthocyanin and polyphenol extraction. A particularly novel application of coffee pulp and husk is made possible with the use of **black soldier fly larvae** (**Figure 25**). These larvae consume coffee waste material together with other food waste (a balanced nutrition for the larvae is of high importance) and convert it into a nutrient-rich organic fertilizer or protein rich animal feed. This form of biofertilizer has been shown to enhance growth in annual crop plants such as lettuce (*Lactuca sativa*) and can be applied directly on the coffee farm as a contribution to soil nutrition to both coffee plants and/or other intercrops. The processing of coffee pulp and husks in this way is already taking place in East Africa. Coffee pulp can also be composted together with mycorrhiza or *Trichoderma* species. for an additive microbial enhancement when used as a biofertilizer.

[1] https://www.twistedleaf.dk/en/

Figure 25. Black soldier fly larvae can be used as a sustainable feed for livestock. (*Source:* International Institute of Tropical Agriculture).

10: Practices to achieve better wastewater management

The conversion of the coffee cherry to green bean is achieved through either a dry, semi-washed or fully washed process. Coffee washing stations therefore produce wastewater as a form of industrial water pollution. In order to achieve better wastewater management, the following practices can help to treat and return water to Ugandan water bodies after processing.

10.1 Plant remediation

Plant remediation is defined as the use of plants for the extraction, immobilization, containment, and/ or degradation of contaminants usually in a biological medium (i.e. water or soil). As a wastewater management process, it is very cost effective, environmentally friendly and has the potential of enhancing ecological sustainability of 'wet' coffee processing. *Plant species such as Phragmites karka* and *Eichhornia crassipes* have been reported to effectively treat coffee industry effluent. By constructing a continuous two-stage wetland with these plant species and a feed tank, an enhanced performance has been demonstrated.

10.2 Adsorption

Adsorption occurs when particles of one matter stick to the surface of another matter (as opposed to absorption where particles 'soak into' the other phase). The removal of organic matter can be achieved by use of several agricultural by-products such as corn stalk, rice and coffee husk, chitosan, chitin, peat, and wood. Coffee effluent can be passed through a physical filter using one or more of these natural adsorbent materials.

Eco-processing equipment is also becoming available to reduce the amount of water needed in the processing of the coffee cherries. However, there continue to be challenges to balance coffee quality and water saving through new fermentation technologies.

iii. Stepwise approach for Ugandan coffee systems

For smooth implementation of Regenerative Agriculture on a coffee farm, a stepwise approach is presented below (**Figure 26**). This approach has considered the key challenges associated with Ugandan coffee farming systems and offers on-farm steps, which can be implemented at the soil, plant, livestock and waste level.

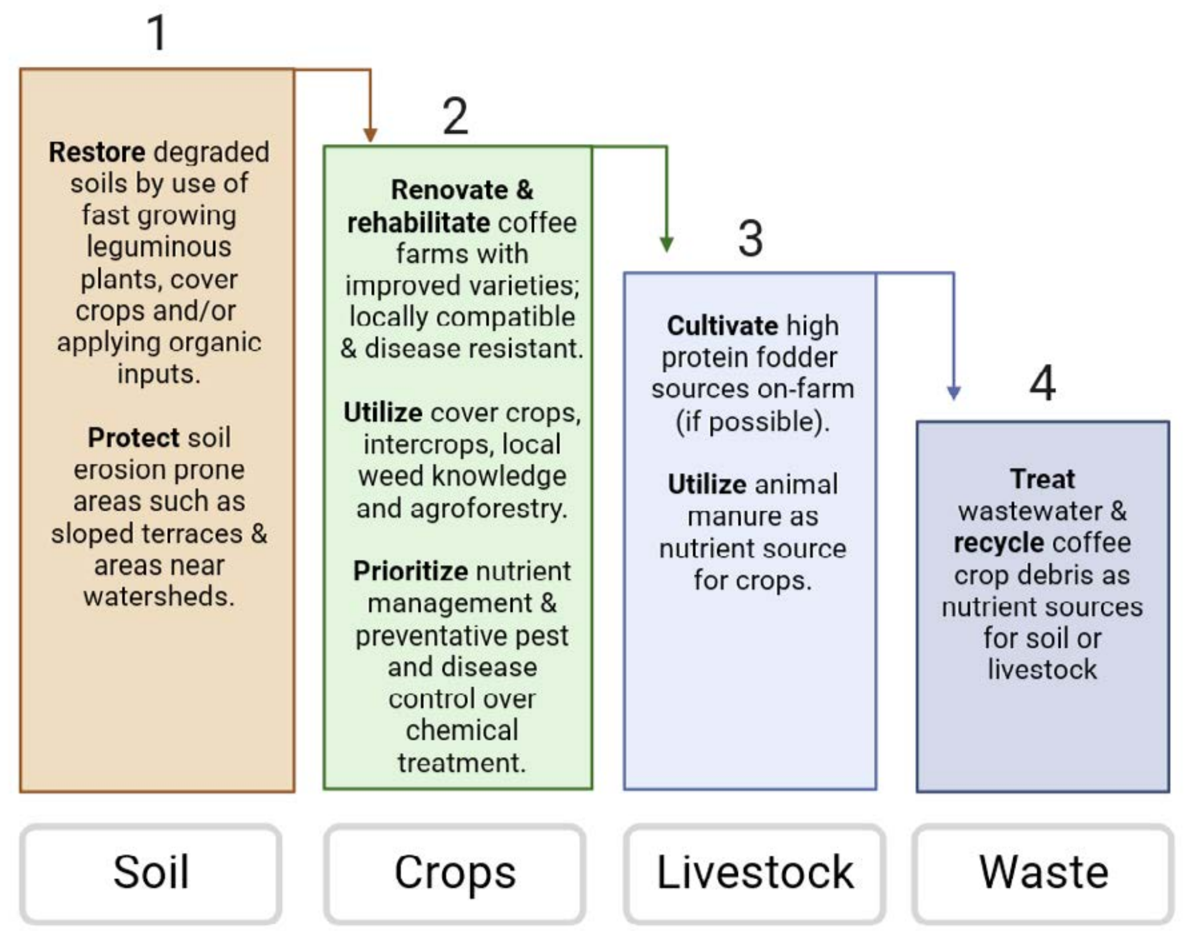


Figure 26. A simple stepwise approach to implementing Regenerative Agriculture on a coffee farm starting with the soil and moving downward towards waste.

