D3. CARBON FOUNDATIONS

A TECHNICAL INTRODUCTION TO THE IMPORTANCE, LOSS AND SEQUESTRATION OF CARBON IN COFFEE AGROFORESTRY SYSTEMS

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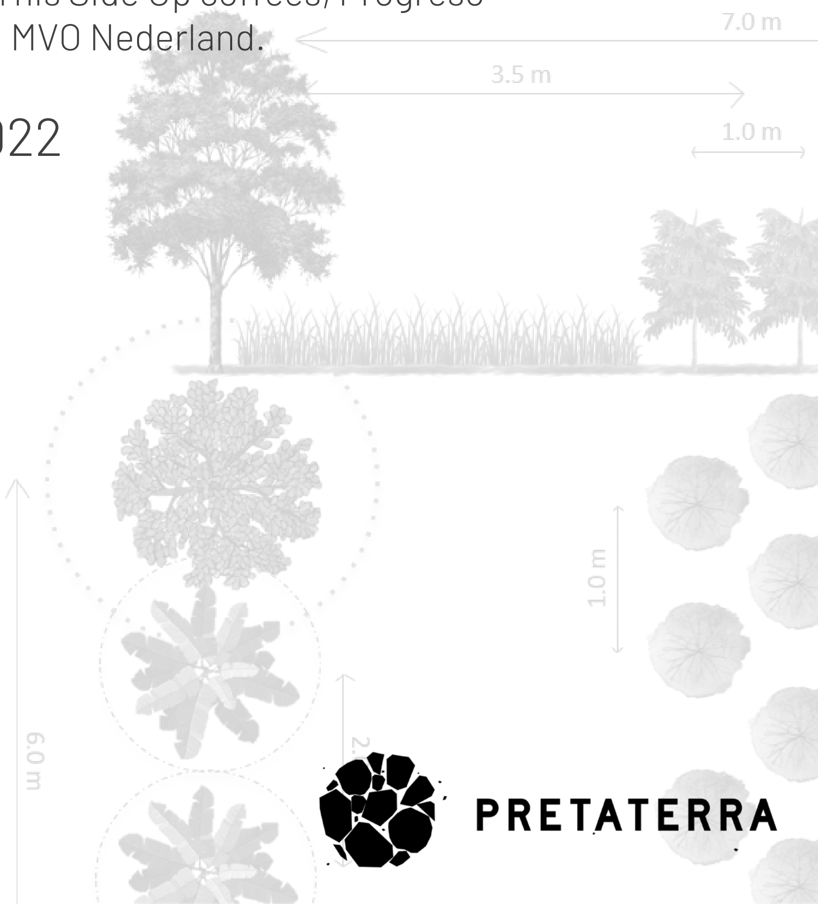

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INTRODUCTION

Mitigation of climate change through agriculture is linked to three main factors:

- Reducing agricultural emissions
- Increasing long-term productivity and resilience of existing agricultural land, to prevent emissions from land use change (e.g. deforestation)
- Sequestering carbon in above and belowground biomass

Carbon is naturally captured and emitted in biological systems on a continuous basis. Agricultural practices typically increase the rate of carbon loss from land use systems, while decreasing rates of sequestration and storage. Agriculture is therefore a leading contributor to global climate change. In agroforestry systems carbon can be sequestered by (A) increasing the amount of carbon sequestered and (B) decreasing emissions associated with agricultural activities. The principles and practices applied here focus on achieving this.

When applied appropriately, these practices can also positively impact other important aspects of the farm, such as resilience, long-term coffee yield, diverse production, biodiversity and water quality.

Each practice included here is generally considered to have a positive impact on emissions from agricultural systems, but the actual sequestration rates will depend on the particular context in which practices are applied, and how they are applied. Specific carbon sequestration calculations should always be made by taking account of local condition, existing land use, new land use and the details of the practice being applied.

INCREASE BELOWGROUND BIOMASS & SOIL CARBON

DECREASE BELOWGROUND CARBON LOSSES

INCREASE ABOVEGROUND BIOMASS

REDUCE OTHER SOURCES OF EMISSIONS

INTRODUCTION TO CARBON IN FARMING SYSTEMS

CARBON ON THE FARM

A Vital Agricultural Resource

Carbon is an essential part of life on earth, landscape health and thriving agricultural systems. It is naturally cycled from gas, to living & dead biomass, and back to gas. Carbon is essential for good soil health.

SOIL & THE CARBON CYCLE

Carbon on farms can essentially be thought of in three categories: gaseous carbon (i.e. carbon dioxide in the atmosphere), living biomass (i.e. all living organisms) and dead biomass (in various forms). Some soil carbon is derived from mineral sources, but this is a relatively insignificant proportion, so is not the focus here.

All of these forms of carbon can be found both above and below ground. Carbon is continuously being transformed from one form to another, at different rates depending on the form of carbon, the conditions, and the practices of the farmer or land manager.

Some forms of carbon are more stable than others. Biochar, for example, can store carbon in soils for centuries and woody biomass (high in lignin) takes years to decay. Non-woody organic biomass such as leaves decomposes in a matter of weeks or months - transforming into other living organisms, carbon dioxide and some more stable forms of carbon materials.

This continuous transformation is called the carbon cycle (as shown on the next page).

CARBON IS CONTINUOUSLY CYCLED IN AGRICULTURAL SYSTEMS

DIFFERENT FORMS OF CARBON ARE MORE OR LESS STABLE

SOIL & THE CARBON CYCLE

WHY IS CARBON IMPORTANT ON THE FARM?

Aside from being the most significant building block for all living organisms, carbon is essential for agriculture because of its impact on soil. Higher levels of carbon stored as organic matter in the soil (often expressed in terms of Soil Organic Matter or 'SOM') are associated with the basic characteristics that make soil healthy. SOM is made of carbon combined with other elements in various forms, and is the foundation for a healthy soil food web. Some of the key influences include:

Soil structure.

SOM creates stable soil structures, aggregating soil particles and leaving space in between (pores), which are vital for good soil functioning, including the presence and transfer of gases (oxygen, carbon dioxide), storage of water, and providing space for soil organisms.

