AGROFORESTRY: A PRIMER

Design and management principles for people and the environment

Editors
Anja Gassner and Philip Dobie

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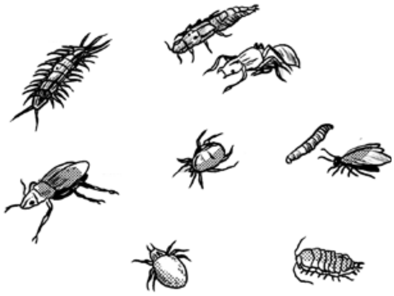

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FOREWORD

At a time when the world faces interrelated global challenges of climate change, broken food systems, widespread degradation of land and water resources, and alarming biodiversity loss, it is easy to feel overwhelmed. This book is here to help by offering practical guidance on how we can tackle these seemingly unsurmountable problems, by working with farmers to make more and better use of trees in fields, on farms and across landscapes – that is, through agroforestry.

Agroforestry tackles global challenges systemically rather than one at a time because trees can help farmers adapt to climate change while sucking carbon dioxide out of the atmosphere, provide habitat for biodiversity, regenerate soil and water resources and provide nutritionally important food and other high value products that boost farm income. Put simply, trees on farms are an investment in ecological infrastructure. Their deep root systems, elevated leafy canopies and longevity add functional diversity to farming systems that make them more resilient to climate change effects, like increasingly frequent and severe floods and droughts.

The beauty of this book is that rather than offering a few prescriptive technologies for farmers to adopt, it sets out principles, that when followed, can support farmers and communities in driving their own local innovation.

The first principle is to start with farmers. To recognise their knowledge, their needs and wants, and their capacities and then to codesign agroforestry practices that match local circumstances. This is important because farmers differ from one another and so need different solutions that suit their context. This leads quickly onto the importance of the second principle of agroforestry co-design: aptness to people, place and purpose.

Agroforestry is not 'a' solution to local and global challenges, it is a basket of options with different tree species, cropping and livestock management practices that can deliver production and environmental benefits tailored to local conditions and changing priorities. It is not always easy to select appropriate tree species and management practices, but it is worth putting a lot of effort into doing this, precisely because trees are long lived components of farming systems. This highlights the importance of the third principle: synergy.

It is synergistic effects that confound the impact of global challenges. For example, the combined effect of climate change and agricultural intensification is reducing insect abundance and diversity, including pollinators that are, in turn, important for crop production, precipitating a downward spiral.

Farming and food systems are complex, involving interactions amongst many ecological and socio-economic components. Because trees add functional diversity to farms, they increase the potential to manage interactions to achieve positive outcomes. Their extensive root systems may enhance nutrient recycling, associations with soil microbes lead to biological nitrogen fixation reducing the need to purchase inorganic fertiliser, they shade crops and livestock reducing heat stress, promote groundwater recharge by increasing infiltration and penetration of water, as well as protecting against soil erosion. Well-managed trees in agricultural landscapes may enhance natural pest control, reducing the need for use of environmentally damaging pesticides as well as storing carbon in soil, vegetation and durable wood products. Trees are also important social and cultural components of landscapes, interacting with land tenure and having variable access and uses, depending on people's gender and ethnicity.

It is clear that integrating trees within farming practice can have positive outcomes. The difficulty is that with so many different tree species and management options, agroforestry is knowledge intensive. And that is why this book is so important. It sets out in simple language, concrete steps for applying the principles of codesign of agroforestry solutions and provides well-illustrated case studies of how this has played out in various crop and livestock systems across different regions of the world. It covers both successes and failures, so that we can all learn from the experiences that these expert authors bring together in this landmark publication.

I encourage people to not only read this book but to take it into the field and use it to guide action. Whether you are a farmer, an extension worker, a policy maker or someone interested in promoting equitable and sustainable agriculture, there will be much within these pages to enhance your understanding of agroforestry and how to put it into practice.

Fergus Sinclair
Chief Scientist, CIFOR-ICRAF

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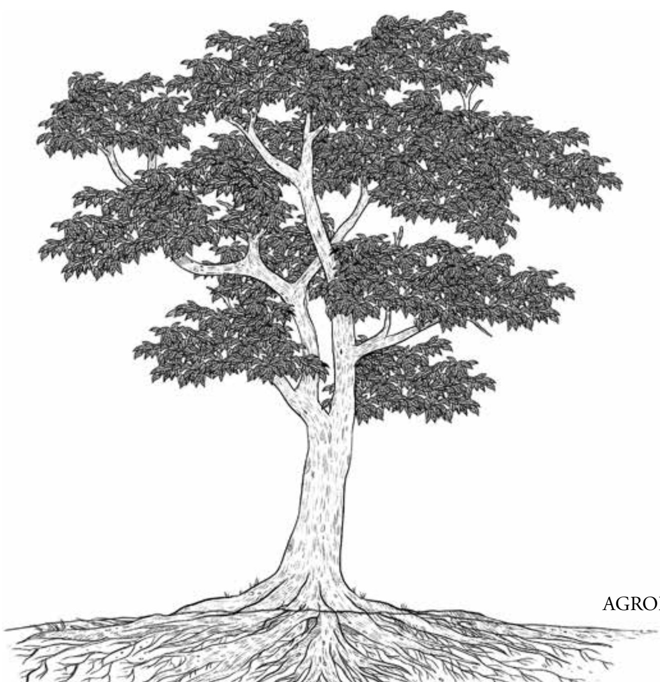
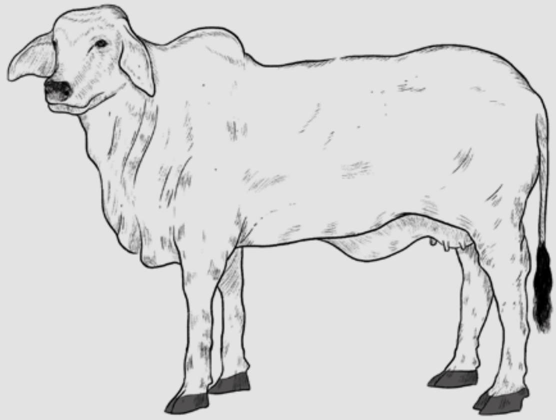


1

INTRODUCTION



Why agroforestry?

Conventional agriculture is very productive. But high productivity comes at a cost: soil that is depleted or eroded, watercourses that are polluted or drying up, and a food system that produces 20–40% of greenhouse gas emissions. Many people now agree that we urgently need to transform the food system, including agriculture. Agroforestry, as a nature-based approach to production and land use, will play an important role in this transformation.

Agroforestry is land use that combines trees with crops, trees with livestock, or trees with both crops and livestock. This mix of components creates an **agroforestry system** in which the components interact in a beneficial manner, improving agriculture in many ways; for example, by improving farm yields, increasing farm incomes, and contributing to soil and water conservation. Agroforestry is a form of 'trees-on-farms' (see Box 1).

Box 1. Agroforestry and trees-on-farms

We use the term 'agroforestry' to mean the use of trees in combination with crops, livestock, or both crops and livestock on the same area of land. Other ways of using trees-on-farms are also common: for example, woodlots; fruit trees planted next to a homestead; riparian buffer strips; and patches of natural forest. Some authors include these and other forms of trees-on-farms within a wider, '**landscape**' concept of agroforestry.

Trees on private farmland are an important part of global tree cover: 45% of the world's farms have more than 10% tree cover. Global carbon storage on agricultural land has been estimated at 45.3 billion metric tons, of which trees contribute more than 75%.[1] These figures exclude large areas of agroforestry on land usually classified as forest.

Trees-on-farms, including all types of agroforestry, have many different functions. They provide habitat that increases the biological diversity of agricultural land, including soil biodiversity and **agrobiodiversity**. They enhance the viability of protected areas by making it easier for animals, pollen and seeds to move between them. They contribute to nature-based solutions to conservation and food production challenges, despite being invisible in most countries' current 'green growth' strategies. Crucially, they supply useful and profitable goods and services to farmers and the community-at-large, including timber and fuelwood; improvement of soil fertility; water regulation; fruit, nuts, and edible leaves; and livestock fodder.

[1] Zomer RJ, Bossio DA, Trabucco A, Noordwijk M, Xu J. 2022. Global carbon sequestration potential of agroforestry and increased tree cover on agricultural land. *Circular Agricultural Systems* 2:3. https://doi.org/10.48130/CAS-2022-0003.

Conventional farming is often based on the production of a single crop. Agroforestry also often focuses on a single **flagship species** (which may be a tree species), but adds (other) trees to the system too. There are many ways in which trees can be incorporated. For example, a farmer may grow a cereal or vegetable crop combined with widely spaced trees. Or, the farmer might plant timber trees around the farm perimeter or along a watercourse. Agroforestry systems range from simple – such as one crop species and one tree species – to complex, with various crops species, tree species and livestock all meeting different needs.

Agroforestry is not new. Farmers have practised it for thousands of years, and scientists have recognized it since the 1970s as a productive and ecologically sustainable form of agriculture and land use. But now agroforestry is suddenly at centre stage. It is promoted as a land-use strategy to support **climate change mitigation** and **climate change adaptation**, biodiversity conservation, sustainable agriculture and other goals. Many organizations recommend or use it as a tool for restoring ecosystems, not only agricultural ones, but also forest landscapes.

Why another agroforestry publication?

Although not a cure-all, agroforestry has great potential to contribute to all the goals mentioned above. However, agroforestry is not just a matter of adding trees to farms. To realize its potential, practitioners need to understand its principles. *Agroforestry: A primer* is a guide to agroforestry principles and concepts, and how to use them effectively.

We took this approach partly because high-quality 'how-to' manuals and guides are already available – not just those with 'agroforestry' in their titles, but many too from the fields of forestry, horticulture and social sciences. More importantly, though, our approach reflects two basic needs.

1 First, it is important to avoid the preconceived '**technological package**' approach that can come from too much reliance on a specific manual. Instead, agroforestry practitioners and those supporting them need to understand how to use principles and concepts to design and adapt practices to their local conditions.

2 Second, it is critical to ensure that the aspirations, capabilities and dreams of farming families are central to the design and promotion of agroforestry. Agroforestry must support not only environmental goals, but also – and most importantly – rural people's goals and aspirations for better lives. Farmers rarely have the luxury of investing their time or their land in activities that do not give them direct, tangible benefits. The trees must contribute to food or nutritional security, or generate income.

Payments for **ecosystem services**, such as carbon credits, are usually of low value and are insufficient to persuade smallholders to plant and manage trees. Trees can be an important instrument to restore and maintain biodiversity and ecosystem services on farmland, but they need to be planted as part of a long-term development strategy. This should include the development of tree-based enterprises and markets for tree products.

Our aim is to support practitioners as they work to realize agroforestry's full potential to contribute to the local and global challenges of the twenty-first century.

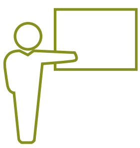
Who will find this publication useful?

This book aims to guide professionals who are supporting farmers in implementing agroforestry systems, such as:

extension workers

planners and managers

researchers



trainers

teachers and students of agroforestry

and professionals from a range of disciplines working on projects and programmes that use agroforestry. These disciplines may include agroecology, biodiversity conservation, land restoration, rural development and others, as well as agroforestry itself.

How this publication is organized

Chapters 2–7 detailing different aspects of agroforestry systems follow this introduction:

2 **Components of agroforestry systems** describes the most important attributes of four key elements of agroforestry systems: crops, livestock, trees and soil life.

3 **Agroforestry systems as circular systems** describes how agroforestry promotes soil health and conservation.

4 **Principles of agroforestry design** outlines three guiding principles that are fundamental to successful agroforestry **interventions**.

5 **Co-design and establishment of agroforestry systems** explains some important considerations in implementing design principles and translating design into practical action.

6 **Planting material in agroforestry** presents guidance on ensuring adequate quality and quantity of seed and planting stock.

7 **Management of trees in agroforestry systems** describes the main activities needed to ensure that trees interact favourably with the other components of a system.

These are followed by **chapters 8 and 9** that provide different sorts of overviews of several agroforestry systems:

8 **From principles to practice: Key systems** presents generic characteristics of several widely used agroforestry systems.

9 **Stories from the front line** uses a series of synthetic case studies to illustrate how farmers, and those that support them, can apply the principles and concepts described in the previous sections.

We recognize that farmers are diverse and include people across genders, age groups, cultures and resource levels. The messages in this book are relevant to all, and we use the term 'farmer' to cover this diversity.

The appendices include a glossary and a list of scientific and common names used in the text. Words and terms included in the glossary are written in **bold blue type**.

Key resources

We have used many sources in preparing this publication. The following have been particularly useful:

1. Tengnäs B. 1994. *Agroforestry extension manual for Kenya*. Kenya: World Agroforestry (ICRAF). http://apps.worldagroforestry.org/downloads/Publications/PDFS/B08037.pdf.
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2

COMPONENTS OF AGROFORESTRY SYSTEMS

Agroforestry systems are composed of trees and crops, trees and livestock, or trees with both crops and livestock. In this section, we explore the attributes of these components in more detail.

A given agroforestry system is often centred on one species, which we call the 'flagship species'. This is the species that the farmer considers to be the most important one – often because it contributes most strongly to their livelihood. Other components, which we call **'flotilla species'**, are added to provide **agroecological services**, such as shade, that support the flagship species. The needs of the flagship species (for example, for light or water) determine the types of flotilla species needed, even when these also produce useful goods. For example, when growing shade-intolerant crops like cereals, farmers need to select and plant trees that do not compete with the cereals for light. In many agroforestry systems, the flagship species is an annual crop, a perennial (long-lived) crop (including tree crops), or a livestock species; it can also be a timber species. Some agroforestry systems may have more than one flagship species. Flotilla species can be trees or crops.

Attributes of crops

Rice

Maize

Potato

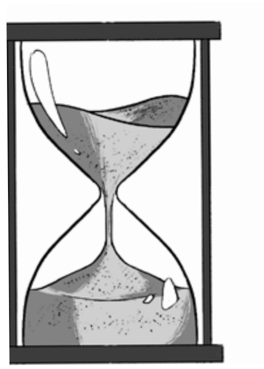
Cabbage

Soybean

Crops grown in agroforestry systems include well-known staples such as maize and rice, as well as longer-lived crops like cassava; cash crops like cacao, coffee and soybean; and crops used to feed livestock.

Lifespan

The lifespans of crops vary greatly. Many staple food crops, such as beans, maize, rice and wheat, are annuals: they germinate, grow, flower and die within a single season or year. All other plants are perennials, with lifespans that range from a few years to decades, or even centuries. Farmers shorten the lifespan of some perennial crops, such as sugarcane and cassava, when they harvest them. Lifespans are also shortened when farmers replace older, unproductive plants with new ones, such as in the replanting of coffee and cacao plantations.



Domestication

Almost all crop species have been **domesticated** to some extent: that is, farmers and plant breeders have altered their genetic characteristics by selection and breeding. In many cases, domestication has altered them so much that they no longer look like their closest wild relatives. Many **modern varieties** of staple crops need more nutrients and water than traditional varieties. Similarly, many improved varieties of coffee and cacao, which are still often grown under shade in agroforestry systems, have been selected in unshaded conditions. For both staple and cash crops, thriftier and more resilient **traditional varieties** may be more suitable to agroforestry systems than alternative, highly improved varieties.

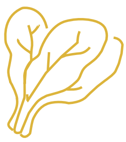
Light demand and shade tolerance

Light is one of the most important resources for plants, and limitations in its supply reduce survival and growth. Different kinds of plants have different levels of tolerance to shade, and some plants do better in shady conditions than under full sun.

Almost all major cereal crops are light demanding, so shade may reduce crop yields.

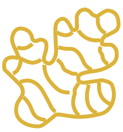
Fruit vegetables – those whose edible part is a fruit, such as cucumber, bell and chilli peppers, pumpkin and tomato – are some of the least shade-tolerant crops. When shaded, they will often fail to flower, which means they won’t produce fruit.

Root vegetables – such as taro, arrowroot, yam, beet (beetroot), carrot and potato – will grow in partially shaded areas that have less direct sunlight, but usually benefit from at least a half-day of full sun.



Leafy vegetables – such as chard, spinach and salad greens – are the most shade tolerant of all vegetables.

Cacao and coffee can be grown successfully under shade in most climatic conditions, and their quality is often improved by doing so (see **Multistrata cacao agroforestry systems in Central America and the Philippines** in Chapter 8).

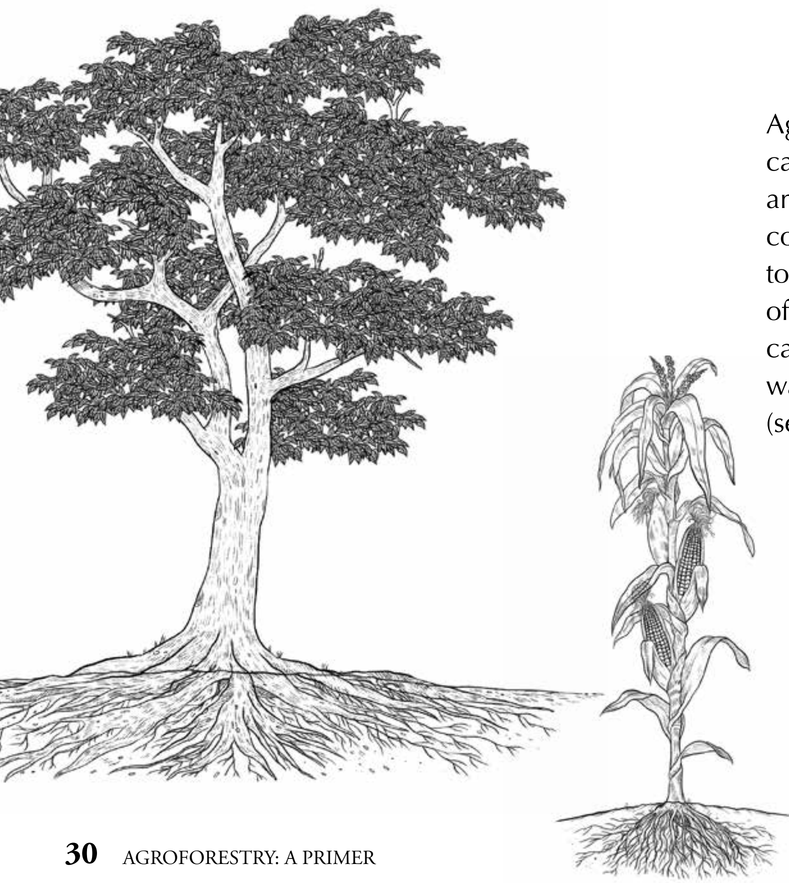


Many other crops – such as ginger, mint, parsley and turmeric – are also shade tolerant. Grass species vary in their shade tolerance, and several tropical forage legumes do well in shade.

Agroforestry systems carefully combine trees and crops to maximize their use of light. Care is taken not to grow light-demanding species in shade, while shade-tolerant species can exploit areas with lower light. Some crops, such as coffee and cacao, are often deliberately grown in the shade of trees, and thrive under those conditions.

Water needs

Crops differ greatly in their water requirements. When combined with other crops or trees, the various components may compete for water. Highly productive species that consume large amounts of water and nutrients, such as maize and other members of the grass family, can severely reduce the growth of tree seedlings. On the other hand, tree roots close to the soil surface can easily outcompete the roots of leafy vegetables.



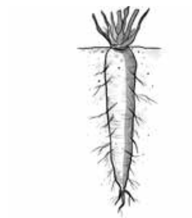
Agroforestry systems carefully combine trees and crops to avoid harmful competition for water, and to maximize the benefits of available water and the capacity of trees to access water from deep in the soil (see Chapter 3).

Root types

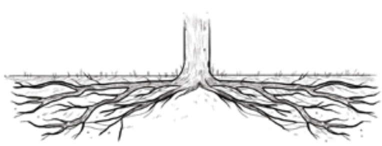
Crops demand a lot of nutrients, and their root systems are adapted to absorb readily available nutrients from the topsoil and from water. Roots can form immense structures of millions of branch roots reaching tens of metres in length. They are both the feet and the hands of the plants; anchoring plants in the soil, but also extracting the nutrients the plant needs from the soil (Figure 1).

Fibrous
(small and of uniform length, shape and thickness)

Tap
(a thick, straight, primary root that penetrates deep into the soil)



Tuberous
(thick roots that store food reserves – for example, sweet potato)



Creeping
(long roots that spread out through the shallower soil layers)

Adventitious
(emerging from stems or leaves – for example, aerial roots, which grow down from tree branches and into the soil)

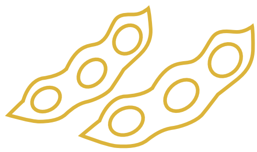
Figure 1. Some root types

Agroecological role

In agriculture, large quantities of **biomass** and nutrients are taken out of the landscape when the crop is harvested. This depletes the soil, and yields will fall unless these are replaced. Agroforestry can return important biomass and nutrients to the system (see Chapter 3, **Agroforestry systems as circular systems**).

Crops also make positive contributions to system functioning. The following are particularly important:

Crop residues are an important source of **organic matter**.



Leguminous crops increase availability of nitrogen to other system components. Other fertilizer species, such as bananas and Mexican sunflowers, can also play important roles in nutrient capture and flows.

Cover crops help to control weed competition.

Fodder crops provide nutrients and water to livestock.

The **high value** of crops often justifies weeding and cultivation activities that also benefit other system components.

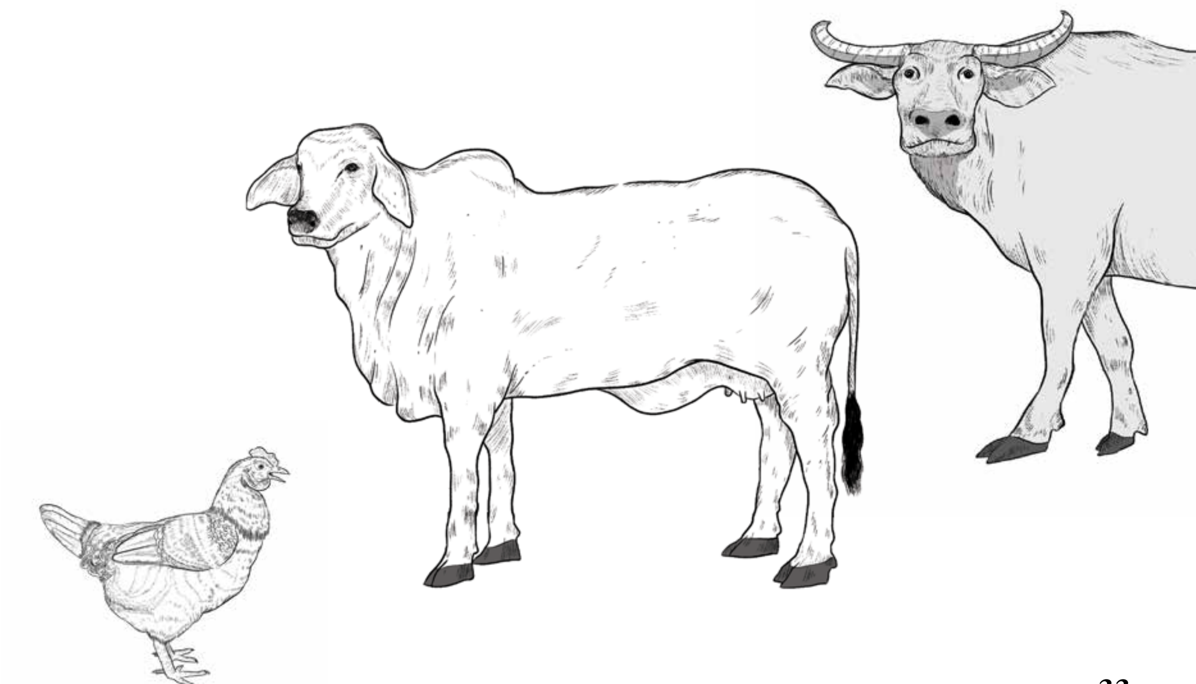
Tree crops play similar agroecological roles to those of other trees (see **Attributes of trees** in Chapter 2).

Attributes of livestock

The term 'livestock' means all domesticated animals that are kept for food and other agricultural products.

Associations between livestock and trees occur in a wide range of agroecosystems. The public often views these associations negatively – for example, when demand for cheap beefburgers leads to expansion of pastureland and to deforestation. However, livestock also interact synergistically with crops, trees and soils, and it is difficult to see how some mixed farming systems could be sustained without the contribution of livestock to household income and maintenance of soil health.

Livestock differ from other system components in several important ways. These affect both the commitment needed to manage them and the potential benefits they can bring. The most relevant characteristics are outlined below.

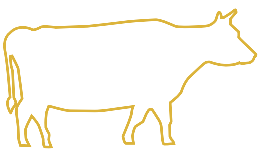


High value

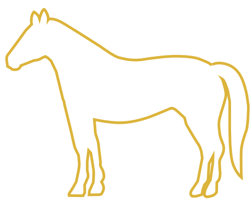
Almost all farming families in the tropics and subtropics keep livestock, ranging from a few chickens to herds of cattle. They do so because livestock offer a range of important benefits. Some of these are listed below:

Nutritional benefits:
dairy products, eggs and meat are important sources of proteins, fats and commonly deficient micronutrients such as iron.

Regular income:
from sale of eggs and dairy products is very important for covering recurring expenses, such as food, transport, ongoing medical costs or school fees.



'Banks on legs':
livestock, particularly cattle, can readily be sold to cover major expenses, such as university fees, weddings or unexpected medical costs.



Draught power:
Oxen, horses and other large ruminants can be used on farm or rented out to pull ploughs, to power low-tech machinery such as sugarcane presses, or for transport.

High needs for care and maintenance

Each animal is valuable, and a large proportion of farmers' wealth may be invested in them. Their loss or devaluation through disease, accident and death – none of which are rare – can have catastrophic consequences: livestock farming is not risk free. This risk, coupled with the animals' need for access to feed and water, means that they require regular or even constant attention. If kept in pens, or confined in other ways, their keepers must feed and water them at least once a day, while free-ranging livestock must either be guarded (for example, by shepherds) or kept within regularly checked fencing. All these activities cost time and labour. On the positive side, the regular contact allows for close monitoring of health and reproduction.

Livestock need large amounts of food and water. For example, cattle need the dry feed equivalent of 3% of their bodyweight, plus 18 litres of water for each 100 kilograms of bodyweight, every day, so a cow weighing 400 kilograms has a daily requirement of 12 kilograms of dry feed and 72 litres of water.

When – as is common – resources are limited, either seasonally or for longer periods, consumption of feed and water is likely to be determined not by such guidelines, but by what is available. This limits productivity. In such 'lean periods', livestock keepers will often concentrate on keeping animals alive and as healthy as possible until the scarcity has passed. Long periods during which feed and water availability falls significantly below these levels will pose a risk to the health and well-being of the animal.