Soil level

Aim: restore degraded soils and protect erosion prone areas

Approaches:

- If soil is substantially degraded, a primary goal is soil restoration to a minimum level at which they become responsive to fertilizers.
- Soil sampling and analysis can provide baseline measurements prior to implementing regenerative agricultural practices.
- Midterm soil restoration can be achieved with fast growing leguminous trees (*e.g., Gliricidia*) (**Agroforestry and Landscape Actions**), cover crops (*Canavalia ensiformis*, *Crotalaria*, *Desmodium*, *Dolichos*, *Lablab* or *Mucuna* spp.) and applying organic inputs (manure, compost, etc.) (**Integrated Nutrient Management**; **Integrated Crop-Livestock Management**). However, note that depending on the degradation level, restoration may take several years. Ensure all sloping cropped areas are protected from soil erosion (**soil conservation**) with cheap and accessible materials (ideally sourced from biomass produced on the farm itself) (**Waste Management**).

Crop level

Aim: renovate and rehabilitate coffee farms with improved varieties

Approaches:

- Increasing soil fertility can be constrained if the coffee plants are too old or vulnerable to pests and diseases. Thus it is important to identify coffee variety/clones/ grafting combinations which are locally adapted and contribute to farmers' objectives regarding resistances to diseases and/or pests or shade tolerance and productivity (**Renovation and Rehabilitation of Existing Coffee Farms; Integrated Pest-Disease Management**).
- Ensuring that the growing medium of coffee seedlings and intercrops are contaminant free (especially from coffee wilt disease or nematodes) and that seedlings are of high-quality planting material (**Integrated Pest-Disease Management**).
- Re-designing the renovated coffee system with multiple crop and tree species and adequate coffee planting densities, as well as protecting watersheds and soil erosion zones (**Intercropping; Agroforestry and Landscape Actions; Soil Conservation**).

Aim: Enhance soil health

Approaches:

- Identify on-farm areas which are prone to periodic or long-term bare soil exposure.
- Select cover crops or intercrops which best suit the site (with consideration for shading and water requirements) as well as the needs of both farmer and soil.
- Keep a record of all rotated species of cover crops or intercrops periodically and adjust species selection based on cost-benefit analysis.

Aim: Keep weed pressure below economic threshold

Approaches:

- make use of local weed knowledge
- Understand the benefits and trade-offs of direct weed intervention (manual, machine-assisted and / or chemical control) in coffee production systems.
- Practice preventive or early responses to control weeds (when they reach a critical economic threshold).
- Minimize herbicide use. Plan to outcompete problematic weeds with timely intercropping planting schedules and agroforestry (**Integrated Weed Management; Intercropping; Agroforestry**).

Aim: Ensure integrated pest and disease management can be carried out

Approaches:

- Identify primary pests and/diseases based on annual-biannual disease pressure or infestation.
- Prioritize preventative and/or non-chemical control methods as a first line of defense against primary pests and/diseases (*e.g.*, use of resistant cultivars/clones, timely pruning of shade trees and coffee plants, plant nutrition, *etc.*).
- . Implement forest corridors or vegetative border hedges to act as physical spore traps for fungal pathogens (**Integrated Pest And Disease Management; Agroforestry And Landscape Actions**)
- Consider using biological control agents (if accessible).

Livestock level

Aim: Enable affordable access to fodder for livestock and organic/chemical fertilizers for crops.

Approaches:

- Cultivate as much high protein fodder on-farm as feasible
- Make use of a diverse range of on-farm sources of organic fertilizers such as manures, compost, and biochar (**Integrated nutrient management; Integrated crop-livestock management**).
- Supplement soil nutrition with inorganic fertilizers if not enough organic fertilizers are available based on yield objectives.

Waste level

Aim: Practice on-farm wastewater re-use and/or treatment and recycling of biomass materials.

Approaches:

- Use on-farm plant remediation and/or adsorption methods to treat polluted effluent from wet coffee processing (**Wastewater Treatment**).
- Re-use wastewater from wet processing in irrigating other on-farm crops (**Waste Management**).

Aim: Prune coffee plants and re-use on-farm biomass material

Approaches:

- Biomass from coffee plants can be used directly as a mulch or applied as an erosion barrier, when secured into bunds along soil erosion zones (**Soil Conservation**).
- Leaves and branches can also be composted and returned to the soil (**Integrated Nutrient Management**).
- Pulp, husks, silver skins and leaves can be used as alternative products (**Waste Management).**

CHAPTER 3. PLANNING AND IMPLEMENTING REGENERATIVE AGRICULTURE

i Planning the transition to Regenerative Coffee Agriculture systems

a. Co-design and participatory planning for high chances of success
b. Visioning and setting goals
c. Dealing with diversity - agro-ecology and socio-economics shape farm typology
d. Tools which can be used for targeting and priority setting in Regenerative Coffee Agriculture

ii Methods for delivering Regenerative Agriculture

a. Top delivering methods for Regenerative Coffee Agriculture
b. Demonstration farms

iii Monitoring and evaluation

a. Rationale
b. Methods of measuring indicators
c. Framework for Regenerative Coffee Agriculture monitoring

CIAT /Neil Palmer. Coffee and banana intercropping systems in Rwanda.

i. Planning the transition to Regenerative Coffee Agriculture systems

a. Co-design and participatory planning for high chances of success

The transition process from current to more advanced Regenerative Agricultural practices requires a clear strategy. The first step is to develop a vision for success and definite clear goals in a participatory manner (see **b) Visioning and setting goals**). The second step is to screen different potential regenerative agriculture practices and participatory priority setting and planning. It is therefore important to keep farm diversity in mind as different practices exhibit different levels of suitability and feasibility across different farm contexts (see **c) Dealing with diversity**). An assessment of the context-specific impact potentials of the practices can inform an evidence-based choice of bundles of practices to implement in different areas, farms and fields (see **d) Tools which can be used for targeting and priority setting**). Importantly, preferences for new practices can also differ across stakeholder groups. Given this, it is proposed to involve a wide range of stakeholders in the planning processes. In this way, high levels of "buy-in" can be achieved, leading to following through plans and the best chances of success in reaching the envisioned goals.