Nutrient storage & release.

The nutrients in soil are made more stable by the presence of carbon. In complex form, they cannot be leached in the way mineral nutrients (i.e. synthetic fertilisers) can be. These nutrients are then slowly released as the organic matter decomposes. Plant-available nutrients are also stabilised by soil carbon, which has a high Cation Exchange Capacity. This effect is most important in sandy soils, which have a low cation exchange capacity compared to clay soils.

Water storage.

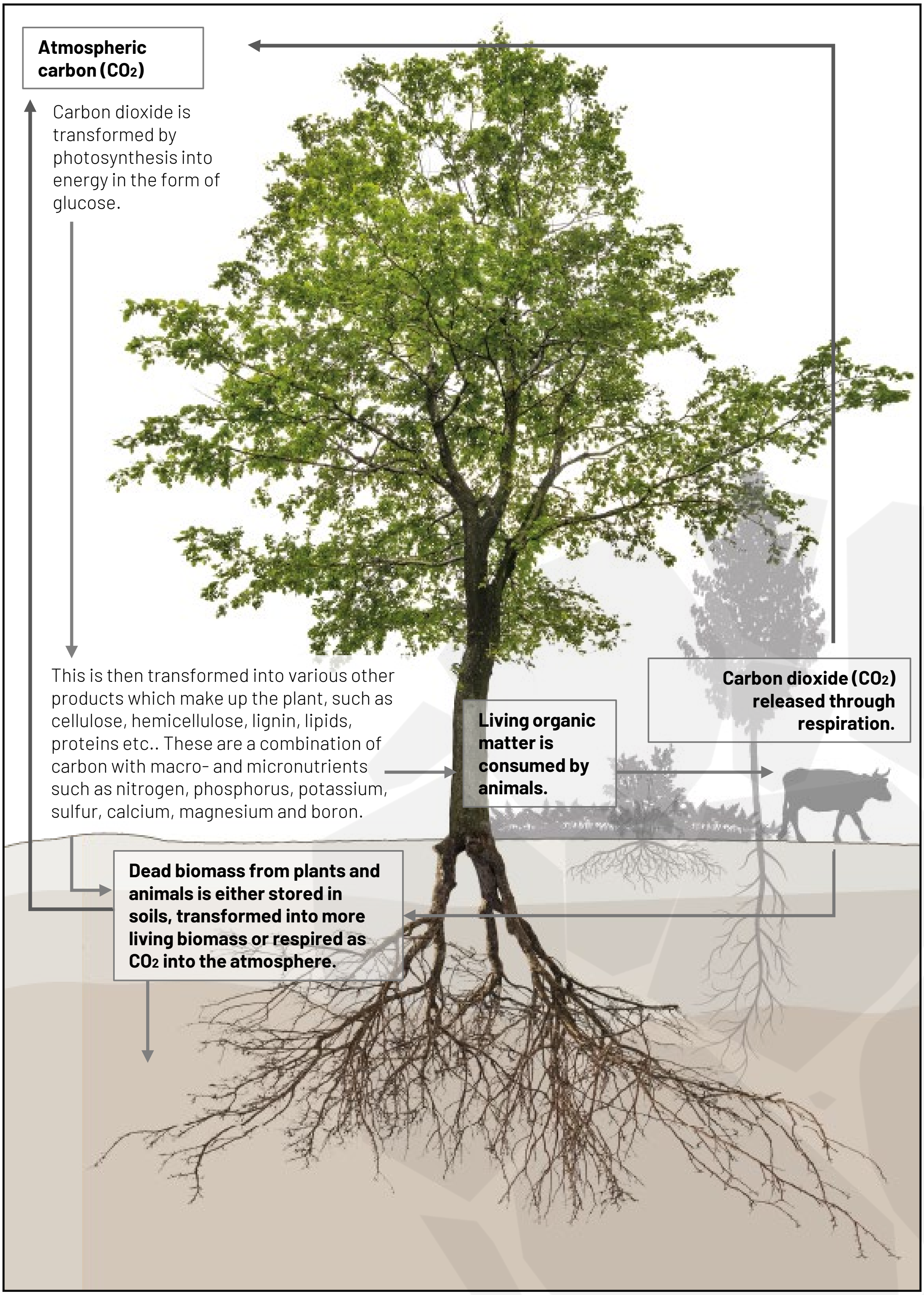
SOM can store up to twenty times its mass in water. It also helps soils to store water by improving the structure. By stabilising soil and creating pore space, the soil is better able to hold more water than soils with less organic matter, where water may either run off the surface (e.g. clay soils) or rapidly drain out of the soil profile (e.g. sandy soils).

Carbon storage.

Stable soil organic matter is an important means to sequester and store carbon over long time periods. Global soils are estimated to have the potential to sequester one quarter to one third of global carbon emissions annually (Lal 2004).

THE CARBON CYCLE

Carbon is continuously cycled through agricultural and land use systems via plants, animals, microbes and fungi. Much is released through respiration, but some can be stored for longer periods in stable form in the soil, as living biomass in long-lived species (e.g. trees) and in products (e.g. wood).



CARBON STORAGE IN SOILS

As described in section 1, atmospheric carbon is transformed into plant biomass via the process of photosynthesis. This plant biomass is then transformed in various ways by animals, microbes & fungi, with some being stored in different living and dead forms, and some being lost back to the atmosphere by various processes such as organism respiration.

FORMS OF CARBON

Carbon exists in a range of forms - some that are more stable, and others which are less stable. This 'stability' is defined in terms of how long that carbon is likely to remain in a particular form without being transformed (e.g. by metabolisation by soil microbes into gaseous CO2).

As described in the graphic below, soil carbon is divided into three main stability categories: Fast pool (least stable), Slow pool (more stable) and Stable pool (most stable). Agricultural practices have the most impact on the fast and slow pools - making these the main focus for increasing carbon in the system.

Broadly, level of decomposition is inversely related to the stability of the carbon contained in a material: materials that are less decomposed, such as fresh plant material are less stable than those that are more decomposed, such as humus.