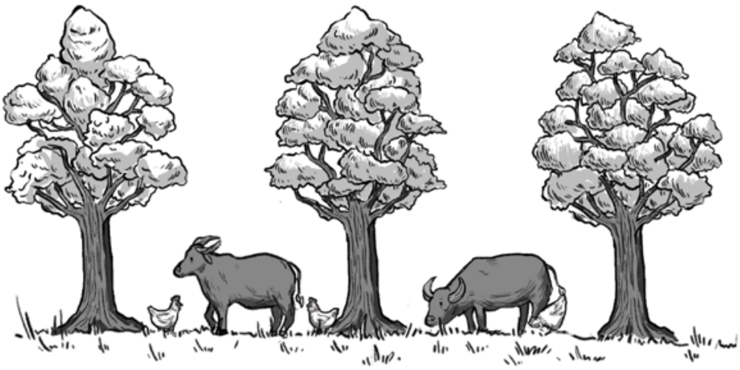
If more feed is available than what is needed for maintenance or survival, then livestock production will be proportional to the intake of balanced nutrients. Dairy livestock are a special case: they require sufficient water to support their milk output volume, irrespective of how much feed is supplied.

Mobility

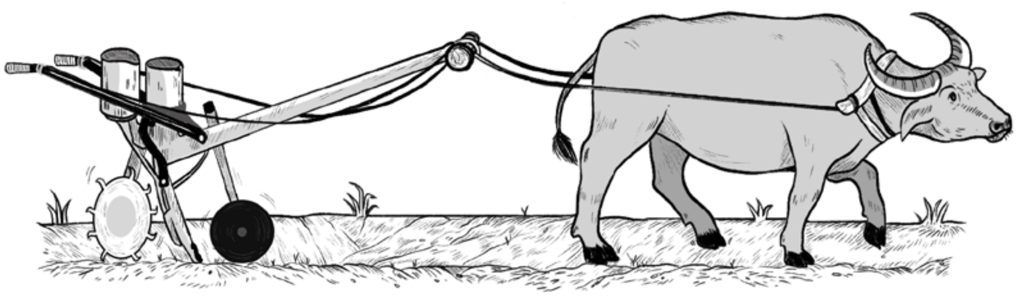
Unlike trees and crops, livestock have brains and often choose to pursue their own objectives, including going where they're not supposed to! This is one reason why they need careful oversight. But mobility also has its advantages. Unlike crops and trees, livestock are able to move to where food and water are available. This ability is useful even within a farm.

Agroecological and environmental benefits

Livestock offer both agroecological and wider environmental benefits. As part of balanced, well-managed agroecosystems, they can be highly beneficial to long-term sustainability. Some of these benefits are listed below.

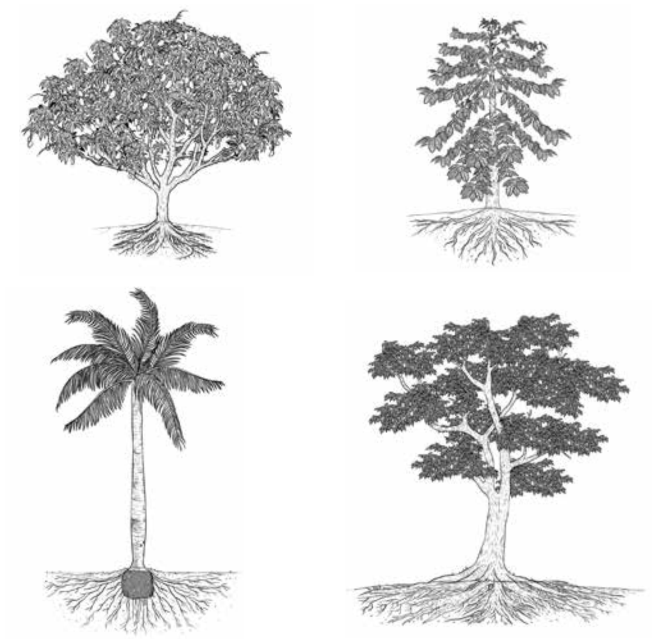


- **Livestock can make farming more efficient** by feeding on weeds or other plants that are planted as forage. Much of the nutrient content from these resources can then be recycled as manure to support other parts of the agroecosystem. Livestock waste (urine as well as manure) is a valuable resource for soil amendment, fuel and other uses.



- **Livestock can contribute to land restoration.** For example, they can provide draught power for operations that would otherwise require heavy and debilitating manual work or the use of expensive machinery. Their livelihood benefits can also act as drivers of adoption of environmental protection measures. For example, fodder plants – including trees – can be grown on contour banks, water diversion banks and other soil and water conservation structures to provide livestock with feed.

Attributes of trees



The role of trees

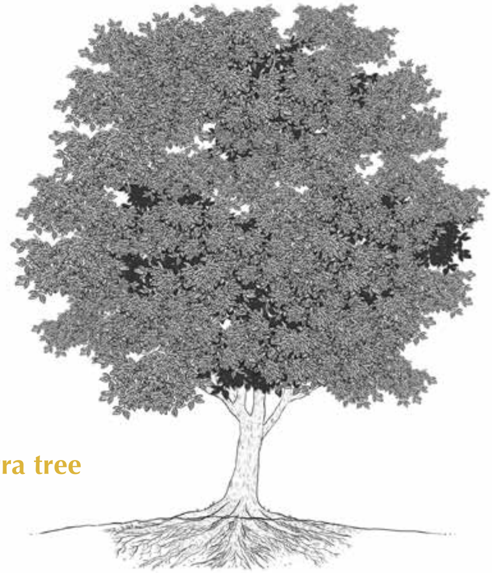
All agroforestry systems include trees. Flotilla tree species have two main functions:

1. They provide agroecological services to the flagship species or to the system as a whole.

2. Their products diversify the main income stream generated by the flagship species.

In selecting flotilla species, we need to consider not simply their own characteristics, including the goods and services they produce, but how well they will combine with the flagship species and other components of the agroforestry system.

In some traditional agroforestry systems, such as the damar and rubber agroforestry systems, the trees themselves are the flagship species. Some large-scale, mechanized agroforestry systems are also designed around timber trees.



Narra tree

Musizi tree

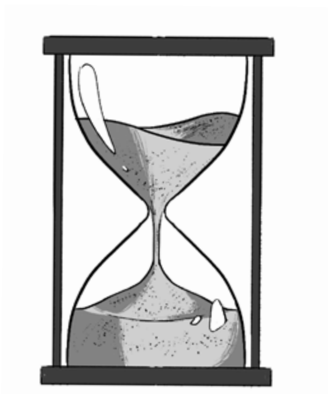
Falcata tree

Domestication

Unlike almost all crops, most trees in agroforestry systems are undomesticated. That is, they are very similar to their wild relatives.[2] Tree species are among the most genetically variable organisms on the planet. Because of this, seed sources for agroforestry trees must be chosen with care; the option of simply buying certified seed does not usually exist (see Chapter 6, **Planting material in agroforestry**).

By contrast, many fruit tree species have been domesticated and, as a result, have less genetic diversity. Clonal varieties of fruit species such as avocado and mango are an extreme, but common, case. They have no genetic variation, unless more than one variety is used.

Lifespan



The lifespans of trees vary from less than two decades to hundreds of years, but most timber or fuelwood species will be harvested long before the end of their natural lifespan. Lifespan and **rotation length** are important for two main reasons:

1. Farmers' choice of tree species is often strongly dependent on when they can expect a return.

2. Timber trees are difficult to harvest without damaging understorey crops. It is therefore better to synchronize felling with replacement (replanting) of flagship understorey species.

[2] Tree breeders have developed improved seed for some tree species. Trees of these genetically improved populations look very similar to those from unimproved or wild populations, although they may grow faster or have better form.

Crown characteristics

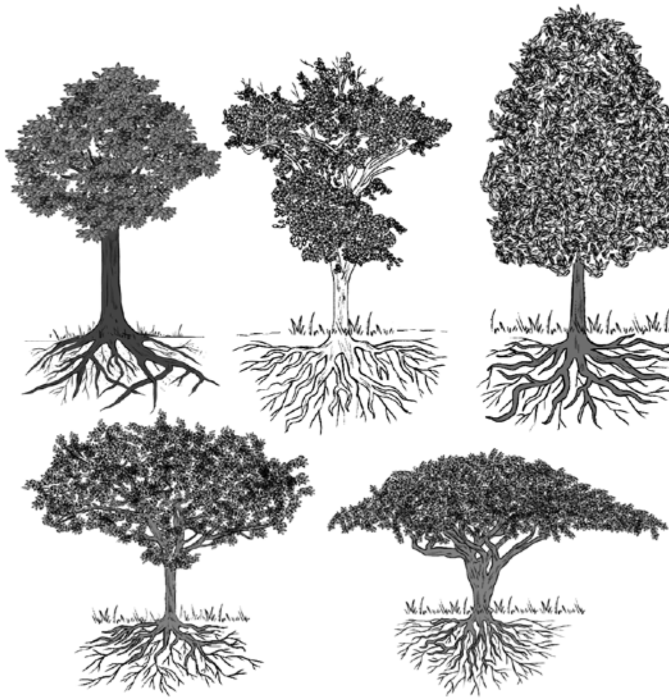


Figure 2. Variation in crown shape in tree species

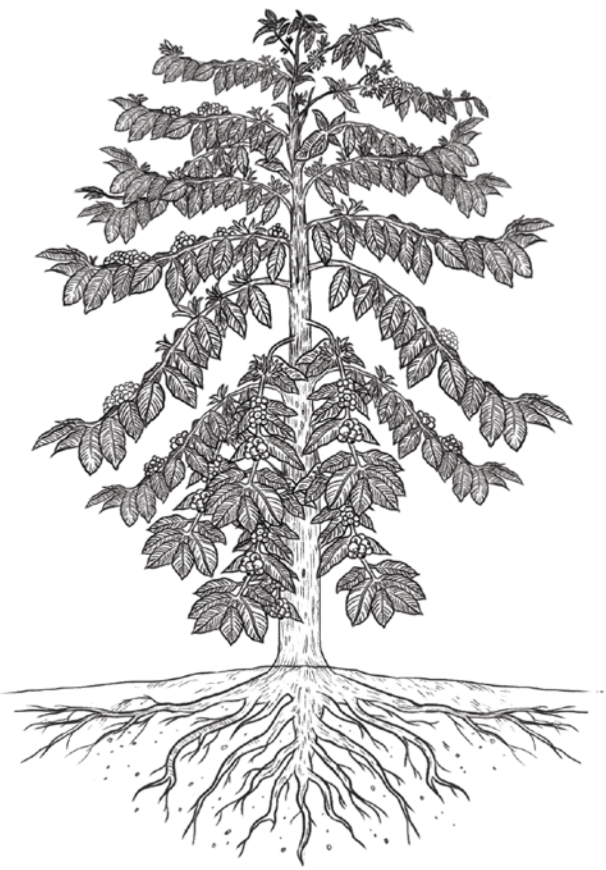
The crown of a tree consists of the live branches and leaves. The shape and density of the crown affect the amount of light reaching flagship species in agroforestry systems, and the choice of crown type and positioning of trees is critical in managing light. Tree crowns take many forms (Figure 2) but can be described simply using measures such as crown shape, size (diameter and height) and density.

Knowledge of crown characteristics of different species is needed to decide on 'the right tree'. If it is not possible to choose tree species with crown types that best suit the rest of the agroforestry system, then crown shape, size and density must be actively managed (see Chapter 7, **Management of trees in agroforestry systems).**

Deciduousness and leaf size

Whether and when a tree loses its leaves is also important: in particular, the timing and duration of leaflessness in relation to crop growth and to seasonal variations in rainfall and temperature. Some tropical tree species are leafless for extended periods at the hottest time of the year.

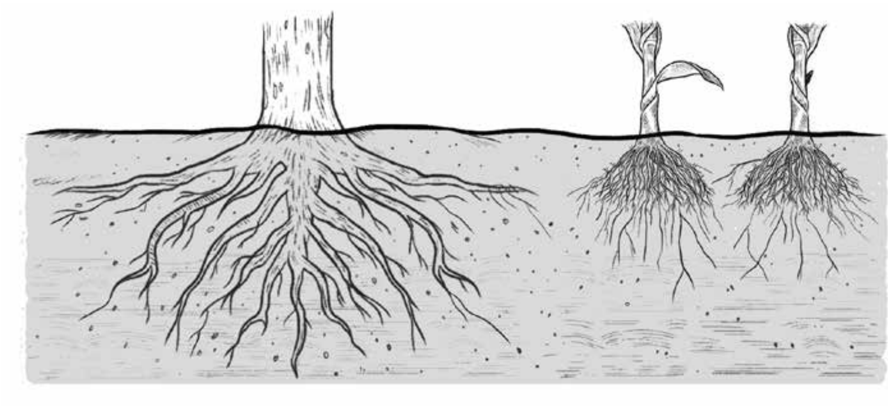
Some tree species naturally produce less shade than others. Such trees may have small leaves, or leaves that tend more to a vertical, rather than horizontal orientation.



Root characteristics

In general, trees have much larger root systems than annuals and other non-woody plants. They can extend for tens of metres – both in depth and horizontally.

However, although they often have deep roots, trees – like other plants – get most of their nutrients from soil layers near the surface, where their roots will compete with crop roots. Woody roots near the surface can also interfere with ploughing.



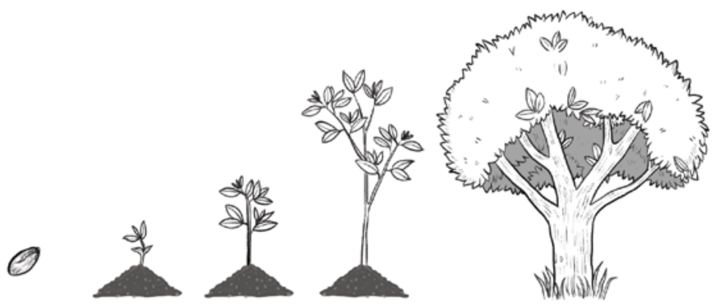
Some types of root systems combine very well with flagship species and other system components, particularly those that are deep enough to bring water and nutrients from layers that crops can't reach, and that have limited horizontal reach – and therefore compete little with crops. Although there is little scientific information about characteristics of root systems, farmers are often well aware of differences between species. This knowledge should be tapped in species selection (see Chapter 5**, Co-design and establishment of agroforestry systems**). However, local soil characteristics, such as density, structure, texture, moisture content and nutrient availability, also affect what the root system of an individual tree looks like.

Growth rate and invasiveness

In general, rapid growth of trees in agroforestry systems is an advantage. It speeds establishment of the system and reduces the time that farmers must wait for financial returns.

However, fast-growing trees use a lot of nutrients, and some species are so vigorous that they may be a poor choice for certain agroforestry systems. For example, all the commonly planted eucalypts are very fast growing, and when moisture or nutrients are not in abundant supply, they will often reduce the growth of flagship and other species. Many other species grow very quickly, but most eucalypts are adapted to survive and grow in nutrient- and water-scarce places, so they require special caution.

Fast-growing exotic species may also produce large quantities of easily spread seeds. The combination of fast growth and abundant seed enables them to invade natural vegetation and farmland, causing ecological and economic damage. Some invasive species, such as mahogany, do not grow particularly quickly. Farmers or their advisers should check candidate tree species against the **global invasive species database** before making final decisions.



Agroecological contribution

The central role of agroforestry in responding to global challenges is very much based on the agroecological contributions of trees. Some of these are outlined in Chapter 3, **Agroforestry systems as circular systems**. It is important to note that the environmental benefits of trees in agroforestry systems go beyond the scale of individual agroforestry systems, providing benefits at the scales of **landscape** (water regulation, **habitat connectivity**), region (climate regulation) and planet (climate-change mitigation).

Soil life

The soil is more than simply the earth in which plants are anchored. In a healthy agroforestry system, it should contain millions of living organisms that play vital roles in the agroecosystem. Without these, the nutrients that plants need to be healthy and productive are not available, and there is almost no biomass circulation in fields. Table 1 lists five important functional groups of soil life; organisms in the same functional group contribute to the same ecosystem function.

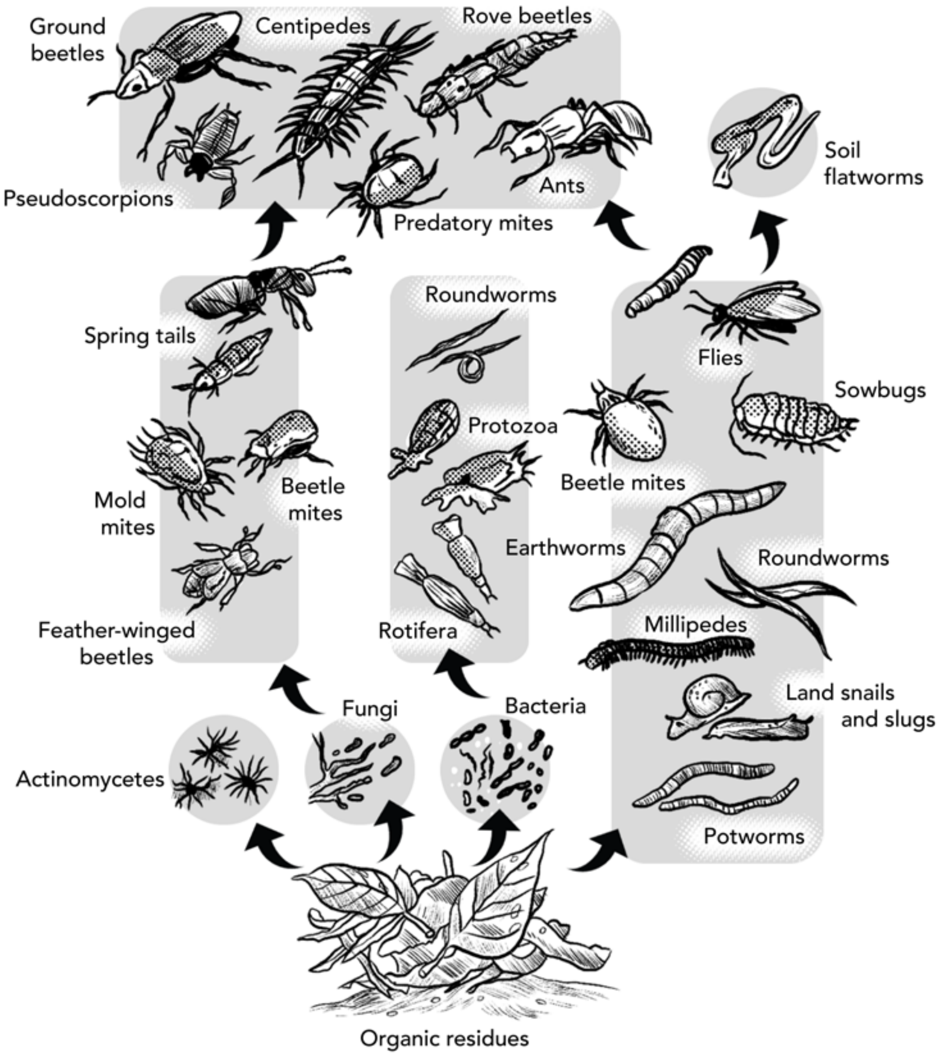
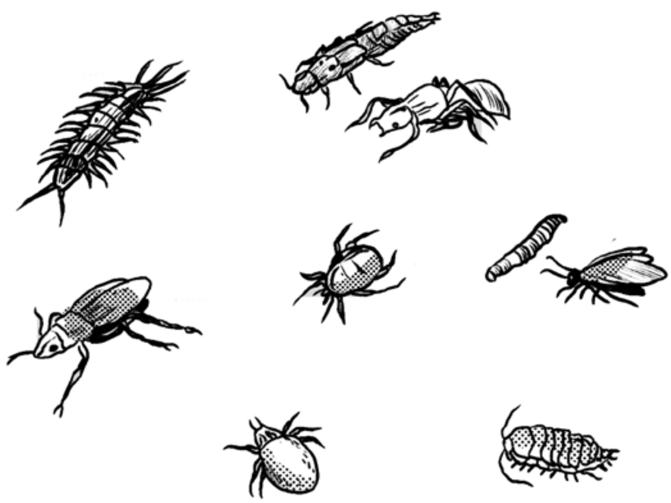


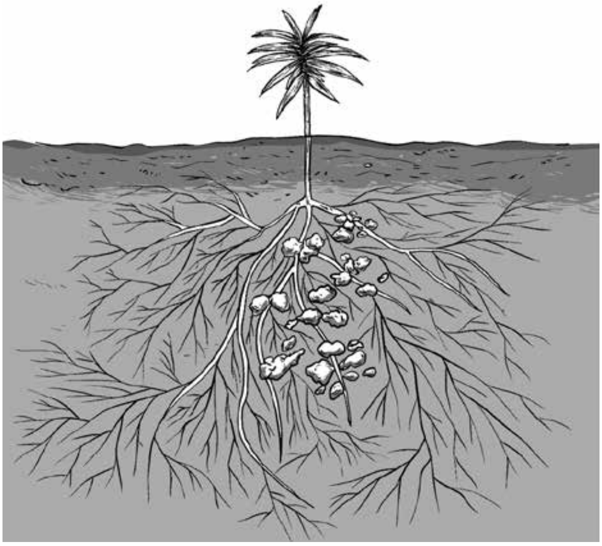
Table 1. Functional groups of soil organisms and the agroecological services they provide[a]

Functional group	Agroecological services provided
Microsymbionts	Plant nutrition and water supply Resistance to pests and diseases
Soil engineers	Soil structure (regulation and maintenance)
Decomposers	Decomposition Formation of soil organic matter
Elemental transformers	Nutrient supply

[a] Based on Swift et al. 2004. Table 1: Relationship between key functional groups of organisms, the ecosystem level functions they perform and the ecosystem goods and services they provide. *In* Biodiversity and ecosystem services in agricultural landscapes – Are we asking the right questions? *Agriculture Ecosystems & Environment*. 104(1):132.



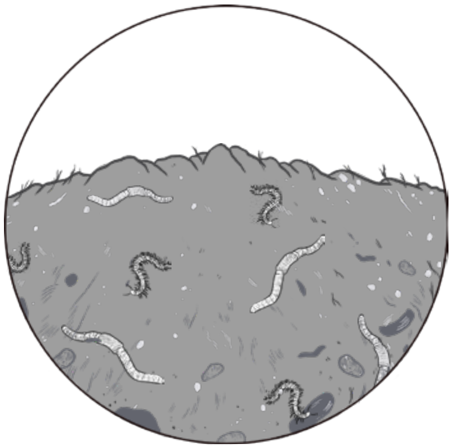
Microsymbionts



Microsymbionts include mycorrhizal fungi and nitrogen-fixing bacteria. Their importance is difficult to exaggerate. Roots are not 'just roots'; in most species they form close, mutually beneficial relationships called 'mycorrhizae' with certain types of fungi. These mycorrhizal fungi greatly increase the volume of soil that plant roots reach, help to make phosphorus available to plants, improve drought tolerance, and help prevent root infections. In addition, increasing evidence suggests that nutrients can move directly between trees through mycorrhizal connections – even between trees of different species.

Nitrogen-fixing bacteria form relationships with so-called nitrogen-fixing trees (see Chapter 3, **Agroforestry systems as circular systems**). In reality, the bacteria, not the trees, are responsible for the fixation process. This is the process by which the nitrogen in the air – where most of the planet's nitrogen is found – is 'fixed' in compounds that, unlike atmospheric nitrogen, can be absorbed by plant roots. These bacteria are responsible for about two-thirds of nitrogen fixation on Earth. Before the invention of efficient methods to manufacture nitrogen fertilizer they fixed almost 100%.

Soil engineers



Soil engineers include earthworms, termites and other invertebrates. They form and maintain the structure of the soil by burrowing, transporting soil particles and transforming these particles into soil lumps of different sizes.

Decomposers and elemental transformers

Decomposition is the gradual breakdown of dead animal and plant matter. Invertebrates start the process; the end point is the release of energy, water, carbon dioxide and nutrients as a result of the activities of bacteria. Elemental transformers are bacteria that obtain energy from simple substances; they convert the complex molecules in organic matter into forms that plants can use as nutrient sources. They are important in cycling important nutrients like carbon, nitrogen and sulphur.

3

AGROFORESTRY SYSTEMS AS CIRCULAR SYSTEMS

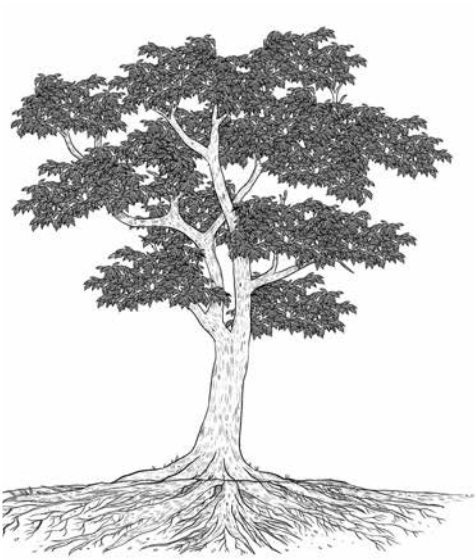
In agriculture, sustainability is often synonymous with increased efficiency of production. This implies increasing yield while reducing, or not increasing, the area of land used and consumption of water and fertilizer. Modern agriculture, which depends on the regular use of fertilizers, is a linear production process, whereby nutrients and water (agricultural inputs) are added to the system and converted into biomass, which is then exported in the form of animal or crop produce. Integrated farming systems, on the other hand, are circular systems that combine a diversity of crops, animals and trees with varying spatial and seasonal arrangements. They mimic natural water and nutrient-flow processes, with less need for artificial inputs like fertilizers, herbicides, and pesticides. In addition, agroforestry systems – one form of integrated farming system – are unmatched by other land uses in their ability to provide multiple goods and services at the same time.

To understand what these advantages are based on, it is useful to explore how agroforestry systems work. The following sections describe how agroforestry contributes to nutrient and water management, soil conservation and erosion control.