Patrick Wallet.

"You cannot protect the environment unless you empower people, you inform them, and you help them understand that these resources are their own, that they must protect them."

Dr. Wangari Maathai, Winner of the 2004 Nobel Peace Prize

b. Visioning and setting goals

As mentioned above, a first step in the planning of Regenerative Coffee Agriculture is identifying of a vision for the intervention, which can be translated into clearly defined goals for all stakeholders.

The main ecosystem services drivers operate over large geographical regions. Given this, recovery of degraded environments cannot be the sole responsibility nor goal of farm-level practitioners. It must rather involve broader processes of co-design and collaboration between neighbors, communities, relevant value-chain actors and policymakers.

As such, there is great need to work across multiple scales and collaborate within the coffee sector together with government agencies, in order to deliver Regenerative Coffee Agriculture. This means that both local and international coffee value-chain partners can participate in visioning, goal setting, implementing, monitoring and communicating Ugandan Regenerative Coffee Agriculture practices.

Farmers should be positioned at the center of visioning and goal setting as a way to build localized Regenerative Coffee Agriculture (as a bottom-up approach). Policy-led initiatives can involve monitoring and indicators, which work on large scales either biophysically (e.g., landscape management and ecosystem mapping or modelling) or commercially (e.g., market and supply chain reconfigurations). Intersectoral approaches implemented over short- and long-term periods collectively maximize synergy and complementarity of aims, priorities, and methods.

By including farmers, agronomic extension workers, scientists, representative of regulatory bodies, as well as supply- and value-chain partners in the visioning and goals setting, Regenerative Coffee Agriculture can become common practice.

c. Dealing with diversity - agro-ecology and socio-economics shape farm typology

There is a high heterogeneity and diversity among coffee farms and their farmers across and within Ugandan landscapes. This heterogeneity occurs across different domains such as:

- Agro-ecological differences – *e.g.*, high *vs.* low altitude, steep slopes *vs.* flat lands, poorly drained soils *vs.* well drained soils etc.
- Social domain *e.g.*, gender (male *vs.* female), generation (youth *vs.* the old), ethnicity.
- Economic: wealth, asset-base, control over resources (*e.g.*, large *vs.* small sized farms); and source of income-generation.
- Farming system *e.g.*, banana-coffee systems, coffee-annual cropping, banana-coffee-cattle system, coffee monocrops etc.
- Farming objectives and aspirations *e.g.*, household nutrition, income, environment, contribution to global goods etc.

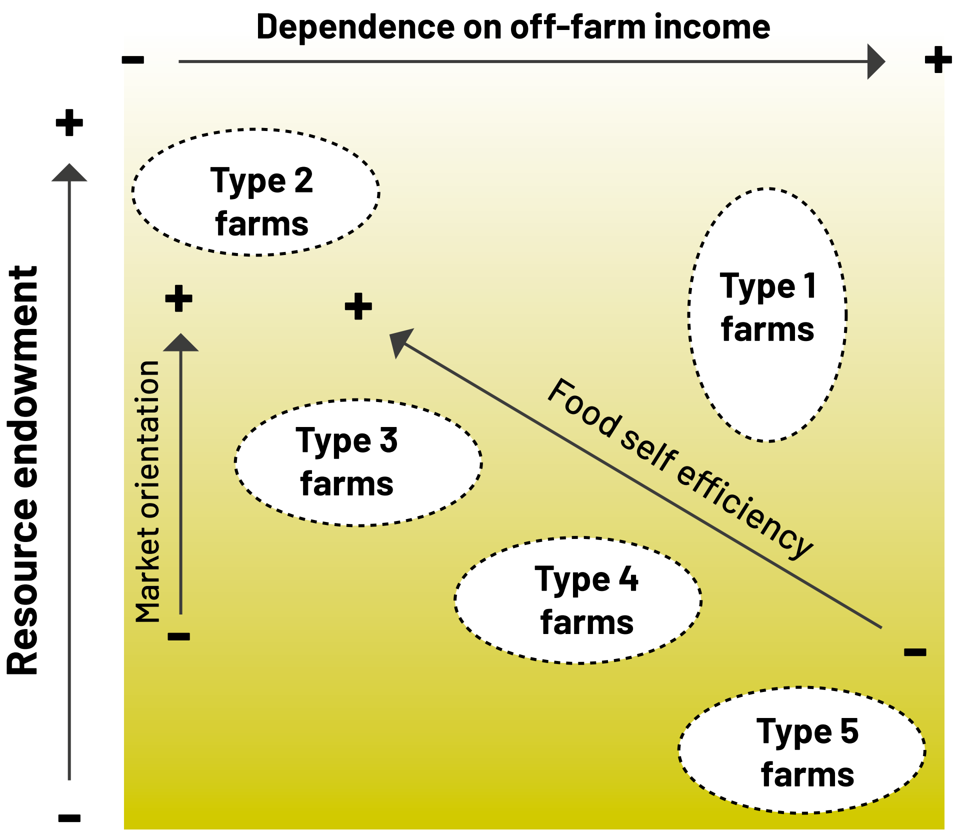


Figure 27. The relationship between farm types and resources. (*Source*: adapted from Tittonell et al., 2010).

Farm Types in Uganda. *Source:* adapted from Tittonell et al., 2010.