Stability also links to the type of material. Softer materials, such as leaves with high cellulose, decompose quickly, releasing their energy and nutrients. Harder materials, such as woody stems and tree trunks, high in lignin, are more resistant to decomposition.

Least Stable ('Labile/Fast pool')	**More Stable** ('Slow pool')	**Most Stable** ('Stable pool')
<5 years	**5 years - decades**	**Centuries - millennia**
Carbon is cycled quickly from atmosphere into terrestrial systems and back into the atmosphere in a timescale of days to a few years (e.g. <5 years).	Carbon is cycled more slowly over timescales of a few years to decades. Either semi-decomposed organic matter between 0.053-2mm in size, or woody biomass.	Carbon forms that change only very gradually under natural conditions, over timescales of many decades, to centuries and even millennia.
Rule of thumb: softer, green biomass is typically less stable, such as fresh leaves or fine roots	**Rule of thumb:** Hard plant materials such as woody (lignified) branches and trunks will decompose more slowly than softer materials.	**Rule of thumb:** organic material that has been significantly transformed from its original plant form, such as through multiple stages of decomposition, so is no longer recognisable as plant material.
Example: when common coffee shade trees such as *Leucaena leucocephala* and *Grevillea robusta* are pruned, the soft leaves are a source of fast-decomposing carbon and nutrients.	**Example:** Mulches of chipped wood from branches and stems of trees and shrubs can be used to cover soils, commonly taking a number of years to break down.	**Example:** Humus - decomposed organic materials bound to other soil particles, resistant to further decomposition by microbes. Charcoal or biochar that is highly unreactive and can last for millennia.
Importance: a vital source of nutrients for soil flora, fauna and plants, ongoing inputs are essential for a productive system.	**Importance:** a source of slow-release nutrients and energy, especially for fungal species. Also contributes to improved soil properties such as structure. Can 'lock-up' nutrients in soil if incorporated.	**Importance:** long-term stability of soil carbon, improved soil properties such as structure, resilience to shocks, and slow release of nutrients.

ORGANIC MATTER IN SOILS

Soil organic matter (SOM) – the combination of carbon with other elements such as nitrogen, phosphorus, sulfur etc. – influences soils on a biological, physical and chemical level, as shown in the table below. Adapted from Baldock & Nelson (2000, p.29).

Property		Function
Biological	Energy source	Organic matter is the source of energy for soil biological processes.
	Nutrient source	Break down of soil organic matter ("mineralisation") influences the availability of bioavailable nutrients (nitrogen, phosphorus & sulfur).
	Ecosystem resilience	Stores of organic matter and nutrients can help ecosystems to recover following disturbances.
	Stimulates or inhibits enzyme activities and plant and microbial growth	Enzyme activity in soils, and growth of plants and microorganisms can be stimulated or inhibited by the presence of soil humic materials
Physical	Stabilisation of soil structure	Soil organic matter (ranging in size from molecules to fungal hyphae and plant roots) can bind together mineral particles in soil into larger particles or "aggregates".
	Water retention	Water retention is directly increased by the water holding capacity of organic matter itself, as well as by improving soil structure and pore geometry.
	Low solubility	Binding of minerals such as nitrogen in the soil, meaning that they are retained in the soil rather than leached away in water.
	Color	The darker colour of soils with higher organic matter content means that they heat up quicker when exposed to direct light.
Chemical	Cation exchange capacity	Retains high levels of cations - positively charged exchangeable nutrients - which are essential to soil fertility e.g. aluminium, iron, calcium, magnesium and ammonium.
	Buffering capacity & pH effects	Reduces the susceptibility of soil to changes based on external inputs, which can help maintain soil pH within acceptable levels for cultivation.
	Chelation of metals	Can bond with metals and trace elements, reducing nutrient losses from soils, reducing the potential toxicity of metals (e.g. aluminium), and increasing availability of phosphorus.
	Interaction with xenobiotics	Can change the biodegradability, activity and stability of pesticides in soils.

A PRIMER ON CLIMATE CHANGE AND AGRICULTURE

CLIMATE CHANGE

Present, future & impacts for agriculture

Climate change is intensifying drought and rainfall events, changing precipitation patterns and shifting climate zones. Without mitigation, this will continue to become more severe over the coming century. Agriculture is highly vulnerable - both mitigation and adaptation is essential.

CARBON, EMISSIONS & AGRICULTURE

AGRICULTURAL GREENHOUSE GAS EMISSIONS

Food system emissions account for 21-37% of all global greenhouse gas emissions (Mbow et al 2019). This includes:

- Crop and livestock management (on farm): 9-14%
- Land degradation and land use change (e.g. deforestation, peatland degradation): 5-14%
- Supply chain (e.g. storage, processing, transport, incl. food losses & waste): 5-10%

Carbon is one of three main types of climate-altering emissions linked to agriculture.

CARBON DIOXIDE (CO_2)

Carbon emissions account for 40-45% of emissions from agriculture (in terms of total warming potential or billion tonnes CO_2 equivalent - 'Gt CO2 eq.'; FAO 2021c). Carbon is stored in and emitted from living and dead biomass both above and below ground. Plant growth directly sequesters carbon from the atmosphere into roots, stems, leaves, flowers, fruit etc.. Carbon is emitted through natural cycles of decay of organic matter, whereby animals and microbes respire, producing carbon dioxide. Different forms of carbon are more or less stable - for example, woody biomass (e.g. tree trunks) are take longer to biodegrade than soft biomass (e.g. leaves). Carbon emissions are also produced through processes such as burning for land clearance.

METHANE (CH_4)

Per unit of gas, methane has a much greater climate change potential than carbon dioxide. It has a Global Warming Potential (GWP) of 28-36 times carbon dioxide over 100 years. Livestock production - especially cattle, sheep, pigs and goats - is the main agricultural emissions source of methane. Emissions levels link to the natural digestion processes of the animal, and manure storage and handling processes (EPA 2021).