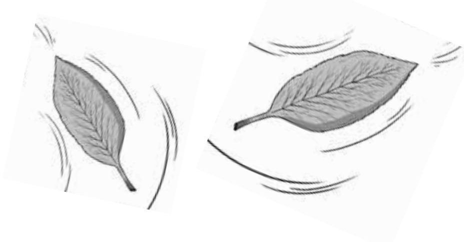
Nutrients and water

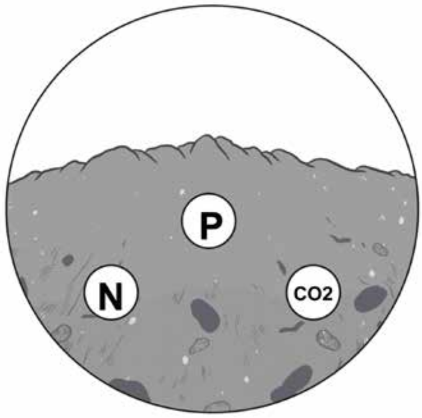
Plant nutrients are the chemical elements that make up the food that plants need to grow and thrive. These nutrients are found in the soil, and come principally from the rotting of leaves, twigs, stems and animal material; the very slow breakdown of minerals in the soil; and fertilizers applied by farmers. Soils that have low levels of nutrients are referred to as having low fertility and are not very productive.

Most soil nutrient sources are found in the upper soil layers. If the soil is in good health – with sufficient air, water and organic matter – it retains the nutrients, which can then be gradually absorbed by growing plants. If the soil is exposed, its upper layers – and the nutrients in them – can be washed away in water runoff. In poor quality soils, particularly those that are sandy textured and free draining, nutrients can also be washed rapidly into deeper soil layers, below the level of crop roots. This is called ‘leaching’.



Trees can play an important role in keeping nutrients available by preventing runoff of water and improving its retention in the soil. Their deep roots can also pull up water and nutrients from far down in the ground. Nutrients make up the ‘building blocks’ of stems and leaves, or are used by the trees in other ways. After the old leaves, stems, twigs and branches fall as litter, they rot and provide more nutrients needed by plants. Trees are therefore important nutrient-recycling ‘pumps’ that maintain good soil conditions for plant growth (Figure 3).





Nitrogen and phosphorus are two of the most important minerals for plant growth. Lack of both is one of the main reasons for resorting to artificial fertilizers, which is why effective nutrient recycling is so important. Nitrogen-fixing trees, which come mostly from the very large legume (pea) family, can substantially improve the fertility of soils, and can be used in several ways in agroforestry systems. One approach is to grow them in rows, with crops planted in between, so that the falling leaf litter directly fertilizes the soil. Young tree branches can also be cut and mixed into the soil. Sometimes 'tired' soils are left in fallow – that is, without crops – to allow trees and bushes to grow back naturally. Fallowing allows soils to recover from overuse, and nitrogen-fixing shrubs and trees, such as some leguminous species as well as alder and casuarina, can be grown on the fallows to speed up that process.

Efficient fixation of nitrogen requires a minimum level of phosphorus in the soil; fixation can be insignificant in soils that are low in phosphorus, and this is often the limiting growth factor. Animal manure is a good source of phosphorus, which is one reason why livestock are an important part of numerous agroforestry systems. Many trees provide shoots and leaves that can be fed to animals; the resulting nutrient-rich manure can then be applied to crops in the system, including by carrying manure to fields from animal pens (see **Livestock with trees** in Chapter 8).

Soil health depends not only on the presence of nutrients and water, but also on its physical quality. Farmers can maintain that quality by ensuring their soil always contains sufficient organic matter. Soils that are low in organic matter are easily washed or blown away, lose water and nutrients, and can become compacted and difficult to cultivate.

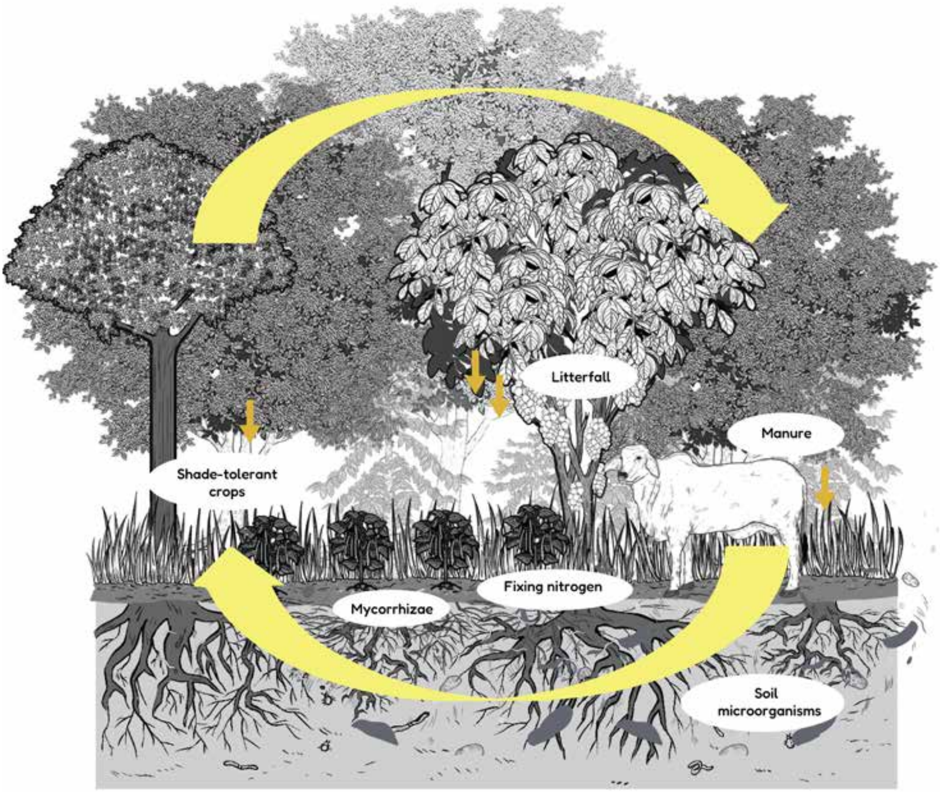


Figure 3. The nutrient cycle

Trees pull up water from the soil through their roots. Some of this water is then released into the air by a process called 'transpiration'. Water that falls as rainfall either evaporates (due to the sun's heat), infiltrates the soil, or flows as surface runoff into watercourses, ponds and lakes. The combined process of transpiration and evaporation is known as 'evapotranspiration'. It is the total amount of water that is released to the atmosphere (Figure 4). Water infiltration into the soil depends on the structure of the soil's surface and lower layers, which is strongly influenced by its organic matter content.

Trees also help to regulate temperature. Their shade reduces daytime temperatures, which can protect crops from extreme heat. At night, the tree canopy increases temperatures by trapping heat, which can prevent frost damage, but may also reduce yield. In **multistrata systems**, the shade cast by upper-storey trees cools the lower storeys, which reduces evapotranspiration and helps to keep water in the soil.[3]

Trees usually consume more water than crops; they may therefore compete with crops for water. Fortunately, crops mostly take up water from the upper soil, while trees usually have deeper-reaching roots and can access water from deeper soil layers, which can reduce competition between the two components. However, the level of potential competition varies depending on the tree species, and expert advice from farmers or professionals is needed when deciding which trees to plant with which crops.

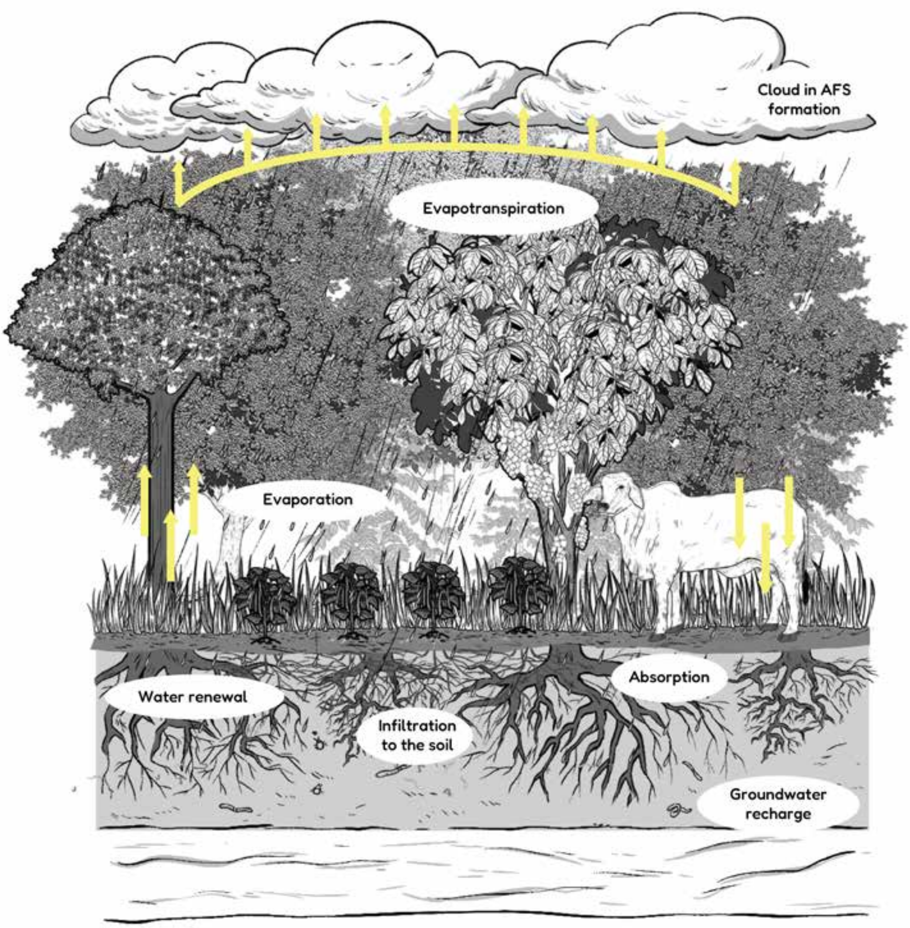


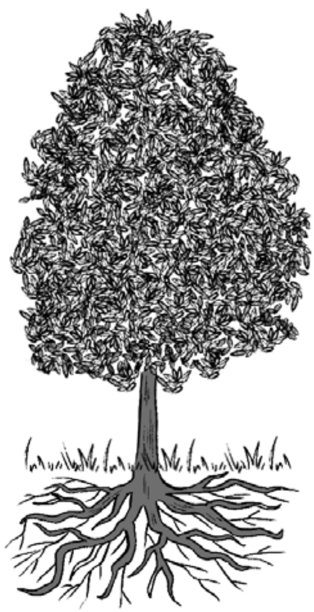
Figure 4. Water cycling in an agroforestry system

[3] For more information on this complex topic see Gosme M, Dufour L, Inurreta-Aguirre H, Dupraz C. 2016. Microclimatic effect of agroforestry on diurnal temperature cycle. Paper presented at the 3rd European Agroforestry Conference, Montpellier, 23–25 May 2016. http://www.repository.utl.pt/bitstream/10400.5/11690/1/EURAF2016%20-%20Book%20of%20Abstracts%20final.pdf.

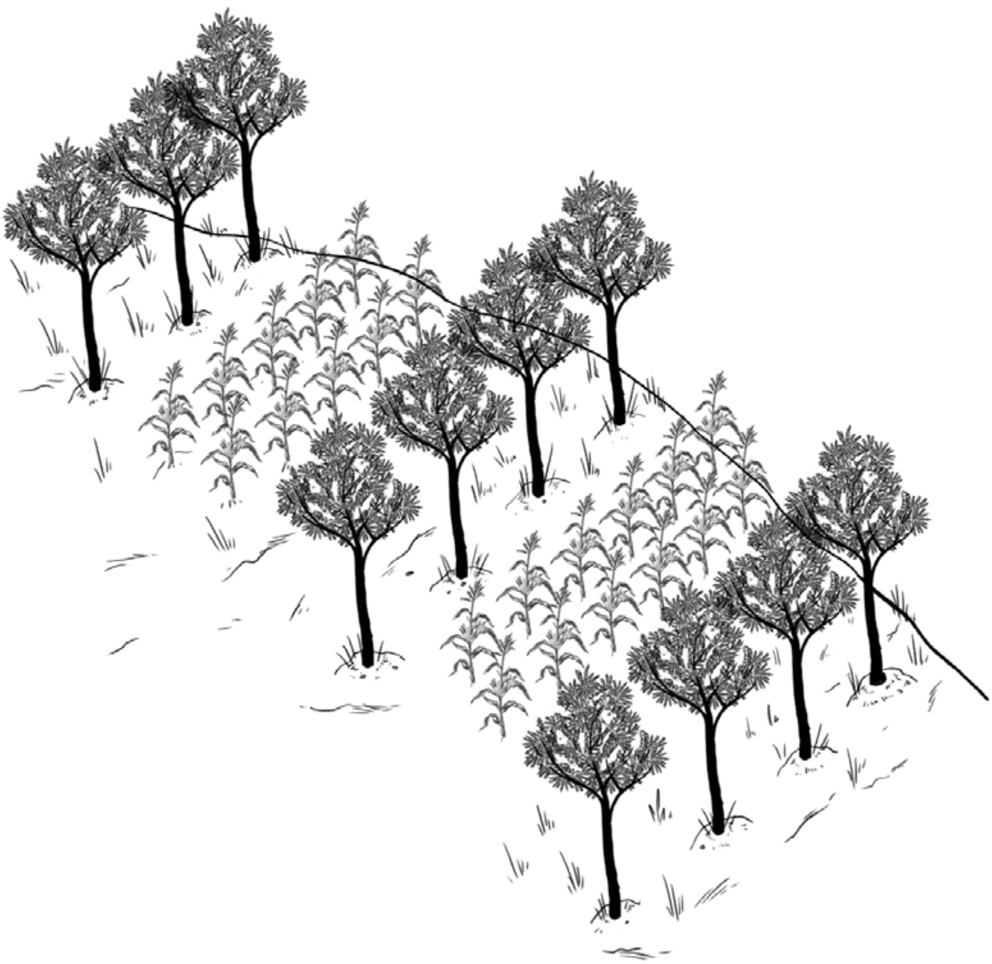
Soil conservation and erosion control

When soil is exposed by the preparation of land for crop planting, it is vulnerable to being blown away by the wind (wind erosion) or washed away by the rain (water erosion). Such soil loss can seriously reduce a farm's capacity to grow crops. The risk of erosion is particularly high in windy locations; in places where the bare soil has been exposed by removal of all vegetation; and on slopes, where rain can quickly wash the soil downhill.

The first way of preventing erosion is to ensure that the land is managed in a way that retains as much plant cover as possible (the cover approach). Then, erosion can be controlled by preventing water flow from carrying away the soil (the barrier approach). Barriers can hold water long enough for it to penetrate the soil, but if local conditions lead to an excessive build-up of water, the barriers should allow controlled runoff to minimize erosion damage and allow the water to reach natural streams and lakes.



In agroforestry systems, trees provide continuous vegetation cover, and their roots play an important role in binding the soil and protecting it from erosion. If planted on slopes, they create barriers that prevent rapid water flow.[4] Grasses like Napier and Vetiver can be planted between tree rows to make the barrier more effective, while providing food for livestock.



[4] Zomer, Robert J, Bossio DA., Trabucco A, Yuanjie Li, Gupta DC, Singh VP. 2007. *Trees and water: Smallholder agroforestry on irrigated lands in Northern India*. IWMI Research Report 122. Colombo, Sri Lanka: International Water Management Institute. 41p. https://doi.org/10.3910/2009.122.

4

PRINCIPLES OF AGROFORESTRY DESIGN

Agroforestry design involves deciding what will be produced, selecting the components of the system, and determining how they will be arranged. These decisions also define how and when the components will be established, and how they will be managed. It also includes other considerations, such as how to support the enabling environment for agroforestry.

Farmers have been designing agroforestry systems for millennia – sometimes consciously, sometimes instinctively. Professionals can support this process in several ways:

- by advising farmers who haven't managed agroforestry systems before, or farmers who are recent migrants to a given agroecological zone
- by helping to ensure that the systems meet wider goals (particularly environmental ones) in such a way that farmers' interests are not negatively affected
- by introducing farmers to new scientific knowledge
- by organizing or supporting collaborative design processes that include all relevant stakeholders.

In this section, we outline three principles of agroforestry design: farmer-centredness; aptness to people, place and purpose; and synergy. Successful agroforestry interventions follow these design principles. Interventions that ignore them have a high chance of failure.

The principle of farmer-centredness

In designing agroforestry projects and programmes, put the goals and aspirations of farming families first, before considering how you will meet other, wider goals.

Farmers' goals and aspirations

Smallholders and their families are as diverse as the land and living things under their stewardship, but they also often have characteristics and constraints in common. These may include the following:

- Very often, farming is not their sole or even their main source of income.
- Their other commitments may leave limited time to spend on their own farms.
- They tend to avoid risk because they are not wealthy enough to be able to absorb financial losses without losing the ability to satisfy basic needs.
- They tend to favour economic activities with short-term returns.
- They will not necessarily occupy their current property forever; for example, they may want to leave for the city or to acquire a more productive property.
- They may have a deep knowledge of local plants, animals, land and agriculture; on the other hand, if they have recently migrated from another region, they may have little local knowledge of their new surroundings.

These characteristics shape the goals and expectations that lead farmers to grow trees on their land. Their main motivations are to help meet their needs for food and income, and to protect the fertility and productivity of their land. Trees may also have other benefits, such as marking boundaries or establishing the household's rights over land.

Applying the principle of farmer-centredness

Many institutions promote agroforestry to support other goals – particularly environmental ones, such as biodiversity conservation, water management, climate-change mitigation or land restoration. All of these are valid goals, but they cannot override farmers' priorities. Farmers should not be 'steamrollered' by persuasive and enthusiastic professionals into installing agroforestry systems that do not meet their needs.

Rather, institutions should first ensure that their proposed interventions meet the following requirements:

They should generate income or provide useful products.

They should reduce the risks faced by farm households, such as food and nutritional insecurity, threats to land tenure and sovereignty, falling prices, droughts, pests and diseases.

Once these requirements are met, institutions can consider how to further their own goals without reducing the benefits to farmers. For example, to support biodiversity goals, a programme to install shelterbelts in pastureland might prioritize native species, especially **keystone species** – providing that these generate the same benefits to farmers as the alternatives. When these alternatives have higher establishment costs, then farmers should be compensated for the extra expense (see **Incentives** in Chapter 5).

The principle of aptness to place, people and purpose

In designing agroforestry projects and programmes, remember that 'one size fits all' does not apply: all agroforestry systems need to be customized to local conditions.

The principle of farmer-centredness guides the overall approach to the design of agroforestry systems by putting farmers' goals first. The principle of aptness is about delivering on these goals. This requires careful consideration of the specific characteristics of place, people and purpose. Such locally tailored interventions contrast starkly with 'off-the-shelf' interventions based on inflexible technical packages.

Aptness to place

All agroforestry designs must be adapted to each farm's specific agroecological conditions: a system cannot simply be transferred from one farm to the next without considering the characteristics of each farm – and each planting location within that farm. For example, although shade trees can increase the biodiversity of cacao and coffee plantations, as well as fulfilling valuable agroecological roles, the natural shadiness of the site must be considered when deciding how many shade trees to plant per hectare – which depends on which way it is facing, on the surrounding landscape and on the cloudiness of the location. Our sections **From principles to practice: Key systems** (Chapter 8) and **Stories from the front line** (Chapter 9) provide other examples of how agroforestry systems must match specific sites.

Aptness to people

The agroforestry system that is chosen must be adapted to local knowledge, the capacity of the farmer, and the availability of labour. Farmers are usually highly skilled and often have detailed knowledge of local soils, climate, indicator species, pests and diseases, and crop management. However, their knowledge is not boundless, and their skills and intuition may be limited to those crops with which they are most familiar. Also, many farmers are migrants, and they may have moved from areas that are very different to their new locations. In practice, this means either that agroforestry systems should centre on crops or products with which farmers are familiar, or that supporting agencies must provide ongoing support (extension and training), or both of the above. The more integrated the components of an agroforestry system, the more labour is generally required, especially in the first few years. For this reason, it is important to design and implement systems that are not too large to be manageable given the amount of labour that is available to the household or landowner.

Aptness to purpose

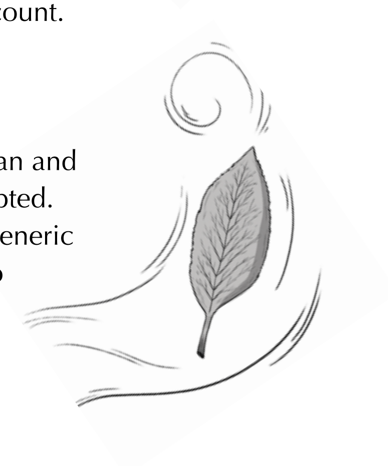
In the past, agroforestry has sometimes been promoted to farmers as a 'silver bullet' technology. In this approach, more emphasis has been placed on adoption of agroforestry itself than on specific products and species choice. By contrast, aptness to purpose means that the agroforestry design, particularly the species used and the products they yield, must correspond closely and rigorously to farmers' expectations. It is not enough for a system to be technically effective. The product or products are central, while the agroforestry system is viewed not as an end in itself but as a way of producing them.

Farmers' species preference is strongly affected by available markets. Trees take a long time to grow and to produce, and it is important to consider whether markets are likely to be similar once the product becomes available.

Feasibility

The principle of aptness incorporates the concept of feasibility. Biological, economic, legal, logistic and sociocultural constraints may make it difficult to shift from an existing farming system to agroforestry. Planners must analyse these constraints carefully and realistically, and make sure that the plans they make take them into account.

The design process (see **Design process** in Chapter 5) requires consideration of all these aspects of aptness. Together, they make up the local agroecological, human and economic context to which interventions must be adapted. Design often includes a component of adjustment of generic options (for example, multistrata cacao agroforestry) to specific local contexts.



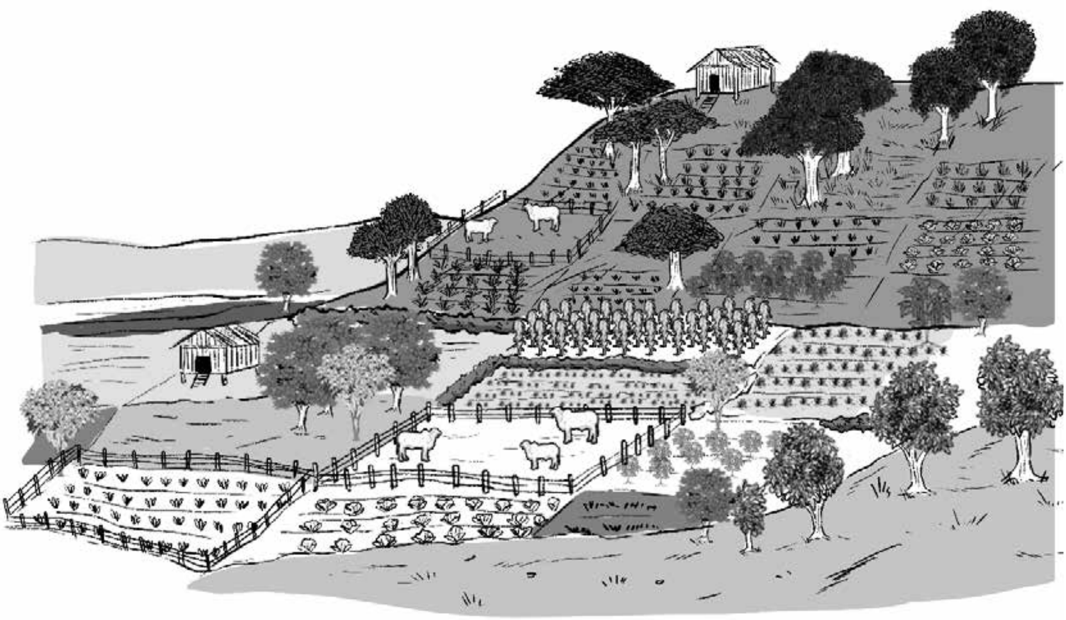
The principle of synergy

In designing agroforestry projects and programmes, harness the full potential of agroforestry by ensuring that trees, crops and livestock interact in mutually beneficial ways that sustain multiple ecosystem services.

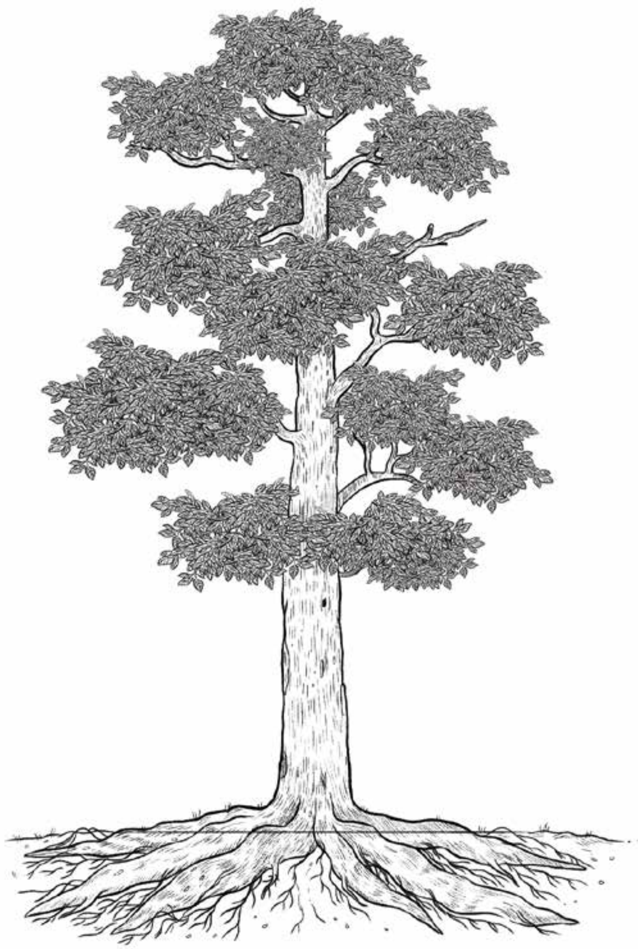
To realize the full potential of agroforestry, systems must be designed so that the components work together in a complementary way. This is referred to as 'synergy'. Basic levels of synergy can be achieved even in simple agroforestry systems in which one crop or a few crops dominate, and trees and livestock are added to provide additional products for the household, income and ecosystem services. To achieve synergy, trees, crops and livestock are arranged to make the best use of nutrients, water and energy within systems, while managing the competition for them.

Full synergy is achieved when the productivity from an agroforestry system is greater than it would be if the components were established in separate **monocultures**. These agroforestry systems are 'more than the sum of their parts'. This is usually achieved by arranging trees, crops and animals in such a way that they have maximum interaction. Competition in these systems is controlled by carefully selecting species that support each other. For example, in **successional systems**, resource sharing between different species is optimized by planting species with different life cycles, which succeed each other over time. These systems are designed to mimic the nutrient and water flows in natural ecosystems, such as forests, and minimize the need to bring fertilizer in from outside the system.