Farm type	Resource endowment and production orientation
1	Predominantly high to medium resources; mainly self-subsistence orientated
2	High resources; market-oriented
3	Medium resources; self-subsistence and low-input market-oriented
4	Predominantly low to medium resources; self-subsistence oriented
5	Low resources; self-subsistence oriented

It is important to understand and deal with this farmer diversity in order to improve our targeting and adoption of Regenerative Coffee Agriculture. Because the variability within a landscape can be vast, it is necessary to group farmers into more homogenous groups or farm types (**Figure 27 & Textbox**). Typology is the approach of grouping the farms into or identifying farm types. Typologies give us a snapshot of the highly dynamic farms in time within an environment and help us match innovations to farm types *i.e.* proper targeting and scaling of our Regenerative Agriculture innovations. The farmer typology will influence the choice and appropriateness of Regenerative Coffee Agriculture practices and monitoring within a farm, as well as the ability of a farmer to adopt such an innovation. Identifying these farm types is therefore an important first step toward matching recommended innovations with farmer resource level.

To understand farm types, simple approaches that require few variables such as using expert knowledge and participatory rankings to complex approaches combining multiple variables can be used. These include:

- Expert knowledge: an expert or opinion leader with in-depth knowledge of a landscape and/or farm can be engaged to a group of farms/farmers that share similar characteristics.
- Participatory rankings: a group of farmers can be engaged to categorize farms or farmers within a landscape using a range of variables.
- Multivariate statistics (*e.g.*, ordination and clustering): a statistical method which compares many farm variables.

d. Tools which can be used for targeting and priority setting in Regenerative Coffee Agriculture

In order to assess the positive and negative impacts associated with adopting new agricultural practices it is necessary to make use of a large number of variables which characterize the changes made compared to any previous system. An appropriate cost-benefit and trade-off analysis can be used to make this assessment and inevitably assess whether Regenerative Coffee Agriculture is relevant to the farmer. This type of analysis needs to incorporate ecological, economic, social and (wherever possible) cultural factors (**Figure 28**). By including all these dimensions, we may better evaluate the suitability of coffee farming with Regenerative Agriculture practices as a means of fulfilling farmers' needs along with other regional or national priorities (*e.g.*, reforestation, biodiversity restoration, watershed protection *etc.*). When conducting such an assessment, metrics should be treated with caution, as they may undervalue the biophysical scarcity of natural resources or ignore whether or not availability of a resource is critical for the surrounding ecosystem. In this way, we avoid proposing a cost-benefit analysis which may be economically rational but ecologically unaccountable.

Figure 28. Cost-benefit analyses relating to a change in farm practice should include ecological, economic, social and cultural factors. In doing so, all pieces of the puzzle can fall into place. (*Source:* www.yesmagazine.org).

When considering a change in farm-level practice, certain trade-offs must also be considered. Trade-offs become particularly relevant when resources are limited and when stakeholders' goals conflict. Four widely-applied approaches to deal with this include: participatory methods; empirical analyses; simulation models; and optimization models. Outputs from these four approaches tend to overlap and often generate complementary knowledge. By harnessing more than one of these methods trade-off assessments can be made across different spatial scales, time horizons and actors' interests. **Table 5** provides some pertinent examples of trade-offs which may be encountered when implementing a Regenerative Agriculture farming system.

Table 5. Agricultural trade-off analysis, which can be used in the decision-making process concerning on-farm practice changes towards a Regenerative Agricultural approach. *Source:* Klapwijk et al., 2014.

Example	Indicators	Nature of trade-off	Alleviation possible?
i. Farm scale production versus environmental impact	Farm level grain yield, farm level greenhouse gas emissions, nitrate-N concentration in groundwater	Agriculture versus the environment; across spatial scales: field to landscape	Agro-ecological intensification, effective application of N fertilizers to increase crop recovery efficiency
ii. Long-term soil fertility improvement through green manure agroforestry species versus immediate food production	Soil fertility (soil C content) after 5 years of green manure treatment versus immediate food production	Immediate food and cash needs versus long-term sustainability of production; across temporal scales	Use of external inputs, to intensify food production on a smaller land area

Example	Indicators	Nature of trade-off	Alleviation possible?
iii. Croppers versus cattle owners versus wildlife in East Africa	Cropped areas, household income, food insecurity	Limited availability of land; across spatial scales	Income diversification, preservation of wildlife and cattle movement corridors
iv. Allocation of crop residues to fodder for cattle versus mulch for soil and water conservation	Milk production versus crop production	Limited availability of organic resources; farm scale	Input use to increase amounts of crop residue produced
v. Sale of labor causing delay in own crop management versus use labor for own production	Labor sold versus crop production and household food self-sufficiency	Seasonality resulting in immediate cash or food needs versus household food self-sufficiency; at farm scale	

ii. Methods for delivering Regenerative Agriculture

a. Top delivering methods for Regenerative Coffee Agriculture

Participatory approaches - these engage farmers in the process of identifying problems and opportunities, but also in testing and evaluating prioritized innovations, and then helping to disseminate these learnings and encouraging practice adoption among the wider farming community.

Data accessibility - Regenerative Coffee Agriculture in Uganda needs to consider accessibility to background data and definitional criteria as an important element supporting the delivery of regenerative methods. This includes translating educational material into indigenous languages relevant to the coffee cultivation areas. An example of a cost-benefit-analysis should also be presented in early stages of Regenerative Agriculture which has both cultural and regional relevance to the farmer. It is important that farmers can understand how stacked enterprises (*aka*. blended services) contribute to economic resilience of the proposed system and easily be able to compare the profitability between those practicing and those not practicing Regenerative Coffee Agriculture.

Cost-benefit analysis – conducting a cost-benefit analysis is a key background element supporting optimal Regenerative Coffee Agriculture delivery.