NITROUS OXIDE (N_2O)

Per unit of gas, nitrous oxide is the most potent in terms of climate change potential, with a GWP of 265-298 times that of carbon dioxide over 100 years (EPA 2021). Soil management practices - such as the use of synthetic and organic fertilisers, manure management, and burning of residues and other plant matter - are the biggest contributor of nitrous oxide from agriculture. Emissions are particularly high when nutrient applications are excessive leading to inefficient nitrogen utilisation and denitrification, whereby soil nitrogen is transformed into gaseous form, largely through microbial action (Wang *et al* 2021). This loss process also has the negative impact of reducing the availability of nitrogen in the soil for use by crop, as well as representing a waste of resources for the farmer.

CHANGING CONDITIONS

CHANGES TO DATE

Since the pre-industrial period (1850-1900), global temperatures have risen by approximately 0.87°C (2006-2015 average). Over land, these increases are greater, around 1.53°C. The impacts of this change vary dramatically across the globe. Generally, it has led to an increase in the frequency, intensity and duration of extreme heat events & drought (e.g. in the Mediterranean, west Asia, north-east Asia, much of Africa and South America), increased intensity of rainfall, shifting rainfall patterns and shifting climate zones (e.g. expansion of arid zones, shrinking of polar climate zones; IPCC 2019).

PREDICTED CHANGES

Climate change-related risks are predicted to increase to the year 2100 and beyond. The impacts described above (e.g. temperature changes, drought intensity, rainfall intensity, shifting climate zones) will continue to increase. Higher emissions will lead to greater intensity of these impacts, while mitigation (i.e. reduction in emissions intensity and sequestration of greenhouse gases) will decrease the impacts. Emissions reductions and increased sequestration in agriculture, as well as measures to increase the resilience of production systems (adaptation) is therefore essential.

IMPACTS ON AGRICULTURE

Broadly, current levels of climate change are associated with "moderate risks" to landscapes and the agricultural system including increased water scarcity, soil erosion, damage from wildfires, vegetation loss, tropical crop yield losses (IPCC 2019, p.17). The risks will become increasingly severe as climate change intensifies (ibid.). Impacts of climate change on agriculture vary, depending both on the types and magnitude of change, as well as the agricultural system itself.

For example, Brazilian coffee-producing regions have experienced significant yield losses due to climate change since 1974 (Koh *et al* 2020). They are at risk of further challenges from increasing temperatures and decreasing precipitation, but with variations across different regions. Minas Gerais in Brazil is considered one of the most vulnerable coffee producing regions. Here, mean temperatures have increased by 1.3°C since 1974, with temperatures frequently exceeding the optimum for arabica (23°C), especially during flowering and fruit ripening. Precipitation has also decreased significantly (>10%). Rural incomes are also highly dependent on coffee income, with low levels of diversification compared to other regions, increasing risk further. Appropriate responses to climate change should be considered in context.

CARBON SEQUESTRATION IN AGOFORESTRY

CARBON IN AGROFORESTRY SYSTEMS

Carbon dynamics & variables impacting sequestration.

Carbon sequestration potentials of coffee agroforestry systems are context-specific.

Key variables influencing carbon stocks include site conditions, aboveground biomass stocks, and belowground biomass & soil carbon stocks.

CARBON DYNAMICS IN AGROFORESTRY

Agroforestry has a high potential to capture and store atmospheric carbon, as well as reducing emissions of nitrous oxide (N2O).

But the carbon sequestration potential of agroforestry is highly variable, depending on:

- Local biophysical conditions (e.g. temperature, humidity, soil type, slope)
- Type of agroforestry system (species mix, system composition)
- Management practices
- End use of the products produced

Some agroforestry systems may be net emitters of greenhouse gases.

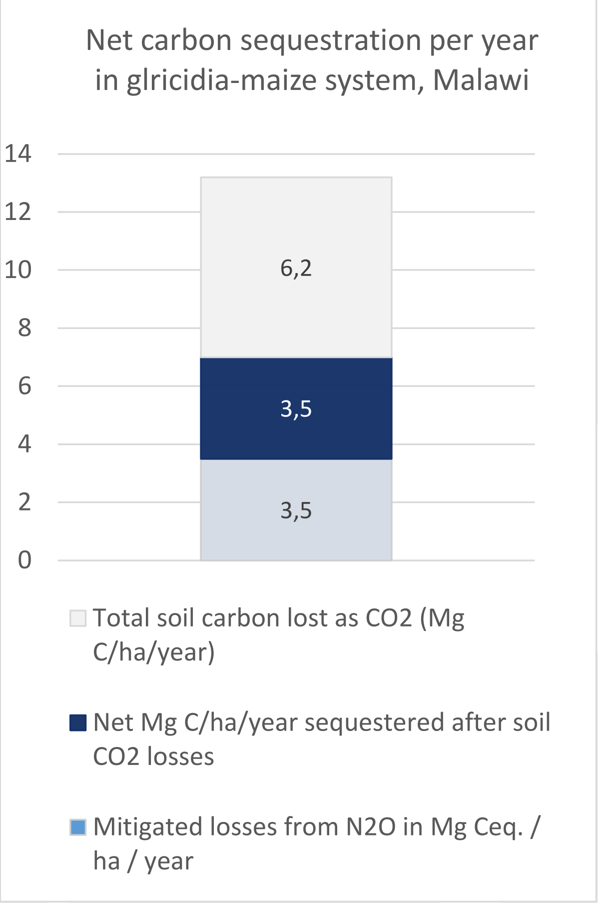
MEASURING CARBON IN AGROFORESTRY

Accurate measurement of carbon stocks, sequestration rates and storage potential is still a challenge. Many estimations are made based on allometric equations that are derived studies that are species- and location-specific. They may also focus on measurements of trees in natural forests rather than in agroforestry situations.

This is made more complicated by the need to balance other losses or gains made in the system. For example, a study of gliricidia-maize intercropping systems in Malawi found that soil carbon dioxide emissions (i.e. from respiration) were equal to 64% of total sequestered carbon over 7 years (approx. 76 Mg C / ha in top 2m of soil). Net sequestration was therefore only 36% of total sequestered carbon volumes.

This guide does not focus on the verifiable quantities of carbon that can be sequestered in a particular system. The coming pages emphasise instead some of the key considerations and best practices for reducing negative impact and increasing positive impact.