Where possible, agroforestry systems should have a high diversity of species. These not only provide a range of food and income opportunities for farmers, but also increase ecological complexity and support ecosystem services such as pollination, shade, soil fertility and biodiversity conservation. Diverse systems benefit farmers by producing food and products for sale, and improving the long-term productivity of the land – while also contributing to local and global environmental benefits.
Some plant species produce substances that reduce the germination and



growth of neighbouring plants. This is referred to as ‘allelopathy’. Trees have more apparent allelopathic effects than other plant types. Local communities usually have knowledge about which plant combinations should be avoided. If that knowledge has been lost, or local people are migrants to the area and do not have it, it is essential to consult a plant specialist before introducing new, unknown combinations.[5]



[5] The science of allelopathy is quite complex. See for example Rizvi SJH, Tahir M, Rizvi V, Kohli R, Ansari A. 1999. Allelopathic interactions in agroforestry systems. *Critical Reviews in Plant Sciences*. 18(6): 773–796. https://doi.org/10.1080/07352689991309487.

5

CO-DESIGN AND ESTABLISHMENT OF AGROFORESTRY SYSTEMS

Farmers have been designing agroforestry systems for thousands of years. They are the users and stewards of the land, and they often have a deep knowledge of the local plants, animals, the soil, weather, and the interactions between them. We use the term 'co-design' to describe the process of bringing scientific and technical expertise together with this local knowledge. It is an important step in creating agroforestry land-use systems that deliver optimal outcomes. The role of outside experts is to listen and learn from the farmer; to share their specialist knowledge, including experience they have gained from working in other regions or countries; and to facilitate the overall design process.

In this chapter, we provide guidance on:

- the kinds of information or knowledge needed to co-design agroforestry systems; and
- how to gather and use this information.

If both these components of co-design are done well, then the systems we design will reflect the principles of farmer-centrality, aptness and synergy.

What kind of knowledge is needed for co-design of agroforestry systems?

In co-designing agroforestry systems, the most important types of knowledge needed are the following:

- knowledge about the needs, aspirations and capacities of farmers and their families
- knowledge about the profitability of different agroforestry products
- knowledge about the local conditions that might affect the profitability or feasibility of such products
- knowledge about the different agroforestry systems in which selected products can be grown.

In most cases, no one person or group is the holder of all these types of knowledge. For example:

- Individual farmers know best about their own needs and aspirations.
- The local community will know about any customary limitations on land use.
- Marketing specialists may have information on current and future demand for products.
- Agroforestry specialists will know how much labour is required to manage different systems.

The information needed for agroforestry design will be different in each case. However, many of the same questions come up often. Table 2 lists the most common ones, and the most relevant knowledge holder(s) in each case. Additional specific questions to be addressed will vary from place to place.

Table 2. Core questions for agroforestry design

Question	Knowledge holders
What does the farming family want to produce on the farm, and how can trees contribute to that?	Farming family
How important is the farm for the farming family, compared to other tasks and any other work that require time away from the farm?	Farming family
Are the farmer and family members interested in planting more trees on the farm? If so, then why? (e.g., to provide better growing conditions for crops, increase fodder production, sell timber)	Farming family
What adult labour is available for maintaining any new trees that are planted on the farm?	Farming family
What previous experience does the farmer have in managing agroforestry systems?	Farmer
What is the farmer's level of technical understanding, and how willing are they to master a new system?	Farmer
What is the soil like in the parts of the farm where the farmer plans to plant more trees?	Farmer
Who is the owner of the farm? If it is not the farmer, what rights do they assert or have over the land? (Trees are a long-term investment and may be incompatible with short-term or insecure land tenure)	Farmer, technical experts
What are the main features of the climate of the area, particularly the mean annual rainfall and the length and timing of any dry season(s)?	Community, technical experts
What risks are associated with farming in the area, including pests and diseases?	Community, technical experts

Table 2. Core questions for agroforestry design *cont...*

Which farming systems and practices are used in the area?	Community, technical experts
Which crop species and varieties, livestock types and breeds, and tree species grow well in the area?	Community
Which tree species with the desired characteristics are available locally?	Farmers
Which crop species and varieties, livestock types and breeds, and tree species can be grown together?	Farmers, agroforesters
What are the most profitable agricultural products in the area?	Community
Can value chains be made to work better for farmers and other actors? (Farmers need to be connected with buyers and producers in order to sell their agroforestry products)	Community, technical experts
Does poor transport infrastructure (e.g., poor roads or absence of roads) make it difficult to get products to market?	Community, technical experts
What laws and government policies regulate production, harvesting and transport of livestock, tree and crop products?	Community, technical experts
Which species characteristics, such as biological traits, income-earning potential, and food value, would allow farmers to best address their objectives? (Several techniques are available to help participants rank their preferences for tree characteristics. It is also important to explore which characteristics are not valued)	Farmers, agroforesters
What are the main agroforestry options suitable for the area?	Farmers, community, agroforesters
What are the labour requirements of different agroforestry options, and how do they fit with households' other time and work obligations, considering the interests of families?	Community, agroforesters
How easy is it to make the transition to agroforestry? (A given agroforestry system may seem to offer what farmers are looking for, but it may be that the challenges of conversion from current land uses are too great for the system to truly be apt to people and place)	Farmers, community, agroforesters

Design process

Finding the optimal agroforestry system for a community or farmer(s) is a journey rather than a straight-line, one-way process from knowledge, through analysis, to formulation of interventions. In a participatory procedure, such a regimented approach would be problematic. The role of those facilitating the journey is to ensure that knowledge and views are sought, obtained and shared; those views are well informed; and that decisions are consensual, even when that means 'agreeing to differ'. Facilitators or extension service providers who work with farmers to develop agroforestry systems need to be:

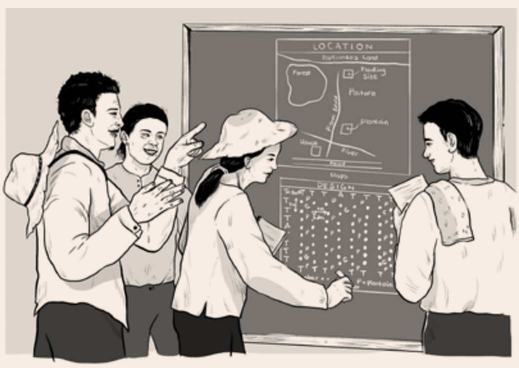
- well versed in local conditions;
- equipped with approaches to elicit information from other knowledge holders;
- receptive to local views;
- able to facilitate the sharing of information between stakeholders.

Box 2. Participatory techniques for gathering village- and household-level information of relevance to agroforestry design

Participatory mapping involves drawing maps with community members, and can help to develop common understanding. Community representatives could add to a map of their village drawn with markers on a large sheet of paper, or scratched into the earth with sticks, to show the distribution of land and social relationships, including common resources and any land-use conflicts.

Transects, also called **group walks**, can help get a sense of how people interact with their production systems and environment. A walk across the farm, combined with group discussions, can help outsiders gain valuable insights and information about the interplay between social and environmental factors.

Role-playing games: a landscape or farm can be represented simply as a board game in which participants are asked to make decisions about management. They can test out different courses of action and their potential consequences; exchange experiences, knowledge and perspectives; and build understanding about why others make particular choices. Subsequent discussion about how well the game represented reality provides further information about how players make decisions in real life.[6]



[6] A lot of useful information on participatory approaches can be found from many sources on the internet. A useful reference for this sort of game playing is Speelman EN, Rodela R, Doddema M, Ligtenberg A. 2019. Serious gaming as a tool to facilitate inclusive business: A review of untapped potential. *Current Opinion in Environmental Sustainability* 41: 31–37. https://doi.org/10.1016/j.cosust.2019.09.010.

Various approaches to participatory procedures of this sort exist (see Box 2 for examples). They need to consider local culture and society, including gendered interests and needs, as well as levels of literacy and broader education. A formal Participatory Learning and Action approach can be appropriate, but supporting agencies should select approaches they are familiar with and that they have capacity to implement.

The time needed for different approaches depends on the depth of knowledge required and the farmers' capacity. Some processes are completed in a day, while others require deep trust and involve long-term relationships between the external agents and community.

Independently of the specific methodology used, facilitators and interviewers should take care to avoid common pitfalls by adhering to the following guidelines:

- Keep in mind that a truly participatory process is not designed to deliver a particular technique to a farmer, but is rather a series of activities in which the expert and farmer learn from each other and develop interventions together.

- Be aware that interviewing farmers is not a participatory approach in itself. In a question-and-answer interview, often used in farmer surveys, many participants will give answers that they think the questioner wants – or indeed will say anything just to get rid of them!

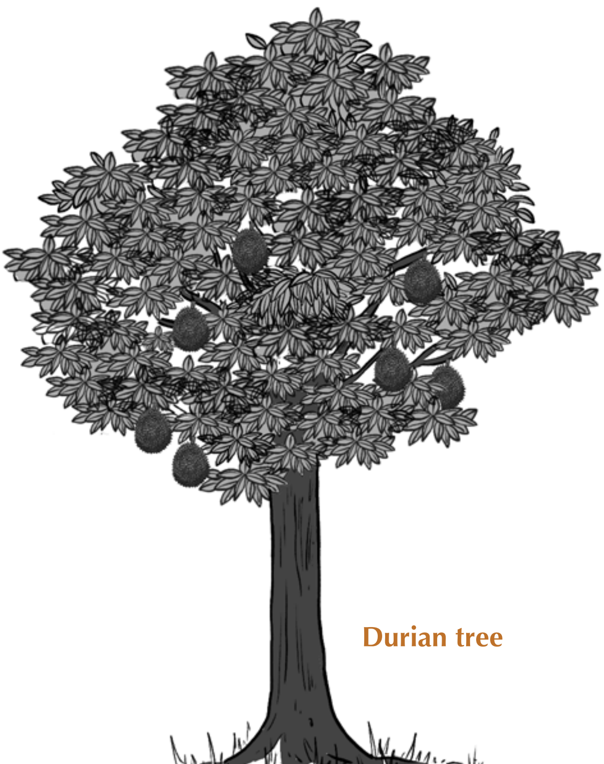
- Consider that farmers are usually not used to discussing their land-use decisions or livelihood aspirations with other people.

- Ensure engagement with those who carry out the physical tasks of farming and those who make decisions – whether these are women or men. Other community members should also be involved: in particular, youth should be included, as they may one day manage the systems.

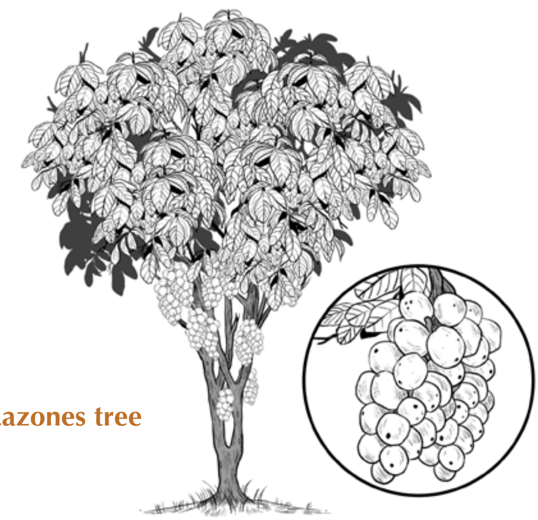
Species selection

Species selection is a particularly important part of agroforestry design because the species choice determines which goods and services will be produced by the system. The design principles of aptness and synergy are particularly important in species selection. Species should be at least compatible with each other, and preferably capable of mutually beneficial interaction, and their products should have high market potential or other uses important to the farmer.

In some cases, specific methodologies or criteria may be used in species selection – for example, the fruit tree portfolio approach (Box 3), or use of native species (Box 4).



Durian tree



Lazones tree

Box 3. Fruit tree portfolios: A targeted approach to species selection

In places where diets are heavily based on starchy staple crops, farming families – and especially women and children – are prone to debilitating nutrient deficiency diseases. The fruit tree portfolio approach to species selection responds to this problem by enabling the year-round production of fruits that are rich in vital nutrients and vitamins. It does so by taking advantage of the varying harvest times of tree fruits.

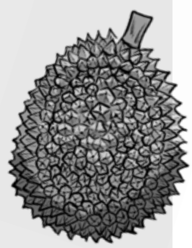
1

The first step in building a fruit tree portfolio is to determine whether a given community experiences food insecurity and serious nutrient gaps. For example, in many parts of the world, farming households experience 'lean seasons' before the main harvest, when stored household food supplies are running short.

2

The second step is to identify additional fruit tree species that can compensate for food and nutrition gaps, especially during the gap periods identified in the first step. Indigenous and underutilized tree species have an important role to play in local farm systems because they are often well adapted to the local soil and climatic conditions, and less vulnerable to variation in rainfall.

Both steps are highly participatory processes. This ensures that the portfolio responds to real needs, and that the species selected are locally available and acceptable to farming families. The portfolios can be further adapted to include other food trees – those that provide nuts, leafy vegetables, seeds and oils – and other crops such as vegetables, pulses and staples.[7]



[7] The fruit tree portfolio approach can be used with virtually any agroforestry system. It can be applied at the individual farm or community level. More details on the approach can be found in McMullin S, Njogu K, Wekesa B, Gachuiri A, Ngethe E, Stadlmayr B, Jamnadass R, Kehlenbeck K. 2019. Developing fruit tree portfolios that link agriculture more effectively with nutrition and health: A new approach for providing year-round micronutrients to smallholder farmers. *Food Security* 11: 1355–1372. https://doi.org/10.1007/s12571-019-00970-7.

Box 4. Trees and biodiversity conservation

Trees-on-farms contribute directly to the conservation of biodiversity by:

- increasing agrobiodiversity – the variety and spatial variability of animals, plants and microorganisms in an agricultural landscape
- conserving indigenous, rare or threatened tree species (in situ conservation)
- providing foraging or breeding opportunities for wild or farmland-adapted animals.

Almost all agroforestry systems lead to an increase in agrobiodiversity (the planted species and livestock), but they do not necessarily contribute to the conservation of naturally occurring species or habitat connectivity. To do so, more native trees and species – those that occur naturally in the planting zone – need to be included in the system. However, from the farmer's viewpoint, native species often have both opportunities and challenges:

Opportunities

- Native tree species are well adapted to the local soil, water and climatic conditions.
- Farmers and local markets are often familiar with the species and their products.

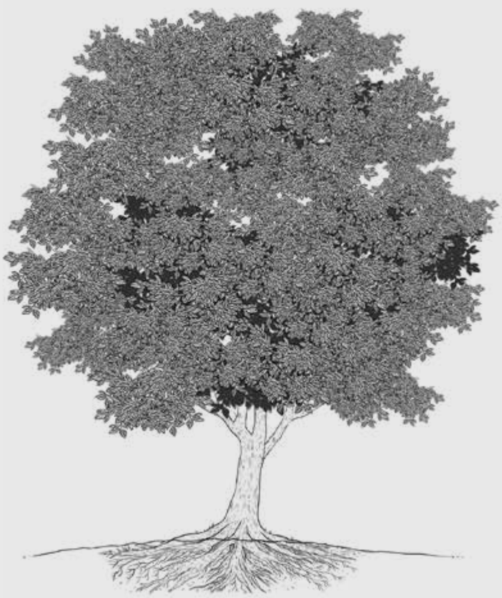
Challenges

- It may be difficult to obtain seed or plants of native species, particularly if they are rare or threatened.
- Many countries control the harvesting and transport of native tree species. These regulations, designed to protect natural forest from overexploitation, often apply (counterproductively) to planted trees on private land. The administrative procedure of applying for felling and transport licences can be complicated.

Box 4. Trees and biodiversity conservation *cont...*

- Farmers often prefer widely available exotic species due to their rapid growth and – in many cases – high demand for their products (poles, timber, fruits, etc.).
- The native species of highest biodiversity value may provide no direct benefit at all to the farmer.

If the challenges to farmers growing native species outweigh the opportunities, then governments or others interested in biodiversity conservation will need to provide appropriate incentives and remove disincentives (see **Incentives** in Chapter 5). Farmers or landowners should be considered as private sector partners in conservation, who will need to be compensated for allocating land, resources and labour. Such compensation should cover not only the planting of the tree, but also its subsequent management and protection.



From design to action: The planting plan and its implementation

Importance of the planting plan

The final stage of design is to draw up a planting plan. The planting plan is important for three reasons:

1. Its preparation provides an opportunity to document the results of the design process. This ensures that everyone involved is 'on the same page' and avoids misunderstandings.

2. The planting of agroforestry systems requires more care than the planting of conventional agricultural, horticultural or forestry plantings, because the layout – the planting locations of trees and crop plants – is more complicated than in a plantation with just one species. A plan is needed to ensure that everything goes smoothly.

3. It helps ensure that the implementation – and not just the design – takes account of the agroforestry design principles.

What needs to be in the planting plan?

The planting plan needs to cover the 'where, what, when and who' of the process. It should be a short document that everyone involved can easily understand. It may be useful to draw up a simple template. Figure 5 is an example of a planting plan prepared in this way. Whatever form the plan takes, site visits are essential, because the plan must be based on specific local conditions of soil, vegetation, aspect, and so on.

For **sequential systems**, it is important to map out the life cycle and productive lives of the different species, so that planting can be timed to avoid productivity gaps and resulting cash flow problems. These can occur between the end of one component's lifespan and the beginning of the next one's productive period.

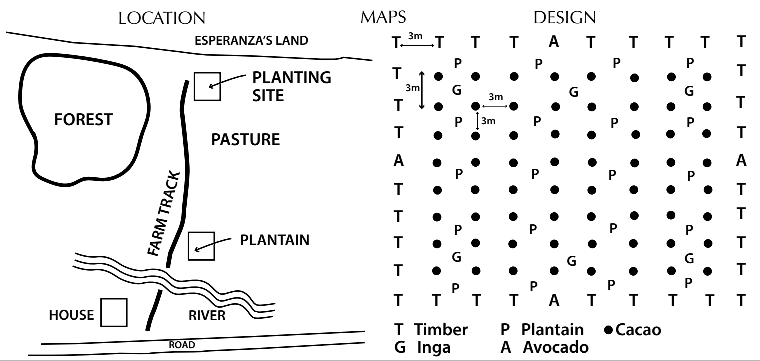
Co-design is guided by the **agroforestry principles**. However, while following these principles, wider considerations should not be neglected. Foremost among these is the safety of all concerned, particularly during establishment of agroforestry systems. Organizations involved in implementing agroforestry activities should ensure the following guidelines are adhered to:

- At the start of the establishment process, do a risk assessment to identify hazards and risks, and measures to eliminate or reduce them. 'Hazard' means the source of danger (for example, snakebite) and its potential severity (high, in the case of snakebite). 'Risk' means the probability of this happening (low, medium or high).
- Make sure that the planting plan specifies responsibilities (who does what). Consider individuals' wishes, skills and physical condition. Some tasks demand strength; others, attention to detail.
- Ensure that edged tools are sharp. Sharp tools speed up all operations and are safer if properly used.
- During establishment, follow the measures laid out in the risk management plan, including the wearing of any safety equipment.

Like agriculture and forestry, agroforestry is a relatively high-risk activity, and adhesion to safety guidelines will avoid accidents that could lead to injury or even be life threatening.

Planting Plan Description

Owner: *Nicholás Torres*	**Date of plan:** *November 2021*
Supporting organization: *Futuroverde (NGO)*	
System: *Multistrata, cacao with Inga, timber trees and avocado*	
Planned date of planting: *September 2022*	
Where:	
Description: *old shifting cultivation parcel of 0.5ha, on slope that runs up to the boundary with Esperanza Valverde's land*	



What	When	Who
Place order for 50 grafted avocado plants	*December 2021*	*Nicholás*
Arrange for help with site preparation (cleaning, marking, hole-digging) and planting of temporary shade	*February*	*Nicholás*
Place order for timber seedlings and Inga (see attached list) and 550 cacao seedlings. Check up on avocado plants	*March 2022*	*Nicholás*
Extract plantain suckers from parcel near river (225) and transport to site	*March*	*Nicholás (transport using Furturoverde's pickup)*
Ensure that all tools needed for preparation are available on site	*start of April*	*Miguel*
Clean site	*April*	*Nicholás and helpers or workers*
Mark site with guide stakes for temporary shade (plantain)	*April*	*Nicholás and helpers or workers*
Dig planting holes for plantation	*April*	*Nicholás and helpers or workers*
Plant temporary shade (plantain)	*April*	*Nicholás and helpers or workers*
Arrange for availability of grafting material (scions of fine flavour cacao varieties)	*July*	*Miguel from Futuroverde*
Clean site	*August*	*Nicholás and helpers or workers*
Dig planting holes for cacao, avocado, Inga, and timber trees	*August*	*Miguel with Nicholás and workers*
Transport all nursery plants to site	*September*	*Miguel*
Plant cacao, Inga, timber trees and avocado	*September*	*Nicholás and workers, helped by Miguel*
Grafting of fine flavour scions on cacao seedlings	*Start of dry season*	*Nicholás and Futuroverde cacao specialist*

Figure 5. A simple planting plan prepared using a template

Incentives

Farmers' main expectation from their land is for it to support their livelihoods, whether or not the farm is their main source of income. In recent years, however, wider environmental agendas have started to affect farmers. They face ever-increasing expectations from the international community and local authorities, who are looking to them to be custodians of the landscape as well as managers of productive small businesses. Sometimes – when agroforestry is both the best economic and environmental option – farmers will need little encouragement to invest in it. But if farmers are to take on additional responsibilities for the landscape, especially if this involves costs to them, then they will need incentives.

Governments who wish to promote agroforestry for livelihoods, income, conservation or restoration should put in place effective incentive systems. Incentives might be financial (such as grants, loans, tax breaks, favourable interest rates for borrowing or access to insurance), or might involve improving the enabling conditions for agroforestry (such as nurseries, high-quality planting materials or improved markets for agroforestry products). They could include schemes of payment for ecological services, or social recognition for practising skilled and responsible farming. Where farmers are expected to contribute to global goals such as combating climate change, conservation or restoration, then they have a right to expect access to global funding – either directly through projects or via carbon-financing schemes (see also Box 4: Trees and biodiversity conservation).

Removing incentives to ecologically damaging agricultural practices, and disincentives to environmentally friendly practices, is also part of the picture. Around the world, conventional high-input agriculture has been subsidized, while farmers have been penalized for harvesting or transporting indigenous trees that they have cultivated on their own land (Box 4). If farmers are to become land stewards, as many policymakers expect, then incentive structures will need to change radically.

6

PLANTING MATERIAL IN AGROFORESTRY

When farmers plant trees, they use a variety of planting material (PLM), including seed, seedlings, rooted cuttings, grafted plants and branch stakes. Planners of agroforestry interventions need to ensure that farmers can get PLM that is apt for purpose and readily available. These two requirements are linked, because insufficient supply of PLM of acceptable quality may lead to use of poor-quality material. In this chapter, we provide answers to two important questions:

- What makes PLM apt for purpose?
- How can we ensure that farmers have access to it in sufficient quantity?

In this overview, we concentrate on seedlings, particularly bagged seedlings, and seed.

Quality of planting material and aptness for purpose

PLM that is apt for purpose has two characteristics. First, after it is planted or sown it survives and grows normally. Second, it yields products in the quantity and of the quality required. These two characteristics usually go together.

Nursery plants

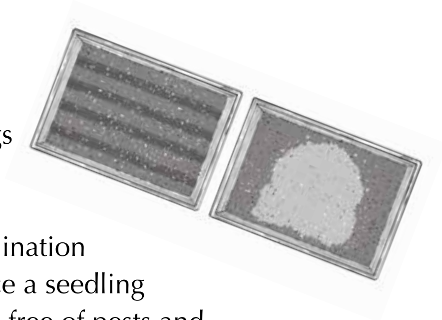
An apt-for-purpose nursery plant should have the following characteristics:

- a single stem, woody at the base and at least partially woody up to about three-quarters of its height
- dark green leaves, without any yellow patches and without signs of pests or disease
- new leaves at the tip
- roots that are not penetrating the base of the bag or other container.

Tree seedlings in containers, such as polyethylene bags, are generally ready to plant out when they are 30–40 centimetres tall, but – in some cases – farmers may have good reason to prefer larger plants. Plants need to be sturdy enough to withstand transport, handling and transplanting. The sturdiness coefficient is a useful measure of plant quality. It is calculated by dividing the plant height in centimetres by the basal diameter in millimetres. Its value should not exceed six. Farmers who regularly plant trees will learn by experience to avoid plants that are too straggly and to always plant sturdy seedlings.

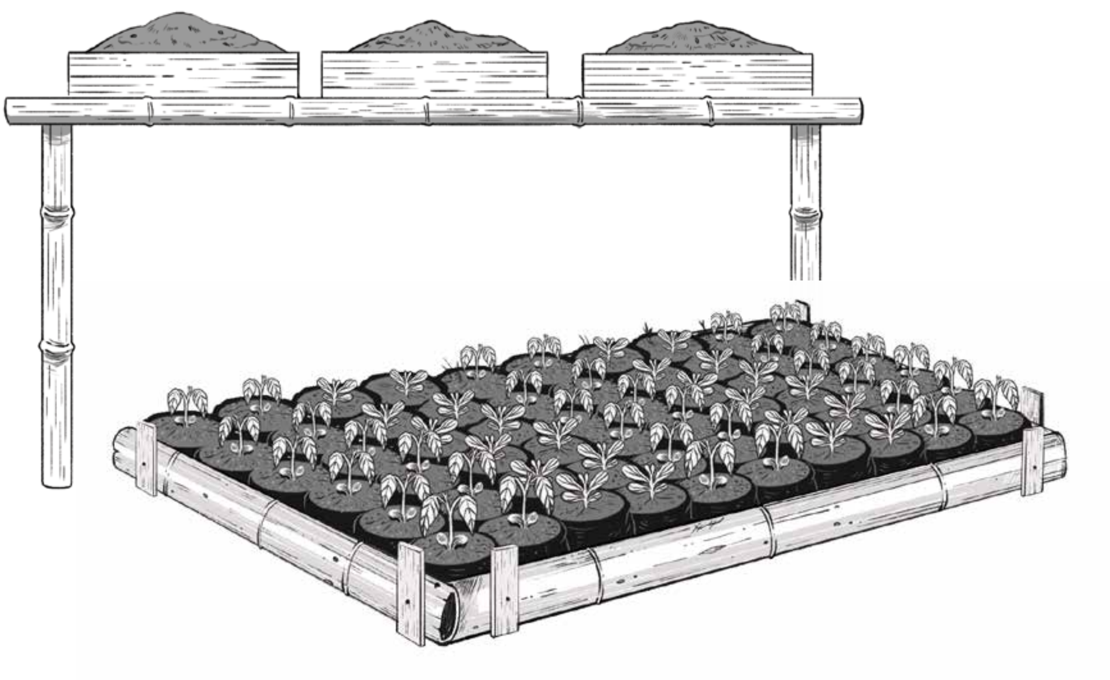
Plants can fail to be apt for purpose in various ways. Those that are too small may be smothered by weeds before the farmer has a chance to carry out the first weeding, or their root systems may be too small to withstand a snap drought after planting. Root systems can also be deformed: as a young tree grows, roots that were severely bent and twisted in the nursery usually get worse, not better, and end up strangling themselves. This leads to slow growth or death. Root spiralling, by contrast, can be corrected by pruning at the base and sides. However, it is better if farmers use plants with no defects.