Demonstration methods which promptly build evidence of the cost-benefits of Regenerative Coffee Agriculture would ideally combine the following aspects in a modular format:

1. Demonstration plots
2. Success stories by different farmer groups (incl. participatory research)
3. Exchange visits between farmers
4. Farmer-farmer and extension-farmer activities
5. Fast, affordable, scalable observations at high spatial and temporal resolution
6. On-the-ground-precise scientific observations
7. Modelling (*e.g.*, scenario analysis, multilayer network modelling and machine learning)

The modularity relates to a biophysical component of the Regenerative Coffee Agriculture system (*i.e.* soil health, crop productivity, water resources, ecosystems, and economic viability).

Importantly, the practices and delivery of Regenerative Coffee Agriculture for Uganda must be agile, outcome-oriented, and motivated to operate for the common good of the nation, encompassing both the environment and the economy.

b. Demonstration farms

Large-scale demonstration of regenerative agriculture across the country's agro-ecological domains is essential in shifting principles from theory to practice. By creating demonstration farms (*aka*. model farms) and farmer-led extension programs, regenerative coffee agriculture practices can be better contextualized within a given region (**Figure 29**). In this way, demonstration farms act as extension facilities and experimentation hubs for coffee farmers interested in transitioning toward regenerative coffee agriculture. Equipped with tools, land, and crops, demonstration farms allow in-field assessment of particular regenerative agriculture farm management practices on local pilot plots. Equipped with tools, land and crops, demonstration farms allow for in-field assessment of particular Regenerative Agriculture farm management practices on local pilot plots.

Figure 29. Farmer training and demonstration farms are valuable tools for the delivery of Regenerative Coffee Agriculture. (*Source:* Alliance Bioversity-CIAT/ WOcimati).

iii. Monitoring and evaluation.

a. Rationale

New research is showing how implementing regenerative agriculture can be accelerated by harnessing farmers' experiences with participatory monitoring and evaluations.

To ensure the transition process is on course, there is a need to define relevant indicators, which can be monitored. A combination of practice- and results-based indicators are used to monitor advancement towards Regenerative Agriculture. Practice-based indicators monitor the adoption of specific practices which contribute to specific Regenerative Agriculture principles, while results-based indicators monitor the effects of practices on the areas of interest.

Whenever feasible, results-based indicators are preferable, as these enable us to consider if the impacts of agricultural practices are site-specific. While the potential benefits of many practices are well established, their impacts in specific contexts are often less clear. Moreover, trade-offs and synergies between different indicators need to be outlined to make informed decisions about the Regenerative Agriculture practices. Analyzing results-based indicators across diverse agroecological conditions (temporal and spatial dimensions) can provide valuable insights into the variation of impacts generated by specific Regenerative Agriculture practices (**Figure 30**).

Figure 30. Different scales at which Regenerative Agriculture practices are relevant. (*Source:* https://ag4impact.org/database/).

While the ideal monitoring scenario would include the use of result-based indicators, many of the outcomes which Regenerative Agriculture intends to contribute to are not easily measured. Greenhouse gas emissions, for example, cannot be measured on every farm as the costs would be too high. Soil organic carbon sequestration occurs slowly due to the high background levels of soil carbon. Therefore, in many cases, practice-based indicators are more feasible. The selected indicators should be easy to measure, document, interpret and be cost effective. Table 6 highlights universal indicators of Regenerative Agriculture which may be applied to the Ugandan coffee system (where access to monitoring materials and equipment is feasible).

Table 6. Universal indicators of Regenerative Agriculture. *Source:* adapted from O'Donoghue et al. 2022

Dimension	Potential Indicators
Soil health	Organic matter, pH, bulk density, aggregate stability, ground cover, nutrient profiles.
Water resources	Soil infiltration, constancy of the plant's access to available water, stream flow constancy and quality.
Biodiversity (flora and fauna)	Above and below-ground flora and fauna diversity and abundance.
Farm resilience (human aspects)	Income, autonomy, quality of life and community stability.
Coffee productivity (main crop)	Quantity and quality.
Carbon footprint (energy)	Inputs: fossil fuels, renewably sourced energy, fertilizer and incidence radiation capture.

In the next section, we provide in-depth approaches measuring both practice- and result-based Regenerative Agriculture indicators (focused on each of the dimensions outlined in **Table 6**). However, given the resource constraints associated with Ugandan coffee farming, a straightforward suggestion for measuring Regenerative Agriculture is annual inspections of visual and/or survey-based indicators in Regenerative Agriculture systems. Charting of aboveground flora diversity and abundance, presence of ground cover (living/non-living), signs of soil erosion and household income/expenses can provide farmers and extension service providers with more regular performance updates of regional Regenerative Agriculture farming.

b. Methods of measuring indicators

Methods of measuring the impacts of Regenerative Agriculture practices are presented according to the following dimensions:

1. Soil health
2. Water resources
3. Biodiversity (flora and fauna)
4. Farm resilience (human aspects)
5. Coffee productivity (main crop)
6. Carbon footprint (energy)

Soil health indicators

As soil quality is the cornerstone of Regenerative Agriculture principles, measuring indicators concerning the soil are paramount. In a recent study conducted in Spain, farmers were issued a visual soil assessment (VSA) manual which helped ascertain whether Regenerative Agriculture could restore degraded agroecosystems in semiarid Mediterranean drylands. Overall, the Regenerative Agriculture farming systems showed a superior performance across many of the local indicators of soil quality (LISQ) when compared to conventional farming systems (**Figure 31**). This study highlighted the need for long-term participatory research in measuring indicators, especially when applied to sustainable farming in arid and semi-arid areas, which are most vulnerable to irreversible land degradation. In general, visible changes in soil quality tend to take a long time to occur, thus justifying the need for extended periods with multiple assessment intervals for participatory approaches in Regenerative Agriculture in Uganda.