This table shows carbon seqestration per year in a gliricidia-maize system in Malawi. Total carbon sequestration was 13.2 tons (Mg) per hectare per year, but 6.2 tons was lost through soil respiration, leaving a net sequestration rate of 7 tons per hectare per year.



CARBON IN COFFEE AGFORESTRY

WHAT IS THE CARBON SEQESTRATION POTENTIAL OF COFFEE AGROFORESTRY?

The table (right) indicates the range of carbon sequestration storage potentials in coffee systems, as well as reference systems such as tropical forest.

Carbon 'stocks' are the amount of carbon stored in a system at a given time. Overall sequestration potential always depends on what land use changes are occurring. Simply put: what type of land use & practices are you transitioning from and to? If carbon stocks in the new land use are higher, then net carbon sequestration is achieved (excluding other external emissions sources such as synthetic fertilisers). If carbon stocks in the new system are lower, then that equals a net carbon emission.

For example, transition from a monoculture coffee system to a multi-strata coffee agroforestry system could increase carbon stocks by 50% or more. By comparison, transition from primary forest to the same coffee agroforestry system could lead to carbon stock losses of 70% (based on figures from Lampung, Indonesia; van Noordwijk *et al* 2002).

Estimations for carbon stocks under various agroforestry scenarios, as well as the carbon stocks of other reference systems, such as tropical lowland forest.

Case	Carbon stock - tons (Mg) CO2 equivalent per hectare	Source
Tropical agroforestry systems, range	Total carbon stock: 39-102 Mg/ha	Albrecht & Kandji (2003)
Coffee agroforestry in Costa Rica, with organic inputs incl. Compost, manure & other biomass	Total stocks: 64-122 Mg/ha Soil organic carbon: 42-84 Mg/ha (69% of total) Aboveground biomass: 23.7Mg/ha (23% of total)	Häger (2013)
Aboveground biomass storage in coffee production systems in Mexico, Guatemala, El Salvador, Costa Rica and Colombia	Traditional polycultures (avg. 305 shade trees/ha, multi-strata): 42.5Mg/ha Commercial polycultures (221 shade trees/ha, multi-strata): 30.2Mg/ha Shaded monoculture (183 shade trees/ha, single-strata, single-species): 14.3Mg/ha	van Rikxoort *et al* (2014)
Soil organic carbon (top 30cm soil) in arabica and robusta production, Uganda	Soil carbon stocks under robusta (*C. canephora*) agroforestry with non-fruit species: 58Mg/ha Soil carbon stocks under arabica (*C. arabica*) agroforestry with non-fruit species: 55Mg/ha Soil carbon stocks under arabica (*C. arabica*) agroforestry with fruit species (*Artocarpus heterophyllus*, *Mangifera indica*): 55Mg/ha Soil carbon stocks (top 30cm soil) under robusta (*C. canephora*) agroforestry with fruit species (*Artocarpus heterophyllus*, *Mangifera indica*): 50Mg/ha	Tumwebaze & Byakagaba (2016)
Monoculture coffee, Lampung, Indonesia	Total estimated stocks: 52Mg/ha	van Noordwijk *et al* (2002)
Multi-strata coffee agroforestry, Lampung, Indonesia	Total estimated stocks: 82Mg/ha	van Noordwijk *et al* (2002)
Reference: Tropical forest in Lampung, Indonesia	Total estimated stocks: 262Mg/ha	van Noordwijk *et al* (2002)

VARIABLES IMPACTING SEQUESTRATION POTENTIAL

VOLUME OF ABOVEGROUND BIOMASS

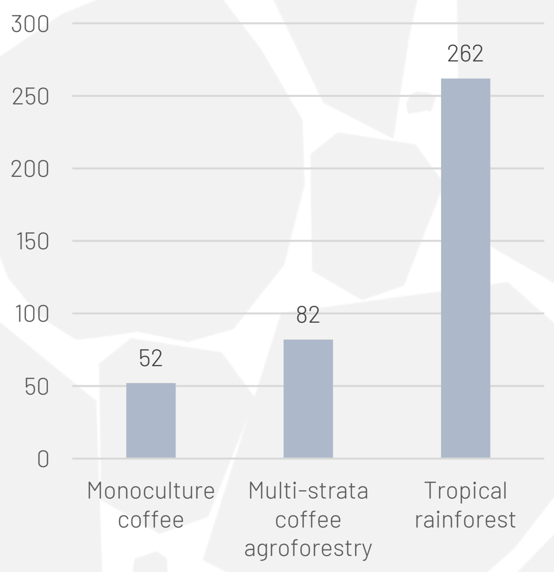
Aboveground carbon storage depends on the long-term maintenance of significant amounts of aboveground biomass in the system. For example, there will be significantly lower above-ground carbon storage in a coffee-*E. poeppigiana* agroforestry system in which the shade tree is pollarded (complete removal of all branches) twice per year, compared to a system where only light pruning occurs, or even less than coffee integrated with a timber species (e.g. *Khaya senegalensis*). Greater tree density and greater tree height broadly contribute to higher aboveground biomass, leading to higher carbon stocks in aboveground biomass.

VOLUME OF BELOWGROUND BIOMASS & SOIL CARBON

Belowground carbon storage is linked mainly to the input of organic matter into the soil, and the rate at which organic matter is lost - such as via erosion. Inputs of organic material into the soil via plant leaf litter, pruning materials, compost, manure and coffee pulp can lead to higher carbon storage in belowground biomass (soil organic matter). Plant roots also contribute significantly to belowground carbon stocks.

The table below illustrates the potential magnitude of difference in storage of carbon in both above- and belowground forms between monoculture coffee, multi-strata coffee agroforestry and tropical rainforest in the same region.

Estimated carbon stocks (Mg C/ha) in three land use systems, Lampung, Indonesia (van Noordwijk et al 2002)



COFFEE SPECIES

The species of coffee also may have an impact on the total carbon sequestration potential of the system. Robusta (*C. canephora*) is typically more productive (in terms of overall biomass) than arabica (*C. arabica*), especially in adverse conditions. As a total percentage of carbon sequestration in agroforestry this may be relatively small - for example, in Costa Rica, accounting for on average 3% of total carbon stocks across 14 agroforestry coffee farms (Häger 2012).