Seed



Farmers and the agencies that support them use seed either to produce seedlings in a nursery, or to sow directly in the agroforestry system. To be apt for purpose, a seed must be capable of germination and, following germination, must produce a seedling that grows normally. Seed should also be free of pests and diseases that might spread to other seeds or plants. Such seed meets the requirements of the following dimensions of seed quality:

- **physical quality** (seed is undamaged, whole, within normal size ranges, clean, and free of soil, plant parts, etc.)
- **physiological quality** (seed is living and otherwise 'in full working order')
- **health** (seed is free of external and internal pests and diseases).



Genetics and aptness for purpose

PLM that meets all the requirements listed above can still fail to be apt for purpose if it is not genetically adapted to the planting site. In a nursery, it is easy to produce healthy, apparently high-quality plants that, however, are not well adapted to nearby planting sites. For example, seedlings of rainforest species can flourish in a nursery in a seasonally dry area because they are watered by the nursery staff, but they would be unlikely to survive a long dry season once planted out.

To be adapted means that the genetic makeup of the PLM equips it to withstand the range of environmental conditions that it will be subjected to when planted out. This includes variation due to climate, soil, competition and management practices. Well-adapted PLM survives and grows normally under this range of environmental conditions. Trees raised from material that is not locally adapted usually have lower growth rate; in extreme cases, poor adaptation leads to complete failure of a plantation.

'Well adapted' does not mean 'improved'. A productive agroforestry system can usually be established with unimproved PLM, **if** it is well adapted and has been produced using **best practices** – including those for seed collection. Fruit species can be an exception to this rule, for the following main reasons:

- Although an unimproved fruit tree may survive and grow well, it might not produce fruit for many years. Trees of grafted improved varieties will usually produce fruit within 2–5 years, depending on the species.

- Some markets might demand fruit of specific improved varieties, such as Hass avocado or Haden mango.

Access to planting material

Farmers have access to apt-for-purpose PLM if:

- best practices have been followed in seed collection and handling and in nursery management;
- appropriate supply systems for PLM are in place.

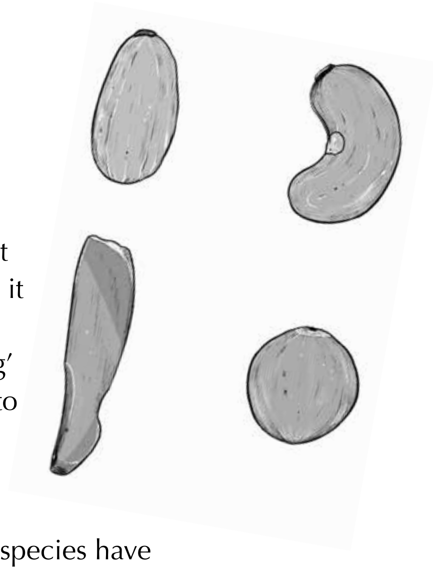
A full explanation of these conditions is outside the scope of this publication. However, we outline some important points below.

Best practices

Ensuring genetic adaptation
Plants will usually be well adapted if the seeds they were raised from were collected in an area that has a similar climate to where they will be planted. Therefore, to find out whether seedlings or seed are likely to be well adapted, it is necessary to know their provenance (where they come from). Exact information is best, but even approximate information may be enough to know whether the provenance has a similar climate to the planting zone.

Lack of genetic diversity may also lead to poor adaptation, even if the seed is local. Inbreeding depression is one problem: if a farmer collects all their seed from one tree, the resulting plants may all be healthy and well adapted, but if these interrelated trees eventually mate among themselves, then the seed they produce will be inbred, with slower growth and lower survival. A small sample (like the single tree just mentioned) is also a risky sample, as it could be highly unrepresentative, with a far-below-average genetic makeup. For this reason, seed should be sourced from at least 30 mother trees, which themselves should be part of a larger population.

For a few tree species, genetically improved seed or plants may be available. Although not usually essential, improved PLM can increase productivity, quality and profitability. However, caution is advisable, because smallholder conditions may be very different from the conditions for which the improved sources have been developed. For example, improved eucalypts developed for highly fertilized and clean-weeded pulpwood plantations in, say, southern Brazil, may not be suitable for smallholder agroforestry systems in, say, Central America. There is no point in paying a premium for plants that are not improved for the site in question.

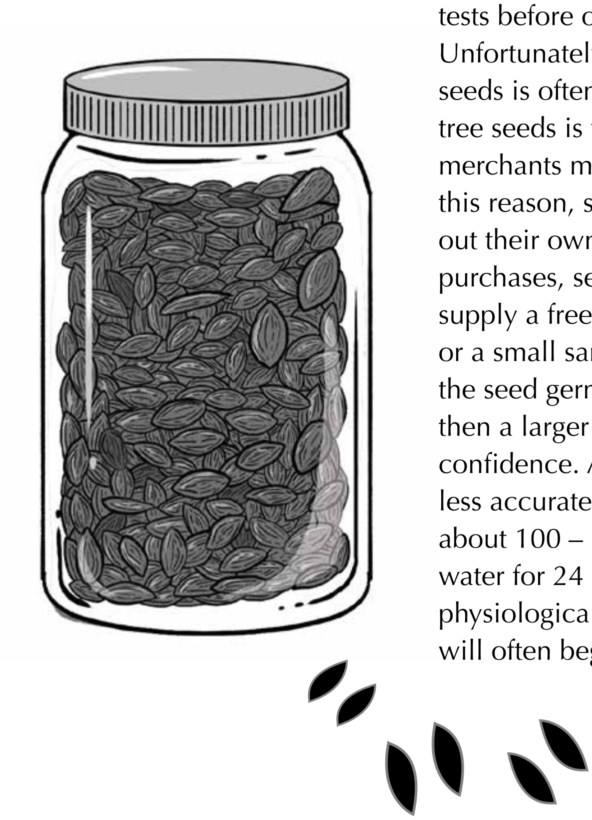


Seed handling and storage

Poor physiological and health quality have particularly serious effects on seed germination and subsequent growth. Often, these result from incorrect seed storage or other seed handling problems. If seed has not been stored in the right conditions, or has been stored for too long, then it will probably be of poor physiological or health quality. What 'the right conditions' and 'too long' mean depends on the species and, particularly, to which **seed storage category** it belongs (Box 5).

Most tropical tree species have recalcitrant seed. However, many of the commonly planted species have orthodox seed. Recalcitrant or intermediate seed should not be offered for sale if it has been stored for more than a few days – unless, in the case of intermediate seed, it is known from experience that it is likely to be viable.

The surest way to know whether seed is of good health and physiological quality is to test it. Seed merchants should carry out germination tests before offering the seed for sale. Unfortunately, while the legal sale of crop seeds is often strictly regulated, the sale of tree seeds is frequently poorly regulated, so merchants may not offer this information. For this reason, seed buyers may wish to carry out their own germination tests. For large purchases, seed merchants may be willing to supply a free sample from the same seedlot, or a small sample can be bought for testing. If the seed germinates to the buyer's satisfaction, then a larger quantity can be bought with confidence. A flotation test is a quicker but less accurate test. A sample of seed – ideally, about 100 – is placed in a container with water for 24 hours. Seed that is of high physiological quality will usually sink and will often begin to swell.



Box 5. Seed storage categories: Orthodox, recalcitrant and intermediate

Seed specialists categorize seeds by how they respond to drying. If drying is possible without killing the seed, seed can be stored for longer.

Orthodox seed can be dried so that it contains very little water. After drying, it can be stored at low temperature for many years or even decades without important decline in health or physiological quality. Orthodox seed dries out naturally before it is dispersed from the tree, but must be further dried prior to long-term storage.

Recalcitrant seed dies when it is dried. In some cases, it can be stored for short periods (days to weeks) if kept in moist conditions that stop it from drying out. Recalcitrant seed does not dry out naturally before it is dispersed from the tree. Some people use the term 'recalcitrant' loosely, to mean any seed that is difficult to germinate. This is incorrect.

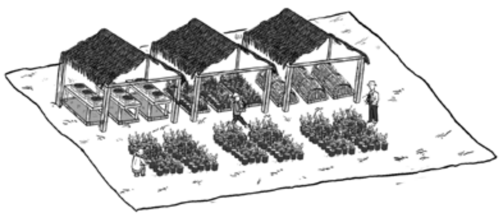
Intermediate seed is between orthodox and recalcitrant. It can be partially dried, but not as much as orthodox seed. Therefore, like recalcitrant seed, intermediate seed cannot be stored for long periods of time.

To find out what category a species belongs to, consult the databases of the international society for seed science: https://seedscisoc.org/.

Nursery practices

Many manuals describing best nursery practices are available. Some commonly neglected elements of good practice are listed below:

- Where possible, sow seed directly in the plant container, rather than in a germination bed: ‘pricking out’ is a common cause of root deformity.
- Use a soil mix with enough clay content to permit formation of a root-plug that, while not hard, remains intact during removal from the container.
- Include forest soil or humus to ensure development of mycorrhizae.
- Harden off seedlings before planting or sale by reducing watering and increasing exposure to the sun.
- Cull (throw away) poor quality seedlings, including those that are past their ‘sell-by date’ (sturdiness coefficient greater than six, or roots growing through base of container and into the soil).
- Keep records to facilitate control and to allow accurate information to be given to PLM users.

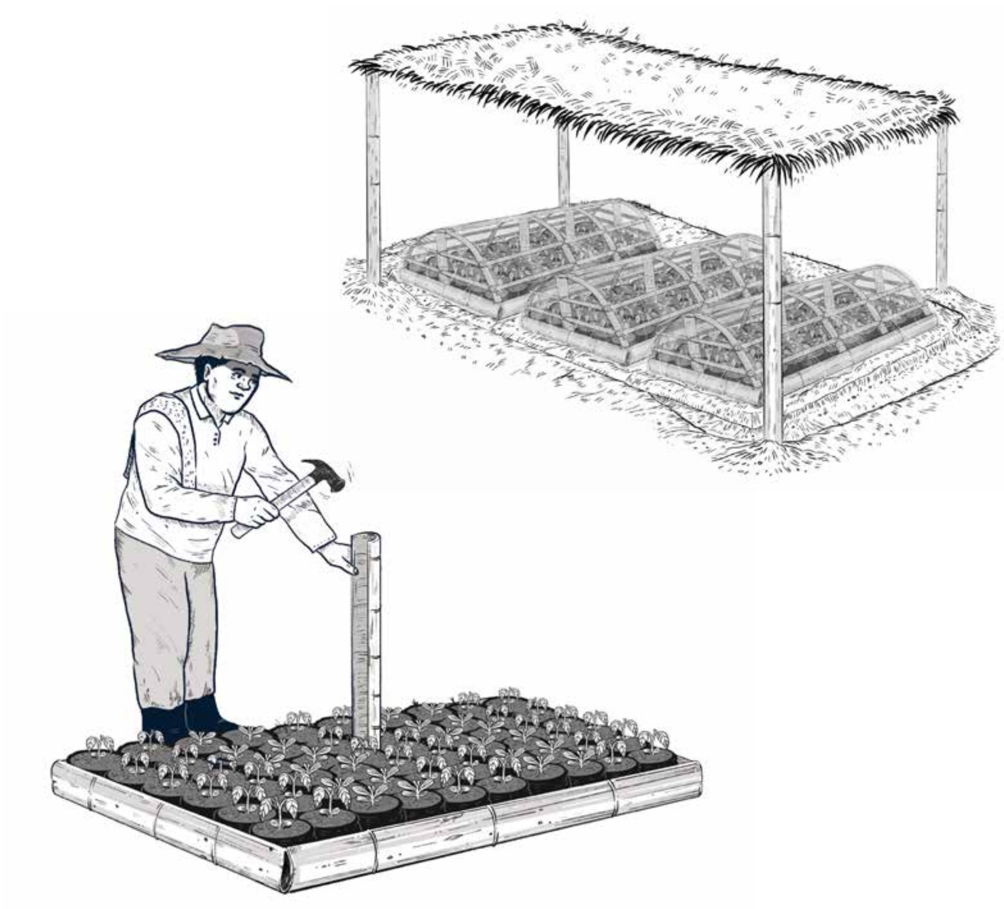


Nursery customers should be wary of nurseries that don’t follow these practices.

Use of apt-for-purpose seed in nurseries is also an aspect of best practice. In the case of physical, sanitary and physiological quality, this is a matter of economics, efficiency and feasibility (plants can’t be produced from seed that doesn’t germinate). To secure genetic adaptation, nursery operators should obtain seed from seed sources that are located nearby, in similar climatic conditions, or that prior experience (including any formal provenance testing) has shown to be adapted.

Choosing a seed merchant or nursery

Several aspects of seed and plant quality cannot be evaluated simply by inspecting seed or seedlings. For example, seed of poor physiological quality can look normal, and poor adaptation of plants and seed may not be visible until the first years of growth in the field. Faced with this problem, farmers and those who support them have two alternatives. The first is to make their own seed collections and operate their own nurseries, in both cases following best practices. The second option is to ensure that the seed merchant or nursery operator is both trustworthy and competent. Trustworthiness can be verified by talking to other clients and by first-hand experience. Competence can be checked in various ways (such as by asking about the practices followed). In the case of gaps in competence and knowledge, supporting agencies may be able to provide training. Such training benefits both producers and consumers of PLM.



Planting material supply systems

A planting material supply system consists of the institutions, installations, policies, laws and value-chain actors that control and affect the access to PLM by users. A full account of approaches to developing context-appropriate supply systems is outside the scope of this publication. However, in the following sections we outline some important concepts and describe seven broad interventions that supporting agencies can make.

Access requires two conditions to be met:

- PLM must be available: this means that apt-for-purpose seed sources of the species must exist, and nurseries must stock plants produced from the seed.
- Farmers must be able to acquire the material (usually, plants), that is, they have the resources to travel to the nursery, buy the plants, and transport them to their farms – or an agency must either support them to do this, or provide the PLM directly.

In supporting farmers' access to high-quality PLM, two perspectives must be considered. The first perspective is that of the project manager or project participant, who needs material for a specific intervention – usually, one identified in an agroforestry design process – to be carried out in a specific place in the near future. The second perspective is broader; it is concerned with the seed and nursery subsector in a specific geographical area, rather than with a specific project. Both perspectives are considered below.

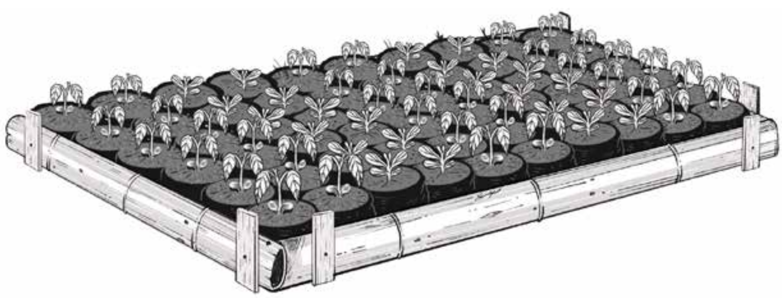
The project perspective
Selection of species should consider the availability of PLM; even if farmers express strong preference for a given species, there is no point in selecting it if no material is available within the relevant time frame – which often means at the start of a project. This time frame also means that, from the project perspective, farmers' short-term access, rather than longer-term sustainability of access or availability, is the main concern.

There are many ways in which support agencies can ensure that farmers are able to access PLM, particularly plants. One way is by distributing plants for free. Two arguments against free distribution are sometimes made:

- Farmers will not value trees that they have not paid for.
- Free distribution of PLM undermines local private sector nurseries.

1 **The first argument** is true in some cases. However, if farmers do not value trees that they have planted on their land, then the fault is with the agroforestry design process, not the farmers. If this argument matches common experience, then it is because projects often have not truly met farmers' needs or aspirations.

2 **The second argument** is stronger. Free distribution of plants in a given region will unfairly affect local nurseries' sales of plants of the same or similar species. If this results in closure of nurseries, then it will also affect longer-term sustainability of plant supply. In most cases, the solution is not to stop free distribution of plants, but rather for the distributing agency to obtain them from local nurseries, at market prices. Such agencies can also provide training to local nurseries, where needed, so that they can fulfil this role.



The broader perspective: developing PLM supply systems
It is easy to design PLM supply systems on paper. However, if these don't reflect common realities, then they will remain 'castles in the air'. These realities include the following:

- There is a need, at least in large countries, for decentralized supply of PLM.
- Regulatory personnel, who often have an agricultural background, often have no expertise in agroforestry PLM quality.
- Regulating the whole supply chain, from seed source to planting site, is complex.
- Drafting, enacting and implementing effective seed laws is difficult, particularly for seed of multiple species with different collection and storage requirements.
- Tree planters and planting material producers often lack financial resources and technical capacity.

The strategic need is to identify farmers' needs and plan how to respond to them, rather than to attempt to construct perfect systems according to preconceived criteria.

In Table 4, we provide a 'menu' of seven broad areas in which supporting agencies may help enhance farmers' access to fit-for-purpose PLM. These are guided by four principles: farmer-centredness (as for agroforestry interventions in general); self-sufficiency (where possible, supply of PLM should be financed by sale of PLM); openness to intervention when markets fail; and a 'no harm' principle that intervention should not conflict with self-sufficiency.

Table 4. Menu of intervention options to enhance planting material supply systems

Intervention	Role
1. Implement a diagnostic study to guide interventions and actions	Ensures that substantive interventions and actions are appropriate and evidence based
2. Support the design, reform and application of laws and regulations	Supports other interventions
3. Promote or establish agroforestry nurseries	Appropriate when planting stock is unavailable due to lack of nurseries
4. Support the establishment and management of seed sources	Appropriate when seed sources are lacking or when they are unproductive
5. Support nursery operators' access to fit-for-purpose seed	Appropriate when nursery operators cannot obtain seed from existing seed sources
6. Support improvements in the quantity or quality of production by existing nurseries	Appropriate when nurseries do not produce sufficient apt-for-purpose plants of the species that farmers require
7. Support farmers' access to nursery plants	Appropriate when farmers are unable to acquire the planting stock that is available in nurseries

7

MANAGEMENT OF TREES IN AGROFORESTRY SYSTEMS

Many tree establishment efforts focus entirely on the planting process, and fail to consider the years of time and effort needed to care for the planted trees and to manage their growth. It is true that the cultivation of trees usually requires less work than crop cultivation. **But trees planted on farms do require management, whatever the system, and this management can be very time consuming.** The design process must ensure that farmers are aware of the demands of management and that they consider these before deciding to establish an agroforestry system. Growing trees requires a long-term commitment, sufficient resources and sound knowledge about how trees interact with their environments, including other components of agroforestry systems. In this section, we provide an overview of how to manage trees in agroforestry systems.

Agroforestry systems differ, but broad management goals are similar

The expertise, knowledge and time needed to manage trees in agroforestry systems depend on the complexity of the system or practice. For example, farmers are likely to spend more time managing the trees in a multistrata system than those in a living fence. They will also need more knowledge and expertise for the multistrata system. In each case, however, management aims at achieving one or more of the following goals:

- System components have adequate supplies of nutrients and water.
- System components, particularly flagship species, are free of pests, diseases and other agents of damage, or are not critically affected by them.
- System components, particularly flagship species, have optimum light conditions.
- Productivity and profitability of the system are maximized.
- Trees grow to the right shape and size for their location and roles.
- Specific environmental goals, if any, are met.

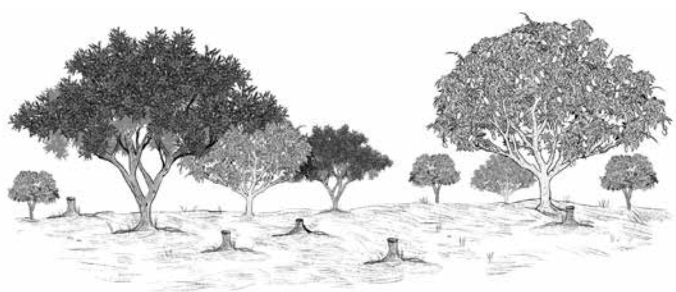
Some tree management activities resemble those used to optimize growth, health and quality in orchards or forestry plantations. Other measures are also needed because of the special characteristics of agroforestry systems.

Thinning

Thinning is the removal of individual trees. It is done by felling the trees at ground level, usually with a chainsaw. The main aim of thinning is to manage competition, particularly between trees of the same species. It increases both the productivity and quality of the remaining trees.

In conventional timber plantations, which usually have trees of one species planted at 3.0 metre or 2.5 metre square spacing, thinning is a very important management practice. By gradually removing most of the trees that were initially planted, it concentrates production on a smaller number of large-diameter, well-formed and valuable final harvest trees. In forestry, thinning is a planned activity: foresters plant many more trees than will be needed in the end, because high initial density improves stem quality, helps to control weeds, and ensures that enough high-quality individuals can be selected for the final crop. Sometimes it is also possible to sell some of the thinned trees for poles, small-scale construction material, charcoal or firewood.

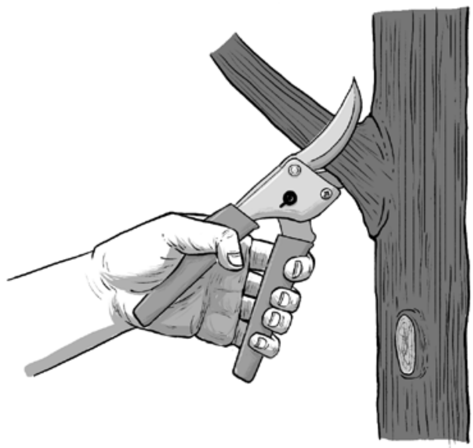
Some agroforestry systems, or parts of them, may resemble traditional timber plantations – for example, woodlots and simple successional systems such as **taungya**. In these cases, thinning practices will resemble those used in forestry. In other agroforestry systems, each tree is intended to be either a permanent component of the system, or – in systems with a successional component – to die naturally due to shade or because it has reached the end of its life cycle. In these cases, thinning is less common. Its intensity and timing will depend on each specific case.



Crown management

Crown reduction is the removal of some or all of the above-ground parts of the tree – that is, its stem or branches. Four types of crown reduction are used in agroforestry: pruning, lopping, coppicing and pollarding. Crown management also includes the decision **not** to reduce the crown when more shade is needed.

Pruning



Pruning is the agroforester's main tool for managing competition. Selective removal of branches from one tree can prevent it from overshading and crowding out another. The removal of multiple branches from the crown may be referred to as 'crown thinning'. A pruned tree is less able to capture sunlight through its leaves, reducing the amount of energy it

captures, which leads to the dieback of some roots. Thus, pruning is also an important tool to control root competition.

Pruning to regulate shade also affects microclimate, including temperature and air circulation, which have important effects on pests and diseases. Shade favours some pests and diseases, whereas others are favoured by unshaded conditions, so crown management will depend on which pathogens are of concern.

Pruning is also used to enhance the productivity, or quality of production, of the tree itself – particularly in the case of timber trees, fruit trees, cacao and coffee. When a timber tree increases in girth, its side branches remain embedded in the wood; they are visible as knots in sawn timber. Pruning of dead and living side branches improves quality by preventing the formation of knots – an essential activity in the production of high-quality timber.

However, no more than one-third of the live crown should be removed in any given year. The belief that removing nearly all the branches of a tree will concentrate growth on the main stem is mistaken; rather, the tree's height and diameter growth will slow down, because it will **photosynthesize** less. Some timber species are self pruning, and should not be pruned artificially, except when live branches of flotilla trees are interfering with flagship trees. Pruning should also be used in all woody species to remove diseased branches.

For cacao, coffee and many fruit species, highly specific pruning techniques – which are beyond the scope of this booklet – have been developed to maximize productivity and quality.

Pruning, especially for high-value tree crops, is a skill that needs training and a good understanding of the physiology of a tree, as some species have highly specific requirements. It must be carried out with care, particularly on high-value trees. The best time to prune timber trees and young fruit trees is usually at the end of the dry season, because airborne fungal spores are likely to be less frequent, and because growth will soon start again and cover pruning wounds. In the case of mature (bearing) fruit trees, pruning is usually carried out after harvest.

Lopping

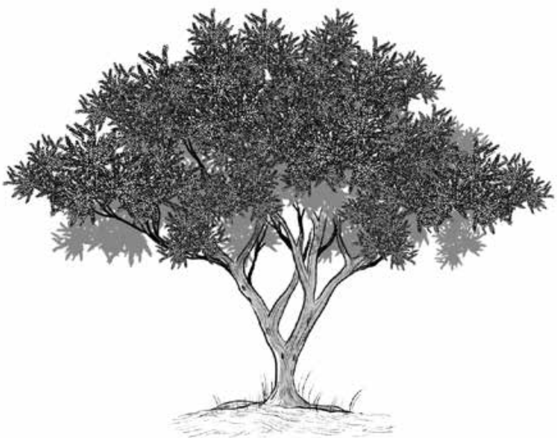
Lopping is used when a 'rough-and ready' approach to crown reduction is acceptable – for example, in pruning live fences or in some forms of **alley cropping**. Lopping may sometimes be used instead of pruning when competition for light can be reduced by removing just part of a branch, particularly when the branch base is difficult to reach.

Coppicing

Many tree species produce new shoots from their stump or roots when cut, and coppicing takes advantage of this. The shoots, once woody and large enough, are harvested for poles, rods and fuelwood. The tree component in alley cropping is also usually managed by coppicing (or lopping). Coppicing can also be used to manage trees on soil conservation structures. In these cases, development of a large crown may affect the stability of the structure. Coppicing will lead to the death of some roots, but the stability-enhancing larger roots will remain.