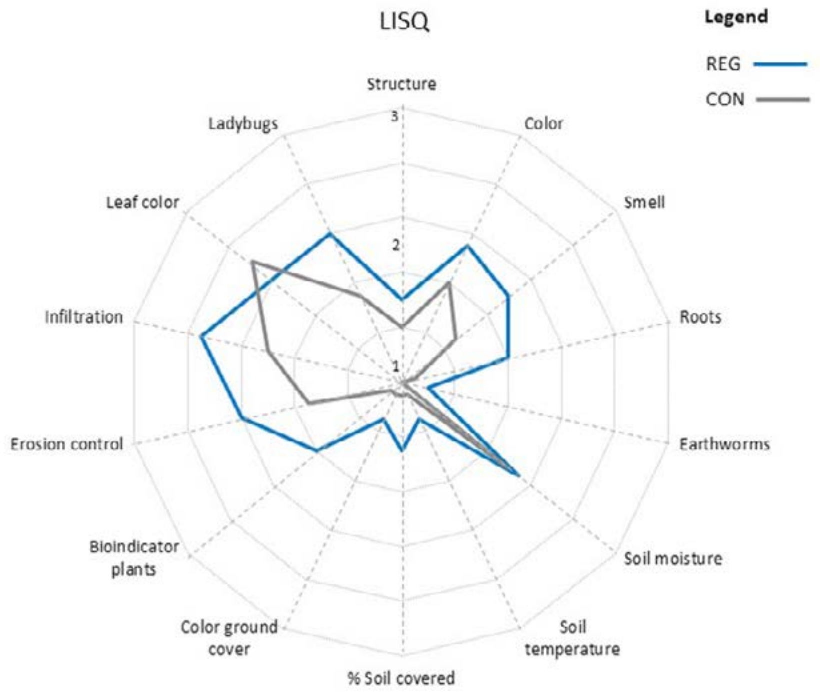


Figure 31. Soil ideotype based on average visual soil assessment by farmers based on 14 local indicators of soil quality (LISQ) comprising the farmer manual. Regenerative Agriculture systems (REG) compared to conventional farming systems (CON). (*Source:* Soto et al. 2021).

There are several soil health indicators, some of which have been used for a long time, while others have only recently been discovered. Most frequent indicators are total organic matter and/or carbon, pH, available phosphorous, indicators of water storage, bulk density, texture, available potassium, and total nitrogen (N). Novel indicators recently proposed are mainly related to soil biota particularly concerning the soil microbial community (SMC). However, despite the increasing body of SMC data, it remains difficult to distinguish microbial taxa between productive and unproductive soils in the tropics.

To meet the needs of practicality and cost-effectiveness, usually only one soil health indicator is measured, namely soil organic matter (SOM) or carbon (SOC) or a fraction thereof *e.g.*, active carbon, which is more sensitive to changes in on-farm management practices. However, soil pH should also be included as it influences nutrient availability and can be measured easily.

Importantly, the method and consistency of soil sampling (**Figure 32**) has a great impact on the results obtained. Depending on where one samples in the coffee system, the results can vary widely. This should be harmonized if one is keen to monitor changes in soil health as a result of adopting the Regenerative Agriculture practices. Reference or control points can be adopted for routine sampling.

Figure 32. Soil sampling in a Ugandan Regenerative Agriculture system. (*Source: Agriterra*).

Water Resources

Monitoring changes in water quality as an indication of changes in practices by individual farmers is not straightforward. Practice-based indicators such as erosion control, amount, type and timing of used agrochemicals as well as post-harvest practices are more useful indicators.

Practice-based indicators relevant for water quality are:

i. Amount and toxicity profile of used pesticides

ii. Nutrient (*e.g.*, nitrogen, phosphorus) use efficiency (kg yield/kg nutrient input

iii. Soil erosion risk

iv. Riparian buffer zones

v. Post-harvest processing type and equipment

Water use efficiency: For irrigation purposes, water use should be monitored and assessed in relation to coffee yield, while post-harvest processing water use can be assessed in relation to processed coffee per volume water use.

Agricultural water productivity = kg of coffee yield / liters of water applied (rainfall and/or irrigation)

Post-harvest water productivity = kg of green coffee beans / liters of water used

Biodiversity (flora and fauna)

Several agricultural practices affect plant and animal biodiversity on a coffee farm. These practices include agroforestry, integrated weed management, integrated nutrient management, integrated pest and disease control, and the use of cover crops. Creating habitat for pollinators and ants, for example, can contribute to higher fruit set and pest control. Intact soil biodiversity can contribute to control soil-borne pests and diseases. The type of shade tree species in an agroforestry system, for example, has been shown to affect bird diversity. An AFS with more than 30% canopy cover from diverse tree species has been found to benefit bird diversity. However, vegetation structure has been reported to play a more important role than shade tree canopy cover. The surrounding landscape context is a crucial aspect of bird diversity conservation. Landscapes without forests typically support a more simplified bird community. A landscape with more than 40% forest area has been suggested as being of particular importance to conservation efforts (although higher percentages are likely needed in the tropics). Importantly, this threshold is derived from ecological considerations, thus, socio-economic factors need to be considered when applying these guidelines locally. Given these factors, plant and animal biodiversity is optimally assessed at coffee plot, farm and landscape scales.

Coffee plot level biodiversity indicators in Uganda are typically related to tree diversity (*e.g.*, using the Shannon index), but could also include the layer below the coffee trees such as weeds, cover crops, and intercrops. Farm-level biodiversity would include crop diversity on-farm, trees on-farm (e.g., boundary planting, riparian buffer) and hedges, and conservation areas, etc. Landscape-scale biodiversity monitoring could include other non-coffee crops, water bodies, anthropic areas (roads, buildings and anthropogenic bare soil) and vegetation classes such as grass-woody savannah, anthropic vegetation, woodland savanna, rock fields, semi-deciduous forest, and deciduous forest.