EXISTING CARBON STOCKS, SOIL TYPE & OTHER LOCAL CONDITIONS

Other important factors have a significant influence on the carbon stocks of an agroforestry system. For example, the soil organic matter (SOM) content at the time of land use transformation will influence the overall stocks. If a farm has recently transitioned from degraded pasture to coffee agroforestry, the SOM may be lower than an older conventional coffee farm. Topsoil erosion on steep slopes is expected to be higher than gently sloped or flat land. Soil type also influences the potential for soils to store carbon in a stable form. For example, clay soils may retain soil carbon more easily than sandy soils.

Comparing figures from studies can be made even more challenging because different studies measure different parameters. For example, some may only measure soil organic matter in the surface soil layer (e.g. top 20-50cm), whereas others may measure to 1m or more. This can also make results misleading. For example, transforming native forest to pasture may lead to a slight increase in organic carbon in topsoil (top 0-0.3m of soil). But at the same time, it can lead to significant losses of carbon from deeper soil layers (e.g. 1-3m depth; Veldkamp et al 2003). Measuring only topsoil changes may give a misleading picture of overall carbon balance.

Yet others can include root biomass in soil carbon estimations while others do not. Because of these variations, specific site conditions should always be taken into account for carbon measurement and certification purposes.

MANAGEMENT PRACTICES

All carbon sequestration potentials are influenced deeply by practice. The next section gives details on the key “dos” and “don’ts” of agroforestry for carbon sequestration.

AGROFORESTRY PRACTICES FOR CARBON CAPTURE & STORAGE

PRACTICES

How to store carbon in living biomass and soils.

There are many practices available for increasing carbon sequestration on coffee farms while decreasing emissions.

Each of these practices, when applied appropriately can also positively impact other important aspects of the farm, such as resilience, long-term coffee yield, diverse production, biodiversity and water quality.

INCREASE BELOWGROUND BIOMASS AND SOIL CARBON

APPLY COMPOST

Compost is well-decomposed organic material made from various sources. It contains high amounts of relatively stable organic matter, as well as essential plant nutrients, beneficial microbes and soil fauna. A well-made compost is a vital resource for increasing soil organic carbon over time, as well as providing other key benefits such as nutrients, soil structure and water-holding capacity, as discussed in section 1. It can also substitute some or all synthetic fertilisers on the farm, reducing emissions from fertiliser production.

For best impact, make sure that the compost does not contain materials that are themselves associated with high emissions. For example, in some contexts naturally formed peat is used as a compost ingredient. Harvesting this peat for compost can be associated with significant carbon emissions - so while carbon is increasing in your soil, it is being emitted elsewhere. Compost made with organic materials on your own farm or very locally is likely to have the greatest overall carbon sequestration potential.

APPLY MANURE

Manure from livestock including poultry (e.g. chickens), ruminants (e.g. cattle, sheep, goats) is a valuable source of nutrients, but also contains decomposed or semi-decomposed organic material which can add to soil organic carbon levels. Manure can either be applied manually, by transporting it from the source (i.e. where the animals are kept) to the target area, or directly by bringing animals into the production system itself. Only some animals - those that do not graze on the coffee or other valuable plants, such as chickens, should be brought into the plantation.

It may also be possible to introduce other livestock if coffee plants & trees are sufficiently protected. For example, temporary fencing may be erected between young coffee and tree lines to graze animals on grass and herbs between, without causing damage. Mature manure is typically planted in advance of times when target plants have most nutrient demand, such as at the beginning of the growing season, or before flowering and fruiting.

APPLY OTHER FORMS OF ORGANIC MATTER FROM LOCAL SOURCES

A range of locally-available products - often by-products from agricultural operations and processing - can be added directly to the soil as a mulch or included in compost production. These may include coffee pulp from fruit processing, palm oil seed cake from pressing, rice husks and so on. Mixing undecomposed organic matter with soil is not advised as it can reduce nutrient availability for crops. Application of microbially active ‘compost teas’ can support the rapid decomposition of these materials. It is also important that these materials are in close contact with the soil. Materials that are suspended above the ground (e.g. by twigs & branches) will not be accessible to soil life, so benefits will be reduced.

INCREASE BELOWGROUND BIOMASS AND SOIL CARBON

PLANT & INTENSIVELY PRUNE FAST-GROWING AND NITROGEN-FIXING SPECIES

Fast-growing nitrogen-fixing species (including a range of popular leguminous shade species such as Erythrina spp., Inga spp., Gliricidia spp. and Leucaena spp.) can rapidly increase the productivity of an area (i.e. transforming more atmospheric carbon into plant biomass). This biomass then contributes to increased soil carbon via roots, leaf litter and by addition of pruning materials to the soil as mulch. Many of these species resprout rapidly after some or all of their branches are cut back to the stem (a practice known as 'pollarding'). They can therefore be routinely cut back to encourage new growth - what we call 'intensive pruning'. The frequency and timing of this pruning will depend on species and context - for example, in cooler or drier areas where rate of growth is slower it may be necessary to prune trees fewer times per year than in warmer, more humid areas. This practice can be linked to the following practice.

INTEGRATE SPECIES THAT HAVE A DIVERSITY OF ROOTING DEPTHS

As with aboveground diversity, when different species make use of different resources (e.g. some root more deeply in the soil, others to a shallow) the overall productivity of the system can be increased - increasing the rate of carbon sequestration. Simply put, more competition will occur between plant roots if all are concentrated in the top layers of soil. Less competition will occur if plant roots occupy different depths. Less competition allows for a higher total root biomass, leading to greater carbon sequestration, both via roots, and by promoting greater total aboveground productivity.

For example, *Grevillea robusta* is a deep-rooted species commonly intercropped with and pepper (*Piper nigrum*). Large forest trees (e.g. timber species like teak - *Tectona grandis*) with deep roots may be effectively intercropped with species rooting at shallower depths like grasses, herbs, coffee, and service species with moderate rooting depth (e.g. *Gliricidia sepium*) to increase total root distribution in the soil profile.