Pollarding

Historically, pollarding was used instead of coppicing in situations where browsing animals would otherwise have fed on coppice shoots. In agroforestry, it is important as a shade management technique, particularly in some simpler multistrata systems, such as coffee with erythrina pollards and laurel in Costa Rica.



a. acacia tree before pollarding

b. acacia tree after pollarding

Weeding

Weeding is the cutting or removal of herbaceous plants, grasses or climbers that grow near or on tree seedlings. Selective weeding targets plants that are visibly affecting the development of the seedling or the adult tree. Sometimes the negative effects of other plants are not very easily visible, but the growth rate of tree seedlings can be strongly impeded, for example by competition from grasses or other aggressive vegetation. A good standard weeding practice, especially when trees are to be established in pastures, is to 'clean weed' a circle around each seedling to a distance of 0.5 metres from the stem. To prevent erosion and drying, the bare soil should be protected by **mulching** with the uprooted plants and plant parts.

Fertilization

Fertilization is the addition of external sources of nutrients to replace those that have been lost to the system and that, as a result, are deficient. In agroforestry, the right spatial and temporal arrangement of trees, crops and livestock allows **organic matter** and nutrients to be circulated on the farm, so that the use of fertilizers can be reduced without losing yield. However, new agroforestry systems often need to be 'kick-started' with initial fertilization, and many will benefit from regular applications afterwards. In many countries, guidelines are available for fertilization of commercial agroforestry systems (for example, cacao and coffee) and fruit tree orchards.

Prunings may be used as mulch. However, woody material, particularly large branches, takes longer to decompose. To speed its decay, it should be placed in direct contact with the soil, and then covered with leaves and other non-woody parts. In some systems, plants such as bananas or plantains, Mexican sunflower and panic grass are deliberately planted to be later cut for mulch.

Some organic matter that accumulates in the fields, such as fresh animal manure or ripe fruit, can attract pests and diseases. These should be composted off-site and later added or returned to the system.

8

FROM PRINCIPLES TO PRACTICE: KEY SYSTEMS

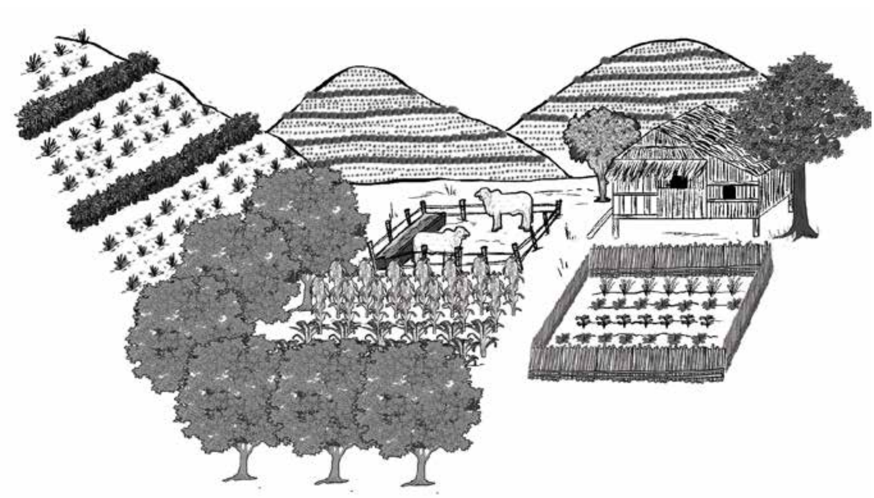
When applying the three principles of agroforestry design (farmer-centredness; aptness to place, people and purpose; and synergy), it is important to recognize that each landscape is unique and should therefore have its own unique agroforestry systems. Trees in these systems can have very different functions, ranging from being flotilla species in systems that focus on food production, to being the flagship species in systems that are designed to restore degraded forested landscapes.

This chapter describes a small selection of featured systems to illustrate the different functions of trees and the resulting design and management implications. The featured systems should not be read as blueprints for direct application, but as examples of common and robust systems that might be used in specific locations after appropriate modifications.

Annual crops with trees (ACT)

In these systems, a tree component provides ecosystem services that increase the productivity of the flagship component, an annual crop. The selected tree species often also provide useful products. Because annual crops are usually sun-loving, the design and management of these systems seek to increase the numbers of trees on the farm without creating competition for light.

ACT systems follow two main approaches. In intercropping, trees are planted among the crops. In niche planting, the trees are planted in 'niche' locations, such as farm boundaries, places with low soil fertility, riparian sections and home compounds. Niche planting is often preferred when cropping areas are very small, or when the work needed to manage competition would be out of proportion to the benefits gained from the trees.



ACT systems are most appropriate for farms that have low productivity, particularly when caused by the following factors:

- low soil fertility
- vulnerable soils – whether due to low organic matter or high risk of erosion
- climates in which prolonged drought or irregular rainy seasons are common.

Trees help to counteract these causes of low productivity by increasing soil fertility, keeping moisture in the soil for longer periods, and preventing soil erosion (see Chapter 3, **Agroforestry systems as circular systems**). These pros need to be weighed against the following cons:

- loss of physical space for the flagship species (because trees will occupy space where crops could be)
- reduction of crop yield due to shading
- in semi-arid regions, potential water competition between trees and crops.

Design guidelines

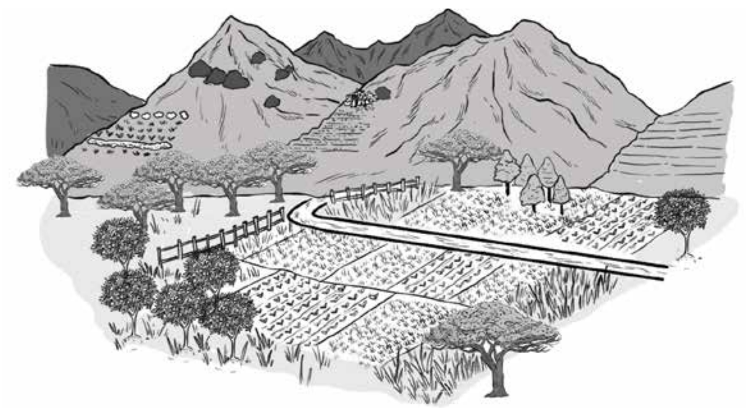
ACT systems are often introduced to farmers as part of agroforestry programmes that aim to restore or improve soil fertility, increase farm productivity, and boost household income and well-being. ACT systems are very variable and context specific. Institutions and individuals supporting farmers should work with them, following guidelines such as those outlined in Chapter 5, **Co-design and establishment of agroforestry systems**. This will ensure that the system is aligned with the farmer's goals and their household's needs.

The benefits of tree flotilla species to the farm, crop and farmer will be highest if the following rules are followed:

- select the right tree for the farmer
- select the right place for the tree
- select the right type of tree for the system, considering growth rate, crown type and root systems.

On sloping land, trees should be planted along contour lines to stabilize the slopes and prevent the soil from eroding. Tall trees and shrubs mixed with grasses can be a good combination, because these each bind a different layer of soil. Having species of different heights also reduces shade. Where erosion is already a problem, trees should be planted at close spacing so that as much as possible of the area benefits from the soil-binding effect of their roots. Later, the trees can be thinned to manage the canopy size and shade.

On flat areas, especially small fields, trees are usually scattered in with crops. This allows the crops to directly benefit from the trees – particularly nitrogen-fixing species – without receiving too much shade.



Planting niches should be identified with the farmer and other household members, making sure that the practical aspects of management are considered. For example, fodder trees should be close to livestock pens. Fruit trees should be planted close to the house, both for ease of harvest and for security reasons – the same applies to other high-value species.

Livestock are an essential part of some ACT systems because their manure serves as organic fertilizer. On steep slopes, zero-grazing strategies are more appropriate, as they prevent livestock from damaging both the soil and the system.

The components (crops, trees, livestock) and how they are best arranged differ from farm to farm, but we list some general guidelines below:

- Trees are usually less demanding of nutrients than are crops. It is generally desirable that trees growing with crops should have deep roots, with fewer roots near the soil surface where most crop roots are found.
- Competition effects can be reduced by watering, fertilizing and mulching at competition zones.
- Farmers can correct excessive shade by pruning or thinning the trees responsible.
- To minimize shading effects, tree rows should be planted parallel to the path of the sun.
- Some tree species naturally produce less shade. Such trees may have small leaves, have leaves that tend to go upwards rather than outwards, or be bare or partly bare (the latter trait is particularly useful if it coincides with the cropping season).

- The chosen species should have deep roots, grow quickly, preferably fix nitrogen, and have a light crown that allows sunlight to pass through easily.
- Highly productive, fast-growing types of trees such as eucalypts and acacias use a lot of water, and they can reduce water availability for other components in a system. These kinds of trees can best be used on farm as a block or woodlot.
- High-yielding perennials that need a lot of light, such as oil palm, are not suitable to be grown under trees, but they make excellent shade trees for smaller plants such as cacao and coffee (see **Multistrata cacao agroforestry systems in Central America and the Philippines** in this chapter).
- In semi-arid areas, termites can cause serious damage to seedlings and mature trees, so mitigation measures like selecting termite-resistant species and employing protection strategies are very important. Strategies include removing dead and damaged wood from trees quickly after damage, mulching to provide alternative food sources, and careful management of the tree (especially when it is young) to keep it healthy and able to resist termites. Pesticides can be used, but they tend to kill natural enemies, and are most effective when used to kill termite colonies rather than to protect individual trees, which is undesirable. Several botanical extracts can be used to control termites.[8]

[8] For more information on controlling termites in agroforestry, see Nkunika P, Sileshi G, Nyejeo P, Ahmed BM 2013. *Termite management in tropical agroforestry*. Lusaka: University of Zambia Press. http://dspace.unza.zm/handle/123456789/6496.

Management guidelines

Many farmers deliberately maintain mature trees in their fields and/or protect naturally occurring seedlings so that they grow into mature trees (a technique known as 'farmer-managed natural regeneration'). However, farmers usually have little experience of managing trees that have been reintroduced into landscapes dominated by annual crops. Unlike farmers who specialize in tree crops such as fruit species, coffee or cacao, or that have timber plantations, they may be unfamiliar with tree growth in height, girth and roots over time, and may not have been trained in how to maximize growth or productivity.

The following points are often key elements of successful management:

- The most important activity in managing ACT systems is the management of the trees' crowns to minimize shading of sun-loving annual crops.

- Several factors affect the amount of time it takes before trees begin to interfere with crop growth, including soil fertility, climate, crown shape, root types and the shade tolerance of the crops in question. Farmers need to be trained to understand how the various elements of an agroforestry system respond to tree pruning and thinning (see Chapter 7, **Management of trees in agroforestry systems**).

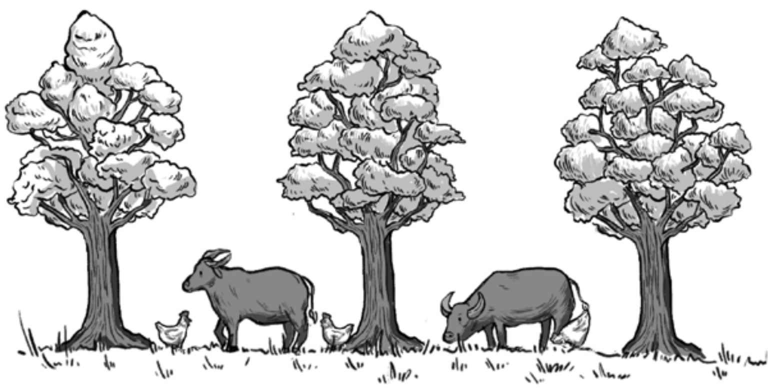
- Warning signs of light competition include yellowing of the crop leaves – which suggests low photosynthesis and chlorophyll levels – and, in cereal crops, stunting and thinness. Trees that are grown too close together usually respond by putting all their energy into height growth, rather than growth in diameter.

- Pruning, coppicing and pollarding are important in reducing competition. They also provide useful products such as firewood, mulch, green manure, fodder and stakes for climbing plants.

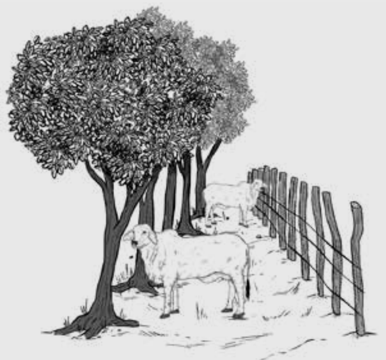
Livestock with trees

Description of the system

We are focusing here specifically on livestock in mixed farming systems. For the integration of trees in intensive cattle ranging systems, see Box 7. As an integrated part of the agroforestry system, livestock offer opportunities for increased profitability, risk reduction through diversification, better human nutrition, improved land use and higher agroecological efficiency. Trees are planted to provide ecosystem services to the livestock; however, they also introduce some environmental and health risks that must be mitigated by informed and careful management.



Box 7. The untapped potential of living fences



An important use of linear planting of trees is as live fences to control livestock. Fencing is very expensive, but live fences are cheaper to establish than their dead post counterparts. Live fencing is widely practiced on ranches around the world, including in Honduras and Nicaragua, where the system has recently been studied in depth.[9]

Fencing prevents animals from straying and allows land to be divided into grazing blocks for rotational grazing. Large-scale cattle producers generally have low tolerance of trees in open pasture, and in Honduras they usually remove them when canopy cover reaches 20%. However, they actively plant trees around field boundaries.

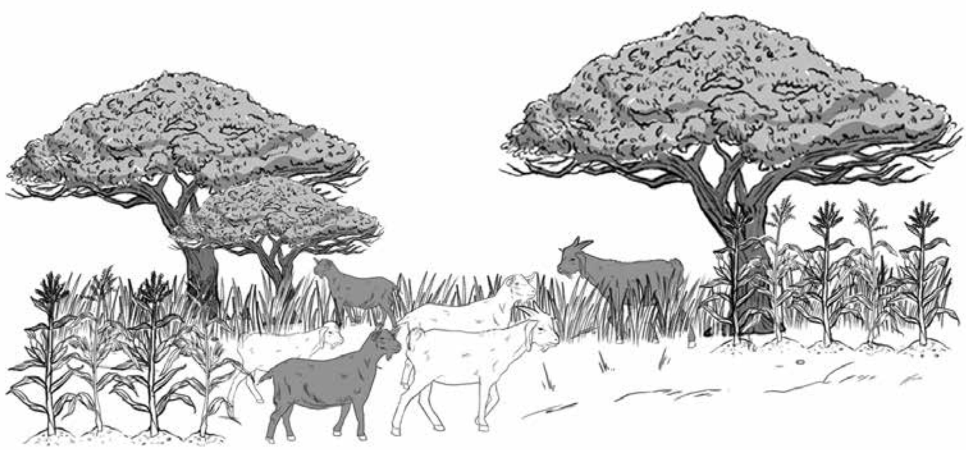
Live fences are very productive. An inventory of cattle ranches across 25,000 hectares in Catacamas municipality, Honduras, identified more than 10,000 fence segments spanning 1,730 kilometres, with a linear density of almost 70 metres per hectare, covering 6.4% of the land. The potential for timber production from live fences in the 2.9 million hectares of pasture in Honduras was estimated to be equivalent to 200,709 hectares of conventional timber plantations, given that one kilometre of live fence is equivalent to the yield of one hectare of plantation.

[9] Somarriba E and Quesada F. 2009. *Agroforestry farm planning: manual for farming families*. 1st Edition. Costa Rica: CATIE.
Somarriba E, Orozco-Aguilar L, Cerda R, López-Sampson A. 2018. Analysis and design of the shade canopy of cocoa-based agroforestry systems. *In* Umaharan P. ed. *Achieving sustainable cultivation of cocoa*. London: Burleigh Dodds Science Publishing, 1–31. https://doi.org/10.1201/9781351114547.

Livestock, especially browsers like goats, can cause serious damage to crops and trees if not controlled. In sloping landscapes, free-grazing livestock can seriously affect soil stability, and thereby undermine the sustainability of the entire farm.

Zero-grazing systems, as opposed to free grazing, are those in which livestock are not free to roam the farm to access grazing, browsing or other feed resources. Usually, this means that animals are housed in buildings or pens, to which their feed is carried. The system is particularly appropriate for smallholder farmers that own livestock but have limited lands and income. Livestock are often kept on small farms to provide food for the farming household and income from milk, eggs or meat. The animals that are kept are usually cows, sheep, goats, pigs, rabbits, and, in some places, guinea pigs.

Although small-scale farmers often tether animals where feed can be found, such as along farm boundaries, on roadsides or in other accessible land, the limited space available on farm usually leads to animals being kept under a 'zero grazing' regime. Trees and shrubs in the system are selected to provide high protein alternatives to add to the basic crop-residue animal feed. This improves the condition of the livestock and avoids using all the available crop residues – some of which should be left on the field as mulch and for soil erosion control – or buying costly commercial feed supplements.



Zero grazing offers farmers several advantages. It can improve livestock management or make it easier, in the following ways:

- It can allow livestock to be kept on farms that would otherwise be too small.
- Because zero-grazed animals are usually kept close to the homestead, household members can more easily manage them as part of their general activities.
- Farmers are more likely to notice pests and diseases.
- More accurate management of the nutrition of individual animals is possible, by feeding them controlled amounts of different foods. This can improve feed use and is an important first step towards market orientation (for example, engagement in the small-scale dairy sector).

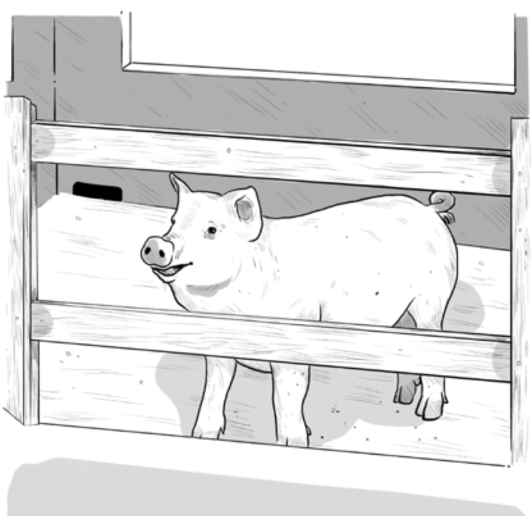
It also offers advantages in overall farm management and other important aspects:

- Manure is easily collected and recycled to crop fields, increasing resource-use efficiency across the whole system. Animal manure is rich in nitrogen and is a particularly important source of phosphorus.

- Confinement of the livestock prevents adverse effects on soil and natural vegetation, and damage to the crops of farmers and their neighbours is also minimized.
- Housed animals are less vulnerable to theft and predation.

Zero-grazing systems also have some potential disadvantages. They are labour intensive, and availability of labour may limit the number of animals that can be kept. Furthermore, buildings and equipment cost money. The investments needed may be recouped by greater future profits, but nevertheless may be unacceptable to more risk-averse farmers. Although the monetary costs may be reduced by using local materials and building methods, they will rarely be zero.

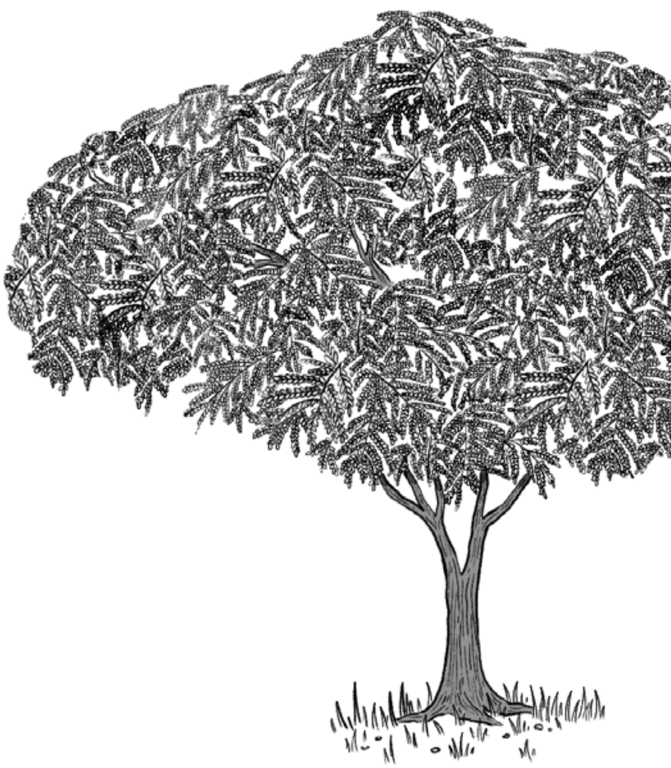
Zero grazing can also have adverse effects on the health of animals and their keepers. For the farming family, close contact with livestock brings an increased risk of zoonotic disease. The livestock, too, are at greater risk of disease and transfer of parasites. For the animals, however, the effects on health and welfare can be more far reaching. Unfortunately, zero-grazed animals are often kept in inhumane conditions, with inadequate space, lack of bedding and insufficient shelter from the weather. Confinement is not healthy for any animal, and a lack of exercise can lead to long-term discomfort and psychological impacts. Where possible, steps should be taken to minimize these animal welfare problems. Those supporting and advising farmers can contribute to this by pointing out the advantages of avoiding adverse effects like foot damage, joint damage, skin damage, increased aggression, other behavioural changes and poor reproductive performance. All of these are distressing to the animal and result in reduced longevity and lower productivity.



Design guidelines

Fodder tree production
Fodder for zero-grazed animals is often provided in the form of grasses, fodder legumes, and branches cut from shrubs and trees. There are many ways to include fodder trees for zero-grazed livestock in agroforestry systems, such as in ACT systems or as living fences. Good candidate species produce large amounts of high-quality, palatable fodder; grow relatively fast; remain productive during the dry season when fodder grass is scarcer; and tolerate frequent coppicing or pollarding. Species that are going to be planted with the main food crops should have small, sparse crowns (to reduce shade) and roots deeper than those of the crop (to reduce competition for nutrients and water). Some leguminous species offer the additional benefit of improving soil fertility by fixing nitrogen.

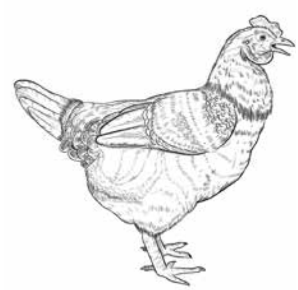
On sloping fields, as in the aforementioned ACT systems, trees and shrubs should be planted along contour lines to prevent soil erosion. In locations such as field boundaries, riparian stretches and small vacant plots, trees and shrubs can be grown more densely in fodder banks, which are permanent plots that maximize foliage production. Associated grass species should be fast growing; highly productive; well adapted to frequent cutting or defoliation; able to provide good soil cover; palatable to livestock; high in nutritional value; and either easy to conserve as hay or silage, or able to stay green in the dry season.

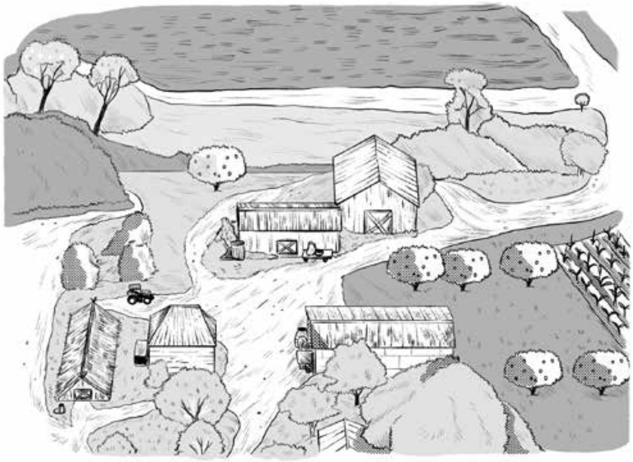


Livestock type

Any type of livestock species or breed may be kept under a zero-grazing system. However, zero grazing requires relatively high capital investment and ongoing managerial and material inputs. Therefore, farmers are more likely to use the system for animals that generate substantial returns, such as dairy cows or sheep reared for meat that will be marketed. Eggs, which can be produced in large numbers from improved hen breeds, often have ready demand and can command a high price. On the other hand, the ease and efficiency of feeding small livestock, such as rabbits, can make them an attractive simple option, both for the family diet and for sale.

Investment in improved breeds (such as crossbred dairy animals or specialized sheep breeds) allows farmers to make the most of the opportunities for higher incomes that zero grazing offers. However, these animals do not automatically produce more: they require much improved feed management (see below) to reach their potential, as well as careful attention to their health and well-being.





Location
The siting of a zero-grazing unit will be influenced by several factors, which need to be balanced. Closeness to the homestead makes monitoring of animals simple, but if many animals are kept, and feed and water sources are not close, the labour needed may be beyond the capacity of the farming family. Other considerations include road access, electric power and availability of local building materials. Each farmer needs to consider their own situation with respect to location and try to identify the most appropriate compromise.

Housing and associated infrastructure
A variety of housing designs can be used for zero-grazing livestock, depending on the farmer's wider objectives. For example, slatted floors can greatly improve manure recycling efficiency, if this is an important consideration. However, slatted housing for large ruminants must be extremely robust, and is therefore relatively expensive to construct. The importance of well-designed equipment, such as feed troughs, should not be underestimated. Inadequate feeders can cause wastage of up to 30 percent of offered feed, and this wastage will reduce profitability.

Management guidelines

Tree and shrub management

Effective management for animal feed of trees, shrubs and other fodder plants can be quite complex: it requires experience and access to good, reliable information – for example from extension services. Indonesia's three-strata forage zero-grazing system, developed for dry areas, is a good example. It combines fodder plants, grasses, ground legumes, fodder shrubs and fodder trees. Its components have differing life cycles or growth patterns, so high-quality fodder is available all year round. Grass and ground legumes are harvested during the wet season, shrub legumes during the dry season, and fodder trees during the late dry season when little else grows.[10] In Rwanda, fodder banks are less complex, as farmers prefer to plant leguminous shrubs such as calliandra with the crops to support soil fertility. Fodder banks are usually designed and planted around a main fodder grass, such as Napier grass, but in rotation with other grass species that are used for other purposes. They are also grown in permanent positions on land not used for cropping, for example along rivers.

[10] For an example of planting for year-round fodder see Nitin IM, Lana K, Sukanten W, Suarna M, Putra S. 1989. The concept and development of three-strata forage systems. *In* Proceedings of the IDRC workshop Shrubs and Tree Fodders for Farm Animals, Denpasar, Indonesia, 24–29 July 1989. 92–102 https://idl-bnc-idrc.dspacedirect.org/bitstream/handle/10625/18656/IDL-18656.pdf.

Feed management

Decisions regarding the appropriate feeding of livestock always involve a compromise between production objectives (which can be multiple and conflicting) and the range and quantities of feeds that can be made available. Some cut-and-carry systems operate efficiently on feed resources that are collected locally from common land (such as roadside grasses), while others may be wholly dependent on planted forages and other feed or food-feed[11] crops. Trees and shrubs, particularly legumes, provide high-quality, nitrogen-rich feed to complement crop residues.