Below are some suggested biodiversity indicators which can be use to assess the coffee Regenerative Agriculture system:

1. *Agroforestry assessment* according to Nitidae (note: agroforestry systems take a long time to set up, and efforts should be valued in the early transition and establishment stages).

   b. *Basal area:* a measure of the area occupied by tree trunks on the ground on the surface of the plot. It can be estimated in a few minutes and can be used to characterize tree cover without exhaustive inventories. Basal area ratio between coffee and non-coffee species is a good indicator to balance trade-offs between coffee and associated species.

   c. *The distribution of the origin of the trees* (remnant/spontaneous regrowth/planted) this makes it possible to characterize the potential diversity of the trees in the plot. The origin typically indicates the different species and can be used as a proxy for biodiversity without an exhaustive inventory.

Other indicators which can help quantify production benefits of intercropping systems (tree, crop and soil microbial diversity. Where available, citizen-science data on plant and animal species richness and abundance can also be integrated into the monitoring system for coffee Regenerative Agriculture. The agro-biodiversity index produced by Alliance Bodiversity -CIAT is also a useful tool.

Farm Resilience (human aspects)

***Land equivalent ratio* (LER)** as an indicator for land use efficiency: the yield advantage of intercropping can be assessed using LER. The LER is interpreted as the area required by sole crops to produce the same yields, relative to the area needed to obtain the same yield obtained through intercropping. The LER is calculated as follows:

LER = (yield coffee intercropped/yield coffee grown in monoculture) + (yield intercrop when grown in association with coffee/yield intercrop when grown in monoculture)

If LER is > 1 it means that intercropping is advantageous in terms of total productivity compared to the same crops grown as monoculture.

Similarly, the economic advantage of intercropping can be assessed using the Monetary Advantage Index (MAI) using the following equation:

MAI= Value of combined intercrop yield × (LER-1)/LER

Profitability: (or cost-benefit balance) in the context of Regenerative Agriculture conversion can be calculated as such:

Profitability of Regenerative Agriculture practice= (h x Δy) – (Δc)

Where:

h: harvested product price

Δ_y: change in yield with improved agronomic practices^ in comparison with current farmer's yield

Δ_c: changes in direct production cost* (incurred by the use of improved agronomic practices)

^In the case of intercropping or agroforestry, a cost-benefit balance needs to be conducted, considering all commercial associated crop yields. In the case of timber, where harvesting might take place in 15 years or more, this approach is more difficult and would need to consider the net present value, considering the discount rate. This would require an ex-ante assessment using assumptions on the timber, coffee, and other associated crop yields in the future.

* If improved fertilizer management practices are introduced, we consider the difference in fertilizer cost per area between improved practices and control for production cost.

Overall coffee farm resilience in Uganda can also be estimated by labor productivity. This is especially relevant for smallholders who may utilize family members for on-farm labor and therefore divert their resources away from other potential household income generation sources.

Labor productivity = coffee yield (kg) / person-days

Coffee productivity (main crop)

A simple calculation can determine the coffee crop productivity of a given farm.

Coffee productivity = yield (kg) / land areas (ha)

The actual increase in yield of improved practices can be determined as the attained yield effect of a single or a combination of agronomic practices obtained on-farm, which depends on the crop variety and the location.

The actual gain in yield due can be determined by:

$$\text{Agronomic gain} = Y_i - Y_a$$

Where:

Y_i is yield under improved agronomic practices

Y_a is previous yield

Carbon footprint (energy)

Coffee production impacts the global climate by emitting GHGs but can also simultaneously capture CO_2 through photosynthesis in on-farm carbon stocks of above and belowground biomass (AGB & BGC) as well as soil carbon.

Measuring Above- and belowground biomass indicators

Measurements for AGB can be performed easily and at relatively low cost (low-person days). As a minimum, the diameter at breast height (dbh) and species-specific allometric equations can provide initial estimations. Tree height can also be included, and some use environmental correction factors.

Belowground biomass carbon (BGC) is typically done using a constant factor related to AGB, so not very informative.

Greenhouse gas emissions

In coffee production, the Cool Farm Tool (CFT) is one of the most frequently used methods in the coffee industry for measuring on-farm GHG (typically following IPCC tier 1 and 2).

c. Framework for Regenerative Agriculture monitoring

A framework for monitoring Regenerative Agriculture practices in Ugandan coffee systems can be devised through harmonizing specific goals, proposed practices and indicators of success or adoption. The stepwise approach proposed in chapter two serves as a backbone to this framework. Both qualitative and quantitative approaches can be applied to the monitoring of a Regenerative Agriculture system. Given the overall challenges of Regenerative Agriculture monitoring, both short- and long-term surveying is recommended on coffee farms. Increases in coffee yield are a core success indicator and therefore feature as a monitored aspect across many of the goals.

Goal 1: Restore degraded soils and protect erosion prone areas

a. Practices applicable: agroforestry and landscape actions; integrated nutrient management; integrated crop-livestock management; soil conservation; waste management.

b. Success indicators: periodic soil sampling (see section c); on-farm tree species' diversity survey (qualitative); use of cover crops (Y/N); using organic manures and composts (Y/N); protecting soil erosion zones (Y/N); re-using on farm waste products (Y/N); are coffee yields improved (directly or indirectly) (Y/N)?

Goal 2: Renovate coffee farms with improved varieties (bolstering both yield and stress resistances).

a. Practices applicable: renovation and rehabilitation of existing coffee farms; integrated pest-disease management.

b. Success indicators: use of new genetic material suitable for coffee growing region and relevant pest &/ disease pressures (Y/N); presence of old trees (%); are coffee yields improved (directly or indirectly) (Y/N)?

Goal 3: Make use of local agroecology knowledge

a. Practices applicable: integrated weed management; intercropping; agroforestry.

b. Success indicators: reduced reliance on synthetic herbicides; use of intercropping (Y/N); generation of on-farm fodder/feed sources for livestock (Y/N); on-farm tree species diversity survey (qualitative); are coffee yields improved (directly or indirectly) (Y/N)?