DECREASE BELOWGROUND CARBON LOSSES

REDUCE SOIL DISTURBANCE

Ploughing and other forms of soil disturbance increase the rate of carbon losses from soils. Bare & exposed soil is more prone to carbon losses through both wind and water erosion. Microbial activity is also increased when oxygen increases, meaning that organic matter is transformed into atmospheric carbon more rapidly. Loss of carbon from the soil can then occur rapidly. This is especially fast in hot, humid environments where microbial decomposition processes are very rapid. Soil disturbance is sometimes necessary for agricultural work, but should be reduced and eliminated wherever possible.

MAINTAIN SOIL COVER & LIVING ROOTS IN THE SOIL

'Dead' mulches can range from a layer of compost, manure, other organic matter, or even synthetic coverings (such as landscape fabric). All will reduce soil carbon losses as well as having other benefits such as weed suppression. Synthetic mulches can be very effective for weed suppression, but may be costly, are non-renewable, will be associated with further emissions in manufacturing and transport, and will not add more organic material or nutrients to the soil.

Maintaining a layer of living or dead cover on top of the soil reduces processes of erosion, as well as providing other benefits such as improving soil water status. Cover crops such as grasses or herbs in a plantation can provide soil cover as well as improving soil health more generally. In many cases, these plants may need to be managed by either mowing or grazing by livestock, depending on the system goals, conditions and specific species involved. This maintenance of living soil cover relates to the following point.

DECREASE BELOWGROUND CARBON LOSSES

REDUCE USE OF HERBICIDES FOR WEED CONTROL

Applying herbicides throughout the plantation creates a lot of bare soil. If it is absolutely necessary to use herbicides, they should be applied to a specific target area. Other methods should be used to combat presence of aggressive weeds, such as spot-weeding by hand, temporary inclusion of grazing stock (e.g. poultry), mulching, and by increasing overall shade density in the plantation, which can reduce the growth of aggressive weeds.

PLANT TREES & SHRUBS TO REDUCE WATER & WIND EROSION

Trees and shrubs can be planted on slopes to reduce soil erosion by water. Living roots help to stabilise soil, leaf litter can provide protection to the soil surface, and improvements in soil structure by trees encourages water to infiltrate into soil rather than washing over it (which takes soil with it). Dense planting of fast-growing species across a slope is especially effective for quickly establishing a barrier to reduce soil erosion rates. Windbreaks on either flat or sloping land can also reduce wind erosion - especially when soil is left bare.

ALL OF THE ABOVE ARE EVEN MORE IMPORTANT ON SLOPING LAND

Processes of erosion are typically accelerated on steeper slopes compared to flat land. These erosion reduction practices are even more important on sloped land.

INCREASE ABOVE-GROUND BIOMASS

INCREASE THE STRUCTURAL DIVERSITY OF PLANTS IN THE SYSTEM

Including a mix of species which have different physical characteristics and resource needs is likely to increase the overall productivity of the system (i.e. how much biomass is created over a period of time). A more productive system is generally likely to have more above- and below-ground biomass and hence greater carbon sequestration. This does however depend on management practices. For example, cutting and burning branches of a fast-growing species like *Grevillea robusta* for firewood will release more carbon back into the atmosphere than using that same material for mulching or compost.

Importantly, this does not have to mean that more species is always better. Species diversity can have many benefits, but the overall number of species is likely to be less important for carbon sequestration than the functional diversity of species, i.e. the different types of species in the system and how well the different species in the system work together. As an example, a coffee monoculture with bare ground from pesticide use is likely to store less aboveground carbon than a coffee plantation with a thick layer of herbs and grasses. The same plantation with the addition of a service species such as *Inga edulis* is likely to have yet more aboveground carbon. Add to this a suitable large timber species - such as *Cordia alliodora* and the system will be yet more productive overall (note, this does not necessarily relate to the yield of individual crops e.g. coffee).

In many contexts, it will not be feasible to have a very high number of species in the coffee system. Selecting an appropriate species mix is important: not all species mixes will be equally suitable or productive. The concept of functional groups is important (described on page 13 of D2: Agroforestry Foundations). Select species from multiple functional groups. In this process, it is helpful to consider the following two points.

	Carbon stocks in shade trees (Mg/ha)	Carbon stocks in coffee plants (Mg/ha)	Total aboveground carbon stocks (Mg/ha)
Traditional polyculture	36,3	6,3	42,6
Commercial polyculture	22,7	7,4	30,1
Shaded monoculture	6,3	8	14,3
Unshaded monoculture	0	10,5	10,5

Aboveground carbon stocks in four different types of system in five Latin American countries. Adapted from van Rikxoort *et al* (2014).

INCREASE ABOVE-GROUND BIOMASS

SELECT SPECIES WITH DIFFERENT (COMPLEMENTARY) ABOVE-GROUND STRUCTURE AND RESOURCE REQUIREMENTS

Mix species that have different above-ground characteristics. I.e. some that are taller than others, with different canopy height and spread. Also select species with different light requirements. The tallest trees in the system (e.g. timber trees) may require the most light, while shorter species (such as coffee or ground cover) may need to be shade-tolerant.

SELECT SPECIES WITH DIFFERENT (COMPLEMENTARY) ROOT STRUCTURES

Roots physically anchor the plants in the ground, and take up nutrients and water. Plants with different root shapes will compete less with each other for these resources than plants with roots that fill a similar space. Plants from the same or similar species will have the same or similar root structures. It is not always easy to know the structure of tree roots, as it is difficult to study. Some known combinations already mentioned are coffee with *Grevillea robusta* and coffee and teak (*Tectona grandis*). Broadly, larger species are likely to have deeper roots, although this is not always the case. For example, both Durian (*Durio zibethinus*) and avocado (*Persea americana*) have relatively shallow roots given their size.

Just as with aboveground biomass production, well-matched species with different root structures are likely to lead to more productive systems overall, and therefore more carbon sequestration.

This diversity of root types will also support carbon storage belowground.

INCLUDE SHADE-TOLERANT SPECIES

As mentioned above, a combination of well-matched species is likely to increase aboveground biomass. Competition for light is a key limiting factor in plant productivity. Combining light-loving species with shade-tolerant species to increase biomass production. Coffee itself is tolerant and benefits from some shade, depending on context, coffee species and production goals (see D2: Agroforestry Coffee Foundations).