Manure collection and handling

Zero grazing offers an important opportunity for farmers to make more effective use of the manure produced by their animals. In some cases, it may be used as fuel, but recycling nutrients by applying it to croplands is also a very widespread practice. In addition to improving resource use efficiency through the system, manure recycling can deliver direct financial benefits by reducing expenditure on purchased fertilizer. Direct application to crops should be avoided. Farmers need knowledge on good composting practice to maximize the value of manure.

Watering

Watering is often overlooked, but is of critical importance for housed livestock, which are unable to find water for themselves. Water requirements have been discussed in the livestock section under the High needs for care and maintenance subsection. Common sense is also helpful: if a farmer expects a dairy cow to produce 20 litres of milk each day, but only offers her 10 litres of water, disappointment is going to be the only outcome!

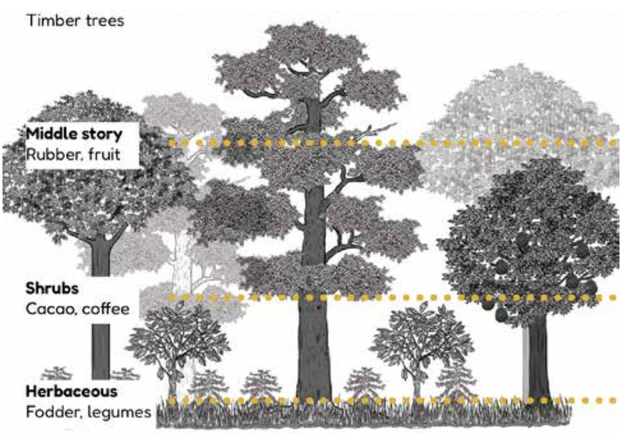
[11] Food-feed crops are those consumed by both people (food) and animals (feed).

Multistrata perennial agroforestry

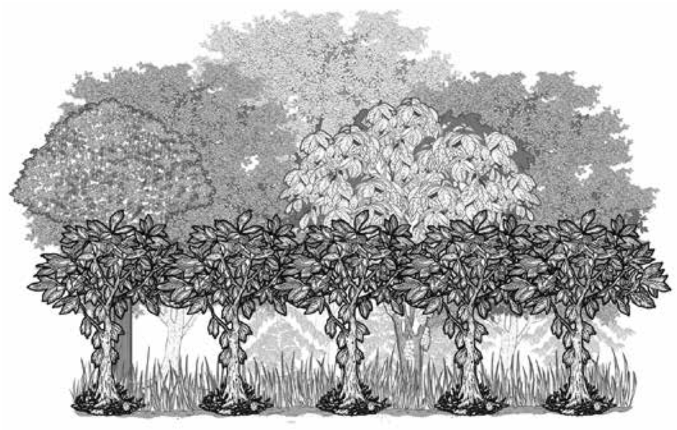
Description of the system

Multistrata perennial agroforestry systems are the most complex of all kinds of agroforestry. They include both simultaneous and successional systems. In a simultaneous system, the same species, with their horizontal and vertical arrangements, are maintained for the system's entire productive lifetime. In a successional system, species composition and structure change over time.

Both systems take advantage of species' differing needs for water, light and nutrients. Simultaneous systems deliberately combine species that reach different heights, dividing into different layers the vertical space between soil and sun. Plants and trees are selected in such a way that, at any given moment, each species or group of species ideally occupies a specific layer based on its relative height and its need for sunlight (see Chapter 7, **Management of trees in agroforestry systems**). However, as tree height



changes over time, management is needed to maintain the different layers. In successional systems, this resource-sharing strategy is taken further by planting species with different life cycles. Over time, the species succeed each other; plants with shorter lives develop alongside longer-lived ones. When they are pruned or complete their life cycle, they leave a beneficial legacy: organic matter in the soil, and the results of their interactions with other plant, animal and microbial species. These improve the soil's structure, fertility and moisture content.



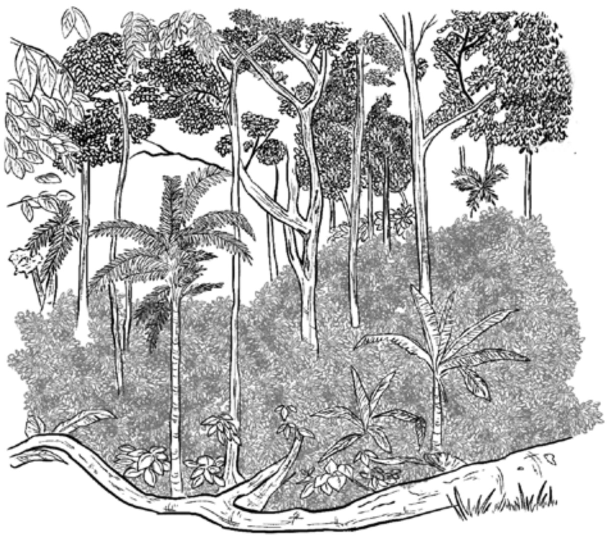
Multistrata systems vary greatly in their design and species composition, depending on the region and the type of farming community. However, they are usually designed around one flagship crop that represents the main production objective for the farmer or the farming community. Often, the production objectives change over time as different products become available, as different components of the system mature, and as market conditions and product values change. Because of the high investment required in labour and planning, it is essential that the farmer is closely involved in design and planning. Only farming communities that fully understand the time and commitment needed to manage these systems will be successful in reaping their benefits.

Design of multistrata systems entails optimization of the use of space by arranging plants in space and time, thereby ensuring maximum productivity of the flagship crop through careful management of the density of the different layers. Well-designed multistrata systems take advantage of existing seed stocks by supporting the natural regeneration of native tree species, while deliberately adding new components with important livelihood potential, such as fruit trees or commodities like oil palm and rubber.

Design guidelines

A carefully designed canopy structure is required to optimize the use of horizontal and vertical space. This is done based on the productive life cycles and heights of different species.

In hilly terrain, trees should be planted following contour lines, to minimize soil erosion.



The system is initially designed around optimization of the productivity of the flagship species (which varies from place to place), with flotilla species chosen to maximize synergies. This requires detailed knowledge of the flagship's physiological needs and productive stages.

Trees that produce a lot of foliage, and nitrogen-fixing species, enhance nutrient circulation in the system. In successional systems, these functional groups of species should be represented in each stage of the succession to reduce dependency on commercial fertilizers. The life cycles and productivity ranges of the different species should be mapped out to time the planting of the successional stages. This avoids productivity gaps and cash flow shortages. It is important to avoid production gaps between the end of one succession's lifespan and the productive period of the next.

Components need to be managed continuously throughout the productive cycle of the system to regulate their population density, minimize competition, and enhance complementarity. Farmers need to be aware that managing such a system is a full-time job. It is very demanding in terms of labour requirements at all stages (planning, planting and management). These demands need to be compatible with labour availability and the farmer's knowledge, experience, learning capacity and aspirations.

Livestock can be included in the system, but plant species then need to be protected from damage and overgrazing. In uplands with steep slopes, zero-grazing strategies are more appropriate, as they prevent livestock damage to both the land and the system.

Management guidelines

The basic principle for managing multistrata systems is to manipulate the species composition and the spatial and temporal structure to provide the right amount of shade at the right time for the plants in the system. This requires detailed knowledge of the phenology of each species – that is, about the timing of leaf loss, production of new leaves and shoots, flowering and fruiting.

Light triggers plant growth and, therefore, extraction of nutrients from the soil. In low-fertility sites, and if fertilizer has not been added, excess light will stress the plant, leading to poor growth and low yield. Signs of stress include discoloration or death of leaves, and general weakness; highly stressed plants can die. Farmers can achieve maximum production for a given level of soil fertility by managing light penetration.

To assess whether the shading of the system is optimal, extension workers can follow an easy, three-step procedure:

1. Assess the exposure to sunlight of the system at different times of the day. Even on the same farm, different areas can receive very different amounts of sunlight, depending on their position in the landscape.

2. Walk through the system at different times of the day and observe the light penetration on the ground. This will tell you whether the system is too dense and if it requires thinning or pruning.

3. Discuss with the farmer the level of productivity that they can manage. How fertile is the soil? Can they afford to buy and apply additional fertilizer? Based on the available sunshine hours, decide on an optimal shade regime to achieve that productivity level.

Using the assessments made in the above three steps, work with the farmer to develop an optimal monthly routine for managing the canopy and stock density.

Multistrata cacao agroforestry systems in Central America and the Philippines

Description of the system

Cacao was first cultivated as a shade crop under the canopies of native trees. In many countries, however, the availability of full-sun varieties, coupled with pressure to increase production, eventually led to replacement of these systems. Yield in unshaded systems can be five times greater than in shaded systems, but they also demand a lot of nutrients, leading to soil exhaustion. As a result, cacao farmers tend to open new fields when establishing plantations, often leading to deforestation.

Because of its shade tolerance, cacao is one of the crops most suited to agroforestry systems, especially for farming families who prefer diversified income streams to reliance on one crop. There is also renewed interest among large chocolate producers in agroforestry, because climate change is beginning to affect plantations in traditional cacao growing areas. Cacao plants are highly sensitive to variation in climate, particularly temperature, but also changes in rainfall and in the number of hours of sunlight. Concern is also growing over deforestation caused by cacao expansion.

The diversity, botanical composition and structural complexity of cacao agroforestry systems varies widely between geographical regions, between farms within a region, and even between sections within a plantation. Across regions, design and management are often deficient, leading to suboptimal shade (excessive, deficient or uneven).

Design guidelines

In this multistrata system, cacao is grown as an understorey of the canopy and emergent layers (Figure 6). In a well-managed system, ground-cover crops such as forage legumes and grasses can also be grown beneath the cacao.

The layers optimize the use of light, water, nutrients and space. The emergent and canopy layers maximize light utilization and provide shade to the cacao trees, which absorb both direct and diffused light.

Below ground, the range in root depth allows the system to exploit more water and nutrients, and protects the soil against erosion and landslides. Deep rooted trees bring up nutrients such as nitrate, phosphate and organic acids from deep in the soil, and make these available to shallow-rooted trees, including cacao, through their litter.

Management guidelines

To ensure maximum health and productivity of the plants, shade levels must be carefully planned, monitored and managed over the lifetime of a shade cacao system.

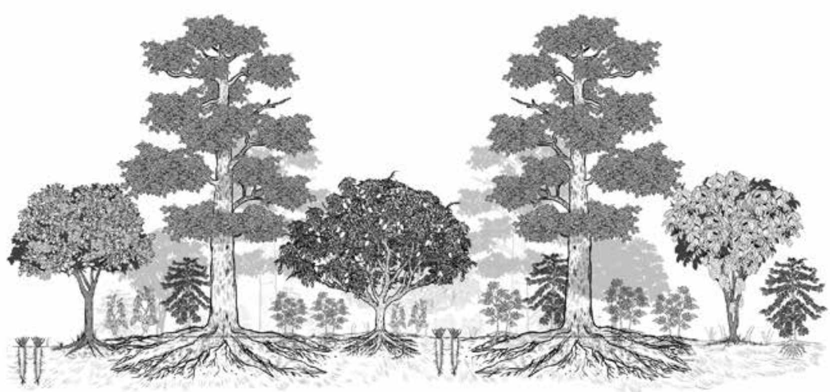
Inappropriate shade levels have dramatic effects. Under-shaded trees will show stunting, signs of water stress, scalded leaves and stems, flower cushions damaged by scalding, fewer leaves and low yield. Over-shaded trees will also show stunted growth, together with elongated stems and leaves, low flowering rates, fewer pods, higher incidence of disease (including *Phytopthora*, cherelle rot, pod rot and swollen-shoot virus), and higher incidence of pests such as pod borers.

The amount of shade required in a particular plantation depends on the degree of self shading, phenological stage, site conditions and canopy characteristics, as explained below.

Self shading
In the crown of a cacao tree, upper leaves and branches cast shade on lower leaves, while neighbouring cacao trees cast shade on each other. Both are examples of self shading. If self shading is high, then less overstorey shade is needed. If this happens, fewer shade trees will be required and the farmer loses the option of producing additional goods (timber, fruit, etc.) and services (cultural, environmental) in the cacao plot.

Self shading is determined by factors related to the form and size of the cacao tree, and to planting configurations and spacings, alone and in combination. Important ones include:

- age of cacao plants (young plants have small crowns, hence low self shading – overstorey shade is needed)
- pruning frequency and intensity (infrequent and light pruning results in tall cacao trees, crown overlap between neighbouring cacao trees and high self shading)
- whether the trees are grafted or grown from seed (grafted cacao trees tend to be shorter and more open crowned than trees grown from seed, resulting in less self shading if the plantation is well managed)
- tree spacing (triangular planting arrangements allow more cacao trees per hectare than square or rectangular configurations. Self shading is higher in such 'packed' planting configurations).



Temporal dynamics

In addition to the changes in self shading that occur as cacao plants grow older and bigger, the light requirements of a cacao tree vary according to its annual cycle: light is particularly needed at the flowering and pod-filling stages. For optimal cacao performance, shade must be adjusted to the monthly rhythms of the cacao plant by timely pruning or pollarding of the shade trees.

Site conditions

Several site factors influence the amount of light reaching the cacao plot and the optimal level of shade required:

- the latitude, exposure and slope of the land determine the amount of sunlight reaching it
- high prevalence of cloud reduces sunlight
- the topography of the surrounding land and the height of the surrounding vegetation affect the degree of lateral shade cast on a plot
- soil fertility: in infertile soils, farmers can only grow low-shade cacao if they apply fertilizers. If they are unable to buy fertilizers, then more shade is needed, because it reduces sunlight and demand for soil nutrients
- rainfall: for each location, it is important to establish the annual rainfall below which the introduction of trees to unshaded cacao would result in poor crop performance due to competition for water
- altitude: cacao can be planted from 50–1,200 metres above sea level. The optimum elevation is around 400–800 metres. Above 500 metres, cacao requires less shade than at lower elevations
- temperature: the higher the temperature, the more shade is required, so cacao trees generally require more shade during the dry season. This has implications for pruning practice: shade trees should be pruned at the onset of the rainy season and allowed to regrow during the dry season to provide the required shade during this period.

Canopy characteristics

The shade cover should be similar in the different parts of a cacao plantation. In practice, however, many cacao plantations have patches with either too much shade or no shade at all. In part, this results from variation in the vertical and horizontal distribution of the canopy cover and its botanical composition. Tall trees cast less intense shade than short ones, and tree species differ both in the time of the year when they become leafless and in the duration of leafless periods.

Case studies

Cacao agroforestry in Central America

Several Indigenous Peoples of the Mesoamerican Biological Corridor, including the Chibchas and Mayas, cultivate shade cacao. These cacao plantations usually harbour between 125 and 145 tree species at densities of 85–166 trees per hectare. Most trees are planted (except in rustic cacao systems, which make use of thinned natural forest), although some are derived from natural regeneration. Shade trees are used for timber (*Cordia alliodora*, *Cedrela odorata*), fruit (*Musa* spp., citrus, avocado, coconut, peach palm, mango), and shade (*Inga* spp., gliricidia, leucaena). Tree canopies have three vertical strata (low <10 metres, medium 10–20 metres and high >20 metres), containing about 50%, 30% and 20% of total tree density, respectively.

In these systems, cacao is cultivated at 100–800 metres of elevation in small plots (1.2 hectares per farm). Cacao trees are typically spaced at 4 × 4 metres (625 plants per hectare) in most countries. They are usually produced using hybrid seed from either controlled pollination or from pods selected on local farms. Grafted cacao has been used only since around 2010 and is still scarce. Most farmers have two or more cacao plots per farm.

Five basic types of shade canopy are used in the region:

1. cacao under shade of one species, either a timber species (for example, *Cordia alliodora*) or a nitrogen-fixing legume (for example, *Inga* species)
2. cacao under two shade strata composed of a mixture of fruit (for example, citrus, *Nephelium lappaceum*, peach palm), legume, and timber species (*C. alliodora*)
3. cacao intercropped with banana and fruit species under one shade species (timber or legume)
4. diversified home gardens with cacao, fruit, timber and legume species
5. rustic cacao ('cabruca'): cacao planted under thinned natural forest.

Cacao agroforestry in Claveria, the Philippines

Claveria is an upper-watershed town in eastern Misamis Oriental Province on the island of Mindanao. Land-use practices in the region affect lives and livelihoods of people living in the 13 downstream coastal municipalities: soil erosion from poor land management contributes to the siltation and pollution of downstream water bodies, and affects the quality and availability of marine resources.

In this context, cacao agroforestry is particularly important, because it provides permanent soil cover and reduces erosion, landslides and runoff. Due to its multiple components, the system acts as a climate adaptation and mitigation measure, ensuring climate-resilient, sustainable streams of products and services. It also helps to buffer farmers against fluctuations in commodity prices.

Cacao combined with rubber, fruits and forage legumes is common in sloping lands in the region. In this system, contour lines with 0.5-metre natural vegetative filter strips are laid out every 10 metres. Rubber trees are planted at a spacing of two metres apart, approximately 25 centimetres above the grass strips; about 500 such trees can be accommodated on one hectare. Two rows of cacao trees at three-metre spacing are planted in the alleys (between the grass strips), 3.5 metres from the rubber rows, resulting in around 660 cacao trees per hectare. Bananas are then planted between the rubber trees at a density of 500 per hectare. Fruit trees such as durian or langsat are then planted in the middle of each cacao row, spaced at 10 metres apart (100 per hectare). Pinto peanut, a forage legume, can also be planted as a ground-cover crop.

Cacao with coconut and fruit trees is also used on sloping lands, while cacao with rubber, vanilla and banana is used on flatter areas. Cacao is also used in parkland systems, both on sloping and flat areas.

Oil palm agroforestry

Description of the system

Agroforestry systems for commercial oil palm are multistrata systems that offer an alternative to farmers and companies that want to produce palm oil, but do not want to specialize in just one crop – or who would like their oil to have a smaller environmental footprint.

The system was developed with farmers in Brazil. Individuals had a strong influence on the spatial design of the systems and the selection of the species, so no two systems are the same. They require agricultural technology packages different from conventional oil palm models. Instead of maximizing palm oil yields per hectare, they aim to diversify livelihood options by combining oil palm with other crops of commercial value, allowing simultaneous production of food crops. They also aim to improve nutrient and water flows by taking advantage of the synergies between the different components. To provide space for the other components, palm density varies from 60 to 100 trees per hectare, whereas the density in conventional systems is 144 per hectare.

Management of oil palm agroforestry systems requires considerable knowledge, so training and technical assistance for farmers are important elements of creating, implementing and maintaining systems that will be successful and profitable.

Design guidelines

Oil palm agroforestry is suitable for all soil types and land types that are suitable for oil palm – that is, well-drained soil in flat areas.

The components and spacing are designed around the flagship crop, oil palm. Flotilla species are selected based on how each farmer prioritizes objectives such as incomes, food provision, and contributions to soil health and biodiversity. In Brazil, farmers selected cash crops such as cacao and fertilizer species, including inga, gliricidia and Mexican sunflower.

To simplify the harvesting and transport of fresh fruit bunches from the oil palm, it is advisable to plant oil palm rows in sections, with light-loving crops and trees interspersed between the sections. In Brazil, farmers have opted for double, triple or quadruple rows of oil palm, keeping the conventional 7–9 metre spacing between the palms.

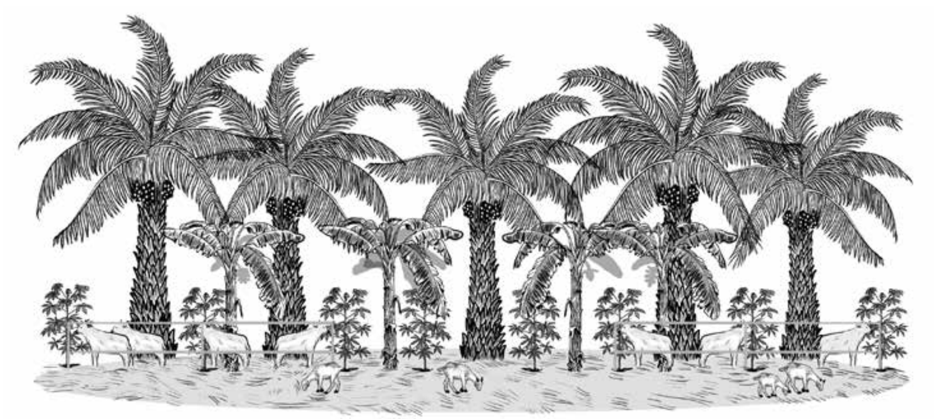
Oil palm is the most productive oil producing plant and has very high light and nutrient requirements. It is therefore important to avoid creating competition for these resources. As in all multistrata systems, competition for light is managed by selecting species that reach different heights, effectively dividing the horizontal space between soil and sun into different layers (see **Multistrata perennial agroforestry** in this chapter), and by actively managing the system once the components grow. Oil palm trees should not receive more than 10–15% shade, so high-strata trees should be placed at maximum distance from the oil palm rows and be carefully chosen for a crown shape that is as porous to light as possible.

Shade-loving crops like cacao, ginger, turmeric, some woody ornamentals and – possibly – coffee can be grown underneath oil palm trees. As oil palm seedlings have very fast-growing, aggressive, shallow roots, perennial components such as cacao must be planted simultaneously to make sure that they establish good root systems and are able to thrive.

The components need to be arranged both to avoid shading the oil palm, and to ensure appropriate light levels for other components in the system. Sun-loving plants should not be planted directly under oil palm. However, it is generally advisable to err on the side of planting too many at the start: it is easier to get rid of surplus plants than to establish them later.

When integrating food crops, it is important to take advantage of the oil palm's life cycle. The palms take five years to reach maximum height and crown cover. During this period, they do not cast much shade, and sun-loving crops like maize and cassava can be easily grown between the oil palm and the other perennials in the system. Beyond this time frame, and depending on the system design and spacing, many understorey crops – particularly the annuals and biennials – will only have adequate light to grow for a few more years. Once the system matures, perennial and semi-perennial food crops like bananas can be planted and can stay in the system for about 8–10 years.

Oil palm agroforestry is relatively labour intensive, and, as in all agroforestry systems, the more integrated the components, the more labour is generally required – especially in the first few years. This adds to the labour demand for the oil palm itself, which tends to increase over time, in contrast to many other crops. As such, it is important to design and implement the system at a scale that is manageable, given the amount of labour that is available to the household or landowner.



Management guidelines

Some of the shade-loving crops that can be grown in an oil palm agroforestry system, such as cacao and cut flowers, may be financially almost as important as the oil palm itself, so their needs and light requirements must be carefully managed. At times when oil palm prices are low and those for other cash crops are higher, farmers can prune their palms more intensively than usual to provide more light and increase the yield of the understorey crops.

Pruning is an important element in any kind of oil palm cultivation, and farmers need to be well trained in the basic principles of managing productive adult oil palms.

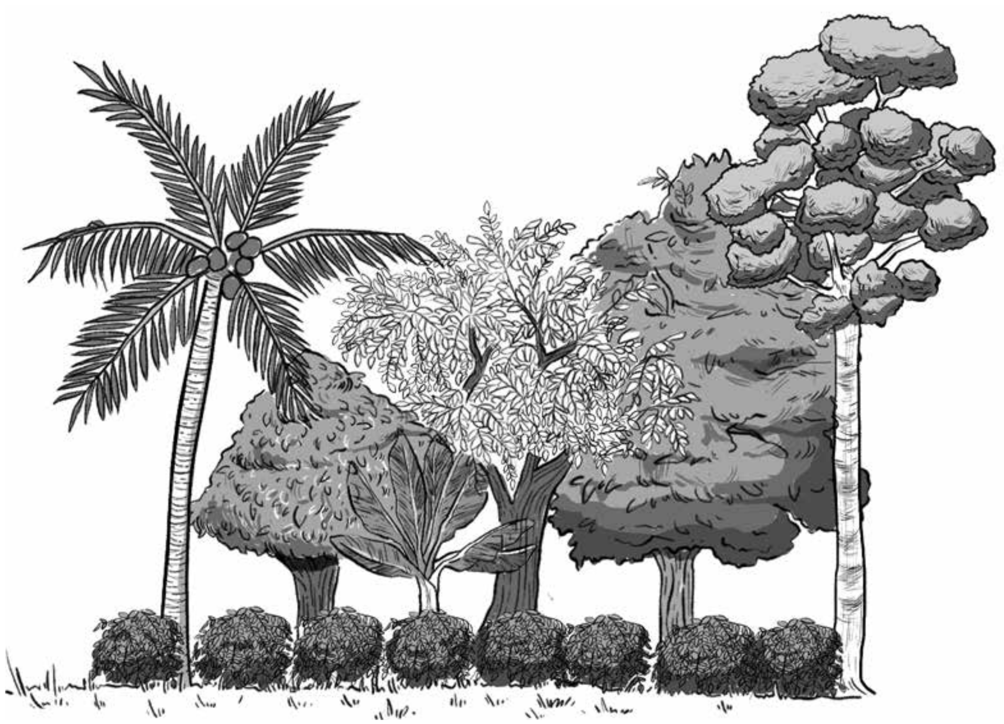
Because oil palm is a 'hungry' crop, it will require fertilizer, especially during the first five years, to ensure good yields and prevent stunting – particularly when farmers are working on degraded soils. Organic fertilizer can be created on-site by composting available biomass, though the system will not be able to supply adequate on-site fertilizer for the first few years.

A biodiverse, successional oil palm agroforest can reduce or eliminate the need for pesticides, though particular organic inputs and agroecological techniques will be required to address these issues, particularly in the shorter-term.

'Slash-and-mulch' of fertilizer species (which produce biomass very efficiently) is an important element of soil health management. This feeds the system on a continuing basis.

Rainforestation farming

System description



Rainforestion farming is a successional, multistrata agroforestry system developed to restore native forest cover and forest diversity, while providing diverse income streams to farmers from multiple crop and tree products, including timber. Such systems are designed to shift the livelihood component gradually from crops to trees, ensuring that farmers have an incentive to contribute to forest restoration.

Rainforestion farming was developed in the Philippines in the 1990s as a solution for community forest areas. Exploitation of the natural mixed dipterocarp forests had turned these areas into highly degraded biological and agronomical 'deserts'. Upland areas without trees were dominated by highly invasive grasses such as *Imperata cylindrica*, a land cover type that does not adequately support the needs of local communities.

Initially, fast-growing exotic species were used to reforest government land, but these proved ill-suited to withstand the typhoons that regularly hit the archipelago. So, researchers – together with communities – began exploring the use of more resilient pioneer and hardwood native tree species, particularly those from the dipterocarp family. The rainforestion farming systems they developed proved to be relatively resilient to environmental shocks such as extreme weather events, as well as livelihood challenges such as market fluctuations and food insecurity.