Goal 4: Prune coffee plants and practice on-farm re-use of biomass material

a. Practices applicable: Soil conservation; integrated nutrient management; waste management.

b. Success indicators: return of leaves and branches to coffee plants after pruning (can be combined with composting) (Y/N); or use of coffee biomass or waste products as an erosion barrier (Y/N) or other alternative product; are coffee yields improved (directly or indirectly) (Y/N)?

Goal 5: Enable access to organic and chemical fertilizers

a. Practices applicable: Integrated nutrient management; Integrated crop-livestock management

b. Success indicators: are a diverse range of on-farm sources of organic fertilizers in use (Y/N)?; are synthetic fertilizers used when deemed necessary through soil testing (Y/N); are coffee yields improved (directly or indirectly) (Y/N)?

Goal 6: Ensure integrated pest and disease management can be carried out

a. Practices applicable: integrated pest and disease management; agroforestry and landscape actions

b. Success indicators: are preventative and/or non-chemical control methods prioritized (Y/N)?; are coffee yields improved (directly or indirectly) (Y/N)?

Goal 7: Practice on-farm wastewater re-use and treatment

a. Practices applicable: wastewater treatment; waste management

b. Success indicators: Is on-farm wastewater treated (Y/N)?; Is wastewater re-used for other on-farm purposes (Y/N)?

REFERENCES

Atuhaire, L., Vanlauwe, M. B., Mugisha, J., & Okello, D. K. (2016). Greenhouse gas emissions from livestock in agroforestry coffee systems in Uganda. Journal of Environmental Management, 183, 238-247.

Bukomeko, H., Jassogne, L., Tumwebaze, S. B., Eilu, G., & Vaast, P. (2019). Integrating local knowledge with tree diversity analyses to optimize on-farm tree species composition for ecosystem service delivery in coffee agroforestry systems of Uganda. *Agroforestry Systems*, *93*, 755-770.

Elevitch, C. R., Mazaroli, D. N., & Ragone, D. (2018). Agroforestry standards for regenerative agriculture. Sustainability, 10(9), 3337.

Ferreira, T., Shuler, J., Guimarães, R., & Farah, A. (2019). Introduction to coffee plant and genetics.

Flores, C. C., & Sarandon, S. J. (2004). Limitations of neoclassical economics for evaluating sustainability of agricultural systems: comparing organic and conventional systems. *Journal of Sustainable Agriculture*, *24*(2), 77-91.

IPCC, Working Group III Mitigation of Climate Change, 2022. Accessed on 19th May 2023 via [https://www.ipcc.ch/working-group/wg3/]

Klapwijk, C. J., Van Wijk, M. T., Rosenstock, T. S., van Asten, P. J., Thornton, P. K., & Giller, K. E. (2014). Analysis of trade-offs in agricultural systems: current status and way forward. *Current opinion in Environmental sustainability*, *6*, 110-115.

Koutouleas, A., Collinge, D. B., & Ræbild, A. (2023). Alternative plant protection strategies for tomorrow's coffee. *Plant Pathology*, *72*(3), 409-429.

Lamond, G., Sandbrook, L., Gassner, A., & Sinclair, F. L. (2019). Local knowledge of tree attributes underpins species selection on coffee farms. *Experimental Agriculture*, *55*(S1), 35-49.

Marie, L., Abdallah, C., Campa, C., Courtel, P., Bordeaux, M., Navarini, L., Lonzarich, V., Bosselmann, A.S., Turreira-García, N., Alpizar, E. and Georget, F., (2020). G× E interactions on yield and quality in Coffea arabica: new F1 hybrids outperform American cultivars. *Euphytica*, *216*, pp.1-17.

Mithamo, W. M. (2013). Effect of intercropping coffee with fruit trees on coffee eco-physiological and soil factors at Coffee Research Foundation in Ruiru Kiambu County (Masters' Thesis, Kenyatta University, Kenya). *Unpublished PhD Thesis, University of Nairobi*.

Mulinde, C., Majaliwa, J.G.M., Twinomuhangi, R., Mfitumukiza, D., Komutunga, E., Ampaire, E., Asiimwe, J., Van Asten, P. and Jassogne, L., (2019). Perceived climate risks and adaptation drivers in diverse coffee landscapes of Uganda. *NJAS-Wageningen Journal of Life Sciences*, *88*, pp.31-44.

O'Donoghue, T., Minasny, B., & McBratney, A. (2022). Regenerative agriculture and its potential to improve farmscape function. *Sustainability*, *14*(10), 5815.

Ochola, D., Boekelo, B., van de Ven, G. W., Taulya, G., Kubiriba, J., van Asten, P. J., & Giller, K. E. (2022). Mapping spatial distribution and geographic shifts of East African highland banana (Musa spp.) in Uganda. *Plos one*, *17*(2), e0263439.

Schreefel, L., de Boer, I.J.M., Timler, C.J., Groot, J.C.J., Zwetsloot, M.J., Creamer, R.E., Schrijver, A.P., van Zanten, H.H.E. and Schulte, R.P.O., (2022). How to make regenerative practices work on the farm: A modelling framework. *Agricultural Systems*, *198*, p.103371.

Soto, R. L., Martinez-Mena, M., Padilla, M. C., & de Vente, J. (2021). Restoring soil quality of woody agroecosystems in Mediterranean drylands through regenerative agriculture. *Agriculture, Ecosystems & Environment*, *306*, 107191.

Tittonell, P., Muriuki, A., Shepherd, K.D., Mugendi, D., Kaizzi, K.C., Okeyo, J., Verchot, L., Coe, R. and Vanlauwe, B., (2010). The diversity of rural livelihoods and their influence on soil fertility in agricultural systems of East Africa–A typology of smallholder farms. *Agricultural systems*, *103*(2), pp.83-97.

Wang, N., Jassogne, L., van Asten, P. J., Mukasa, D., Wanyama, I., Kagezi, G., & Giller, K. E. (2015). Evaluating coffee yield gaps and important biotic, abiotic, and management factors limiting coffee production in Uganda. *European Journal of Agronomy*, *63*, 1-11.

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