INCREASE ABOVE-GROUND BIOMASS

STIMULATE PLANT GROWTH (E.G. THROUGH PRUNING)

Plant growth can be stimulated in a number of ways. This can have many benefits on the farm (e.g. by improving production of a desired crop), and can also increase carbon capture and storage. In general, a system with healthy soil an abundance of water and an appropriate species (mix) for the site will produce more than one with poor soil, insufficient water and inappropriate species. Getting that right is a key starting point.

It is also possible to stimulate plant growth by pruning at the right time. Plant growth (e.g. of a branch) often follows a pattern with rate of growth increasing to a certain point, and then decreasing. Some species - such as grasses, or the fast-growing species already mentioned (e.g. *Leucaena leucocephala*, *Gliricidia sepium*) - regrow easily after cutting. By cutting at the appropriate time, when growth is slowing down, it is possible to use the cut biomass (e.g. as mulch, composting material, or fodder for livestock) and reset the growth to produce more biomass.

This links to soil carbon-building practices described in the previous section.

PRODUCE LONG-LASTING PRODUCTS

Aboveground biomass is also an important long-term store for carbon in the products that are produced. Products such as timber for use in construction are likely to store the carbon they contain for at least a number of years, if not decades or even centuries. Compared to, for example, producing firewood, the carbon sequestration potential of this “aboveground biomass” is greatly increased.

REDUCE OTHER SOURCES OF EMISSIONS

REDUCE SYNTHETIC/MINERAL FERTILISER USE

The production of synthetic fertilisers - especially nitrogen - are very energy-intensive. They are therefore responsible for a large proportion of agricultural greenhouse gas emissions. Reducing synthetic fertiliser use on the farm is a key means to reduce carbon emissions in coffee production. Maintenance of healthy soils through compost, manure and organic matter inputs, and reducing soil carbon losses as described in previous pages can all contribute to this reduction in fertilisers. Across 6 conventional coffee farms in Costa Rica, NPK fertiliser application ranged from 600-3300kg per hectare per year (Häger 2012).

REDUCE OTHER ON-FARM EMISSIONS

Fermentation of coffee in water (wet processing) is associated with higher carbon emissions than dry processing. If feasible, changing from wet to dry processing can reduce emissions. Machinery used on farms are also a source of emissions, including from processing machinery (e.g. for de-pulping), farm vehicles, small equipment such as chainsaws and grass mowers. Fuel use efficiency and use of manual techniques where appropriate can reduce emissions from equipment.

It may also be possible to reduce farm emissions by using low-emissions building materials. For example, wood is a renewable resource that stores carbon, whereas concrete is associated with high carbon emissions. As an example, production of low-strength concrete blocks can emit approximately 60g CO2 equivalent per kg of concrete, and reinforced concrete including steel approximately 200g CO2 equivalent per kg (Barcelo *et al* 2014).

	Emissions for different regions at production plant gate (kg CO2eq./ton product)				
Product	Europe	Russia	USA	China	Avg.
Ammonium nitrate	1180	2850	2520	3470	2505
NPK 15-15-15	730	1400	1270	1730	1283
Triple superphosphate	180	250	190	260	220
Muriate of potash	230	230	230	230	230
OBS. Production at plant gate means that transport to the point of application on the farm and other associated emissions are not included. Source: Brentrup, Hoxha & Christensen (2016).					

PRODUCE COMPOST EFFICIENTLY

Compost application on the farm has many benefits for carbon sequestration, farm productivity and resilience. But compost production is also associated with potential challenges from water and air pollution. The microbial activity essential to composting emits both carbon dioxide and methane. Composting processes should aim to efficiently decompose organic materials into stable organic matter and nutrients, while minimising carbon losses through carbon dioxide and methane emissions (as well as other pollutants such as Nitrous Oxides and Nitrates).

Broadly, efficient composting depends on (A) an appropriate mix of ingredients - as shown in the table opposite; (B) good aeration of the materials throughout the process and (C) the maintenance of appropriate moisture levels throughout the process.

Rates of carbon loss will vary depending on how the compost is made. Sierra *et al* (2013) found that an average of 55% of carbon was lost across a number of conventional and vermicomposting (composting with worms) procedures. High temperatures can increase carbon losses during later phases of the composting processes, so in hot areas, produce compost in cool, shaded locations

	Emissions (kg CO_2eq./ton compost	
Composting method	Compost process only	Total emissions
Static pile, aerated	3	207
Windrow method	47	1418

*Total emissions include construction of the composting facility, sourcing composting materials and the composting process itself. Source: Pergola *et al* 2018

Material type	Percentage of total ingredients (volume)	Examples
Green	30%	Grass, fresh green leaves, fruit & vegetable scraps
Brown	40%	Straw, small branches, woodchip & sawdust
Manure	20%	Cow, chicken, horse
Conditioner	10%	Clay, mature compost, healthy soil

Basic ingredients ratio for efficient compost production.

APPENDICES

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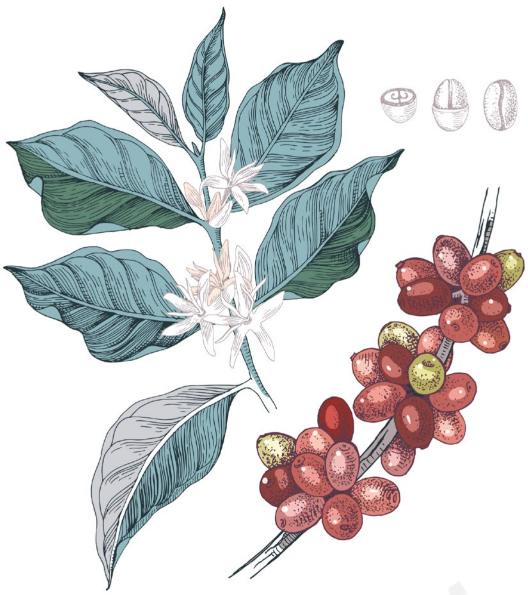

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