Rainforest farming is often used on government land, so specific attention needs to be given to tenure rights. On land where the community does not have the right to harvest the timber, farmers must be compensated for their labour in planting and managing native timber trees. In this way, the community becomes a partner in a private–public restoration effort.

Seedling sales have also provided a major source of income for many rainforestion farming communities, especially if governments actively promote procurement from community managed nurseries in national reforestation programmes.

Design guidelines

- Rainforestation farming systems build on traditional community knowledge. Soil types, whether of ultramafic, sedimentary or volcanic origin, affect what species can be grown in the system. A good knowledge of the site, the forest species, and their interaction is essential.

- It can also be extremely valuable to involve all family members – including children – in the development of a rainforestion farming system, because the management needs and benefits from a successful system will span generations.

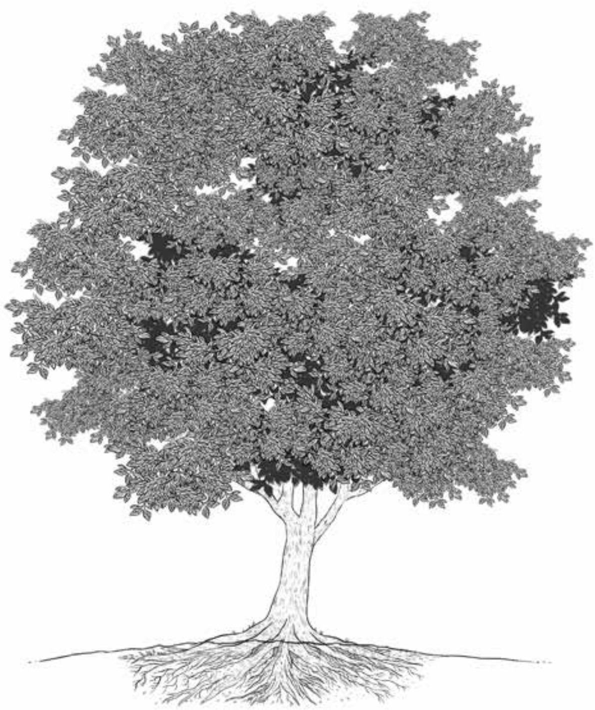
- For areas with little tree cover, a successional model in which agricultural crops give way to fruit trees, which in turn give way to timber trees is common. The spatial layout must be adjusted to the individual growth of the trees to ensure that fruit trees aren't too quickly overtopped by the timber trees, which could lead to an unacceptable decline in production. In open areas, native tree spacing of 2,500 trees per hectare is currently recommended, as this allows quick canopy closure and site capture.

- Many dipterocarp seedlings are sensitive to light and temperature. For this reason, they are grown under a canopy of nurse trees. This canopy is made up of fast-growing, native, pioneer species planted together with the fruit trees. The shade of any pre-existing exotic tree species, such as mahogany or mangium, can be taken advantage of, but these should be slowly replaced by native trees. Existing trees can be used as supports for other crops such as yams and black pepper.

- Sun-loving root and ground crops, such as cassava, sweet potato, taro, yam and pineapple are planted at the early stages, but once trees grow taller and denser, and light infiltration is less than 70%, they need to be replaced with shade-tolerant crops such as coffee, cacao and ginger.

- On Leyte Island in the Philippines, abaca has been a particularly successful cash crop for rainforestion farming. This endemic relative of bananas is harvested for its high-quality fibre, which is widely used and valued internationally in products such as teabags. Traditionally, it is grown under nitrogen-fixing trees such as *Erythrina fusca* and narra. It is fast growing and quick to recover after extreme weather events such as typhoons, and is most productive in an environment with around 50% shade. The fibre extracted from the abaca's pseudostems amounts to only around 2% of the plant's biomass; the rest is left on the farm as mulch, so abaca can be cultivated in one spot for around 40 years. One option for integrating abaca into a rainforestion farming system is to plant it a couple of years before planting canopy trees, so that it then provides useful shade for the tree seedlings when they are small.

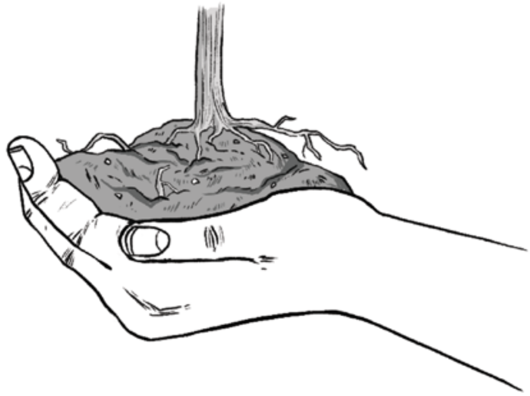
- Integration of animals such as chickens and small ruminants is encouraged to enable nutrient cycling from their manure.



Management guidelines

- The guiding principle for managing rainforestion systems is the same as for all other multistrata systems: that is, to manipulate the canopy structure through spacing, thinning and pruning to provide the right amount of shade at the right time for all the plants in the system.
- The strong emphasis on timber trees is a distinguishing characteristic of rainforestation systems. Consequently, silvicultural treatments such as thinning and pruning to remove overhead shade, and cutting of vines and climbing bamboo, need to be done continuously.
- Naturally occurring tree seedlings need to be actively managed and protected by controlling competing grasses, shrubs and climbers (assisted natural regeneration).
- On degraded sites, the natural dipterocarp seedling stock is usually very scarce or absent. Dipterocarps therefore must be planted, a process called 'enrichment planting', using seeds and seedlings collected from or near mother trees in natural forest.
- Dipterocarps do not produce seeds every year. Rather, seed is produced every 2–10 years. In such 'mast years', all trees of a species produce their seeds at the same time. Dipterocarp seeds are recalcitrant, so seed storage is not possible.

- In years when there is no seed production, wildlings (small seedlings from natural regeneration) can be extracted from the natural forest. This practice is not harmful in places where natural regeneration is abundant (for example, under mature trees). Wildlings are often damaged during extraction and transport, but if they are placed in a shaded recovery chamber – a small, closed structure of bamboo and acetate plastic sheets, with relatively constant temperature and high humidity – their survival rate will be close to 100%.



9

STORIES FROM THE FRONT LINE

In this chapter, we illustrate how the application of the design principles is used to adapt generic agroforestry models, like those in the previous chapter, so that these work for individual farmers and their contexts. We also show how neglect of the principles can cause problems. We do this through a series of synthetic case studies, based on real-life situations.[12]

[12] The specific situations portrayed are fictional, and any resemblance to real locations, real persons or real institutions is completely coincidental.

Hidden hunger and land degradation: An NGO responds to a village's request for assistance

Agroforestry systems exemplified:
Zero-grazing livestock production, trees integrated with seasonal agriculture

The farmers' needs and the response

Villagers in a mixed farming area in Kenya have been worried about erosion and declining productivity. This is not their only problem. For example, many of the mothers worry that their children are not getting all the vitamins they need for healthy growth, especially towards the end of the dry season when food can be scarce.

Mary, one of the villagers, heard about agroforestry when visiting her sister in a neighbouring village, where an NGO called TreesFP was carrying out a project. She was able to arrange a visit by the project leader, and eventually the NGO began activities in her village.

Mary comments, “We weren’t sure about accepting help from TreesFP. We liked the name – it means Trees for People – but some people have had bad experiences with agroforestry projects. But we decided to listen to what they had to say.”

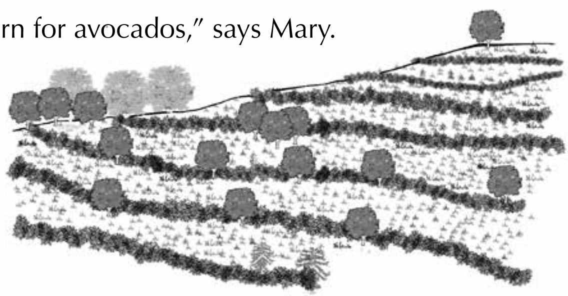
Rose, an extension worker, was appointed as team leader by TreesFP.

“It was difficult at the start, as some of the villagers expected us to come with ready-made solutions,” she says. “There were comments like ‘What use are you, if you don’t know what we should do?’ It took a while for me to explain that we had to share our different sorts of knowledge in order to find solutions.”

Mary says, “It is true what Rose says. TreesFP were able to help my neighbour Judith to install what they call a zero-graze system for her cattle. That didn’t suit me, but it was fine for Judith because she has grown-up children who can help her with the work. Mine are small, but TreesFP helped me plant my fruit tree portfolio.”

Her neighbour Judith comments, “We now have our cattle in feeding pens, close to the house. TreesFP taught us how to plant fodder banks of Napier grass and agroforestry trees, which we cut and carry to the cows. This means that they are no longer overgrazing our sloping land and causing erosion. We collect and carry manure to the fields and fodder banks to fertilize them. It is a bit more work, but it is worth it. And we also give Mary some fodder for her cow.”

“But only in return for avocados,” says Mary.



How the design principles were used and applied

Rose explains:
"The zero graze and the fruit tree portfolio are just two of the interventions that we helped farmers with. That really illustrates how seriously we take the **principle of farmer-centredness**. We don't come with ready-made solutions. You have to work them out with the farmers.

"The **principle of aptness to place, people and purpose** is nicely illustrated by the cases of Judith and Mary. We quickly realized that Mary didn't have the time or the family labour to dedicate to a cut-and-carry system, but she was keenly interested in having a wider choice of fruits, year round. Through careful selection of the species to be planted, we were able to ensure that the trees would not interfere with the crops, particularly the maize, which would be seriously affected by any shade. In fact, we went beyond species – we were able to get some dwarf varieties of both mango and avocado that work for her. At the level of the village, too, the high participation we had in the portfolio process will ensure that we have a good match with local conditions and needs.

"Judith and some others really wanted to minimize the labour needed for the cut-and-carry system, so in most cases we established fodder banks of Napier grass close to the feeding pens. Also, in many cases we were able to plant the fodder shrubs like calliandra quite close to the pens. But the majority of the fodder trees are in the contour plantings that we established on the former grazing land. To choose the species, we asked the farmers to rank their preferences, and then we discussed in a workshop which species would work best together.

"With respect to the **principle of synergy**, finding the species that work best together was part of that. Even clearer, though, is the nutrient cycle that the villages now have going with the cut-and-carry system. The manure goes straight back on to the same fields that have previously been degraded by the cattle. That means that they are indirectly transferring nutrients from the fodder trees and grass back to the pastureland. In a few years, it should be possible to use the pastureland for crops, or to reintroduce livestock again, but with sustainable stocking rates.

"The principle of synergy also helps people to think out of the box. Mary is now growing some leafy vegetables and medicinal species in the partial shade cast by some of the fruit trees."

Land restoration for livelihoods and biodiversity conservation

Agroforestry systems exemplified: Simplified cacao multistrata system, sequential biodiverse fertilizer-species system, complex cacao system

The farmers' needs and the response

Ignacio, his son Julio, and Ignacio's cousin Rafaela are smallholder farmers in the Peruvian Amazon. Like others in their village, Santo Domingo, which is at 500 metres above sea level, they wanted both to increase their incomes and recover some of the degraded pastureland on their farms. For this reason, when they heard that people from FuturoVerde, a local NGO, were going to make a presentation in the local primary school about farm diversification and land restoration, they decided to attend.

Rafaela comments, "A few years back, we heard that FuturoVerde had received some money from Europe that they wanted to invest in sustainable agriculture, so that got us interested. I wasn't expecting much, but the agronomist from FutureVerde, Miguel, comes from near here, and he convinced me that this was something we shouldn't miss out on."

Miguel from FuturoVerde explains more about the opportunity: "The funding comes from an impact investor based in Switzerland. They invest in land restoration projects that also strengthen local livelihoods and contribute to biodiversity conservation. They contacted us to help them in building a portfolio here. As you probably know, Santo Domingo is in the buffer zone of one of our most important national parks."

Ignacio comments: "Attending that meeting was one of the best decisions we ever made. We were able to work with FuturoVerde to come up with solutions that really suited us. Not like that other NGO, who only wanted us to stick to their technological package. So, in my case – as you can see, I'm not as young as I was – they helped me install a cacao system that I could manage, same with my cousin Rafaela and her rehabilitated pastureland. And with my son Julio …"

"… I can explain Dad," says Julio. "I told them that cacao is the future, but a cacao that promotes biodiversity and is good for the environment. They knew that I was willing and able to put the time in … I think that my cacao plot is now one of the most diverse in the region. All this was possible because there is money to help in the establishment process, which is the most difficult part for us."

How the design principles were used and applied

Miguel explains: "You can see some differences and similarities in what we ended up doing with Ignacio, Rafaela and Julio. Ignacio's plot is fairly simple: a ground cover of centro[13] that helped to control weeds, fix nitrogen and add organic matter to the soil in the first years, cacao at 4 metres spacing, inga shading, and an upper storey of mahogany."

"I'm very proud of the mahogany," says Ignacio. "When I was young, mahogany was abundant here. Now it's all gone. So, with these mahogany trees, I'm helping to restore things to what they were before." Julio, his son, adds: "I think they also add to the sale value of the property, in case one day we want to move on."

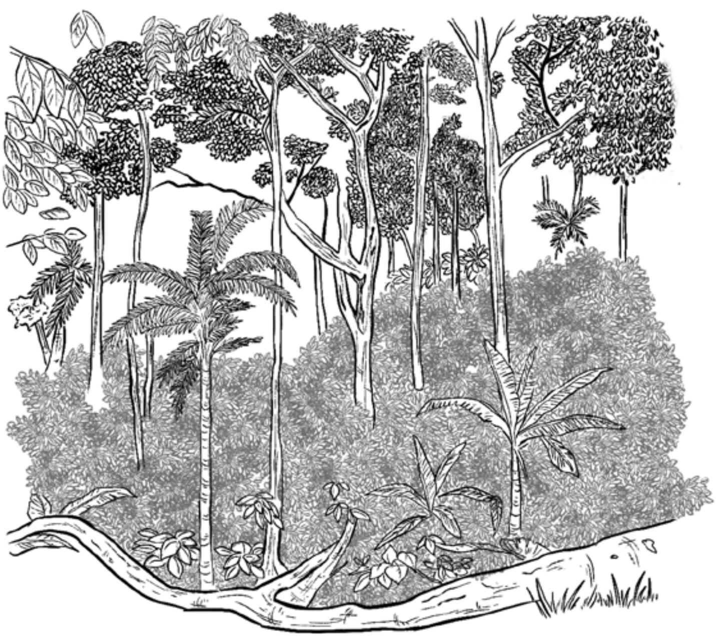
"As I was explaining," continues Miguel, "what we did with each farmer depended on the situation. For example, in Rafaela's case, she had a lot of degraded pastureland that she wanted to recover. She decided to opt for a sequential system, which means that the components change in a planned way as time goes on. First, we planted fertilizer species in five-metre-wide strips along the contour lines. Some of these just work by producing a lot of biomass, which then goes back to the soil after being cut back: for example, highly productive grasses like panic grass. We also planted Mexican sunflower, which is a great accumulator of phosphorus and potassium. Plus the leguminous species, of course – trees like gliricidia and inga, both of which tolerate these acid soils, and shorter-lived legumes like stylo and pigeon pea. Between the fertilizer strips, we planted one-metre-wide beds with annual crops and the fruit trees and plantain that you can now see. Eventually these are going to shade out the fertilizer species, and the organic matter will come from the trees themselves. If you come back in five years, it will look a bit like a forest – but one that will be full of productive species, what we call an agroforest."

[13] *Centrosema molle*, a ground cover plant widely planted in Latin America.

“I suppose we didn’t treat the land very well over the years,” says Rafaela. “Also, it is quite steep. Before I installed my restoration system you could see the earth, all dry and hard, through the blades of grass. Like that field you can see over there.” She points to a neighbour’s land: the criss-crossing tracks of the cattle on the gentle slope can be clearly seen. “I’m really happy that my land will be healthy again.”

“And then there’s Julio,” says Miguel. “His cacao plot is a lot more complex than his dad’s …”

“Yes,” says Julio, “with the cacao, the ginger, the turmeric, the black pepper, the annato, not to mention the timber species in the overstorey, it is complex. Managing this plot is a bit like managing a herd of cattle. You get to know each animal – each tree, in this case. You need to know when the flowering is coming, when the tree most needs light; you need to know how to read the signs that they give you. I pollard the gliricidias when the cacao is coming up to flowering time, because that’s when it needs more light. Later on, when the cacao trees get bigger and start to self shade, I’ll probably thin out some of the gliricidias and prune the other trees in the second storey. Sure, it’s labour intensive, but I’m a cacao farmer. It’s what I do. The more I put in, the greater the rewards.”



"So," says Miguel, "you can see that the farmers' interests were paramount, even though FuturoVerde and our funding partner have other goals. We explained all that to the community. Transparency first. Don't forget too that what you see with these three cases is only a sample of what we did. We've been able to negotiate a cacao export deal with one of the big cacao trading houses, and we've also given training in agribusiness management. We don't just come here to 'do agroforestry'. In some cases, we thought that other types of production were more suitable. That's what the **principle of farmer-centredness** means in practice.

"I think you can see how seriously we've taken the matching of these systems to what the farmers wanted … to what their land is suitable for, too. But if we're talking about the **principle of fitness to people, place, and purpose**, then you have to take into account the wider objectives. I mentioned before that our funding partner is interested not just in livelihoods, but also in enhancing biodiversity. If all we'd done had been to establish systems like Ignacio's simple cacao, then I don't think we'd have met those goals. What we've done is to diversify the structure of the landscape here, as well as to increase connectivity with remnant patches of forest. Simple cacao on its own wouldn't be enough, but when it's combined with agroforests, complex cacao, and other actions (like the boundary and riparian trees we've been helping people put in), what you have is a much more uneven landscape, with lots of different niches for wildlife. It's a far cry from the old mix of degraded pastureland and forest remnants.

"It's pretty clear that the **principle of synergy** is what underlies these systems. For example, in Ignacio's system, the cacao and inga give strong lateral shade to the young mahogany trees. That reduces the incidence and severity of mahogany shoot borer. That's why almost all Ignacio's mahoganies have just one, straight stem.

"Then look at Julio's system. We gave it a kick-start using organic fertilizers – manure, rock phosphate – but now you have a closed system where the only things coming out are the cacao seeds. He composts the pulp and the pods, and it goes back to the plot. The soil is moist, even in the dry season, because of the trees and the organic matter. Julio is like a manager of synergy, helping to channel light and nutrients where they are needed. Or we can talk about how Rafaela's fertilizer species prepared the ground – literally – for what she has now.

"But it's more than that, because our intervention was designed to have an effect greater than the sum of its parts. The different interventions complement each other, as far as biodiversity is concerned. Then the biodiversity value helps make demand for the cacao beans more stable, with the different kinds of certification we have. And one of Julio's sisters is talking about opening a tourist lodge, so people going to the national park can also learn about how agroforestry and trees-on-farms can help with conservation. So, we have synergy of different sorts and at different levels – agroecological at the plot level, ecological at the landscape level … even economic synergy."

Forest restoration through 'rainforestation'

Agroforestry systems exemplified: Complex sequential multistrata system

The farmers' needs and the response

Historically, management of the once magnificent dipterocarp forests near the community of La Pacífica in Leyte Province, Philippines had not served community members well. A village elder explains what happened: "When I was young, the land was covered with forest. Then the logging companies came in, and they left a wasteland. There were a few low-value trees left, but all the upland areas were covered by this kugon[14] grass. A wasteland is what they left, in spite of all the promises. We wanted to bring the forest back, but no one really knew how."

[14] *Imperata cylindrica*, a highly invasive grass native to tropical and subtropical areas worldwide (except the Americas).

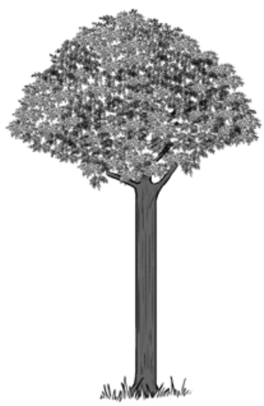
The villagers were at first sceptical when Angel, an agronomist who works with the local municipality, visited them to tell them about what he called ‘rainforestation’. Angel comments, “People are right to be sceptical, but they heard me out. I told them that we had technical back up from an international research centre and a local NGO called ReForesta, and I invited a group to go and see the work that they’ve done in one of the other partner municipalities.”

Gabriela, a community leader adds, “When we made that visit, we talked to other villagers, and we could see there was something in this rainforestation. That was ten years ago. Now you can see the results. Over that time, we’ve used agroforestry to bring back the forest. We have 50 hectares in total, and the time and energy we’ve put in are paying off. On top of that, the community nursery is making money from selling seedlings.”

How the design principles were used and applied

Villagers in the area have a lot of experience in cultivation of abaca[15] so they were pleased when the agronomists from ReForesta told them that it would work well in the rainforestation system. Angel explains: "Some of the dipterocarps grow best under light shade. Traditionally, that's also how people have cultivated abaca. When we explained about rainforestation in the agroforestry design workshop, the people at one suggested that abaca can provide some of the shade that the dipterocarps need. We also use some fast-growing native trees that fix nitrogen, especially agoho and narra.[16] We start off with some staple crops. Cereals can be used in the first year but we also plant some root crops that are a little more shade tolerant. The villages chose sweet potato and taro. Also some pineapple – not a root crop of course, but they do well in the kind of shade that the system has over the first two years. We also plant the abaca at the very start."

"At the end of the first year, the villagers start harvesting the root crops and replacing them with shade crops. They chose ginger as a cash crop, with some robusta coffee, just for their own use. By the end of the second year, all the root crops and the pineapple have been harvested, and we put in the dipterocarp seedlings. We also thin the agoho and the narra to reduce competition with all the other components. We do a second thinning much later, when we thin out some of the dipterocarps. That also allows enough light for continued abaca production, or even to put some cacao into the system. In the long term, the villagers will be able to selectively harvest the dipterocarps, as they have full tenure rights over the forest and its products. But I think that right now they are just glad to have the forest coming back."



Community leader Gabriela also had the idea of installing a community tree nursery. She comments, "Of course,

[15] *Musa textilis*, a species of banana native to the Philippines and grown for its fibre.
[16] *Casuarina equisefolia* and *Pterocarpus* spp.

the nursery is not an agroforestry system – we understand that – but it is an important part of **our** system. We collect local seeds of all the species, as well as what we call wildlings: orphan seedlings that we take in and look after until they are in good condition for planting. Sometimes it's the best way to get plants of the most valuable species, as many of them only produce seed once every few years. We can't wait that long!

"We received training in nursery operation from ReForesta, so we know all about things like root quality, sturdiness index and mycorrhizae. Here, we are experts. We don't sell the plants, but the municipality pays us and some other community and private nurseries to produce them, and then they give them to the projects. It's a win-win, a bit like trees and mycorrhizae."

Manolo, lead agroforester with ReForesta, takes up the story: "The rainforestation idea came from a partnership between Visayas State University and the German Technical Cooperation Agency, and has proved to be highly successful.[17] However, it won't work on the ground unless what we do is **farmer-centred**. So, we explain that part of our interest is to restore the dipterocarp forest, but that it has to be done in a way that benefits them from the start. It has to be farmer-centred, whatever global challenges you have in mind. In fact, that's one of the benefits of a sequential system – if it's done right. There are no gaps, no time when the income dries up. Here, you get the cereals and root crops, then the abaca and the ginger kick in. I think Angel didn't mention that most of the villagers also plant various other fruit species, either at the same time as the narra, or when the dipterocarps go in. Here, there will always be something to harvest. I was happy when the villagers suggested abaca, as it's a very thrifty species, perfect for agroforestry. The fibre that's extracted from it only makes up about two percent of the biomass – the rest stays in the system as mulch. It's **synergy** in action – abaca loves the shade that the narra and agoho give, and I guess the nitrogen that they fix … but it all goes back to them and the other components."

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[17] For more information, see: Rainforest Information Portal. 2010. Manila: Rain Forest Restoration Initiative. Accessed 2 June 2022. http://www.rainforestation.ph/index.html.

When things haven't gone right

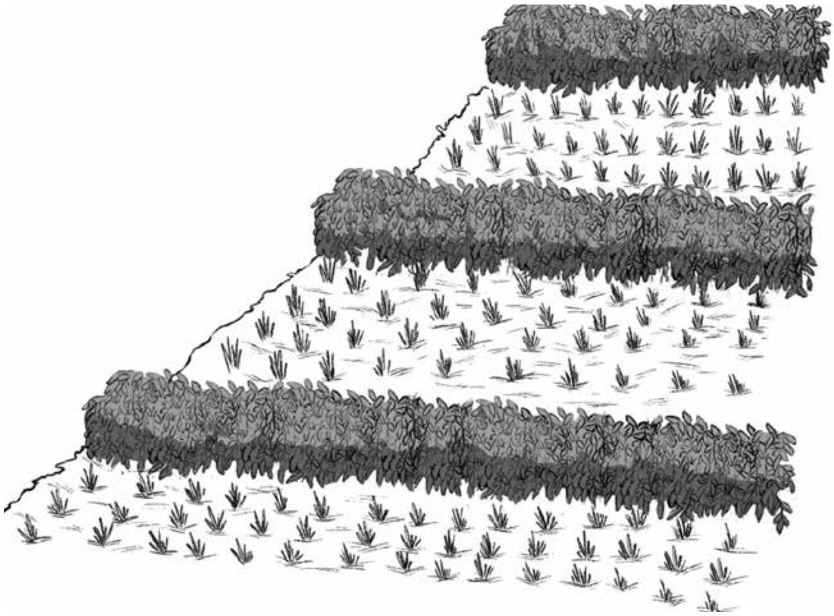
The farmers' needs and the response

The villagers in the Kenyan community we described in the first story have become agroforestry enthusiasts, but it hasn't always been that way. Mary explains: "As I said before, some people have had bad experiences with agroforestry. That was a long time ago, when I was quite little. But you know what they say, 'once bitten, twice shy'. And even those who were not bitten can be shy of the dog."

Extension worker Rose takes up the story. "After Mary told me what she could remember, I tried to find out what happened. I have a friend who works for the organization that led that agroforestry project, and she found some old reports and talked to some of the people who were involved. And, in the reports, I also found the names of some of the participants, who are still here in the village. In the final report there is even a nice picture of Mary when she was little, standing by one of the eucalyptus trees that they planted. She looks very happy in that photo."

"I think that they'd just given me a very big mango," says Mary, laughing.

"Let me tell you what happened," says Rose. "They planted trees in two different places, the same as we did with TreesFP: in the lowland near the houses, like where Mary has her fruit trees, and in the pastureland, like where Judith used to have her cows. But that is where the similarities end …



“They knew that people were short of cattle fodder and timber, so on all the boundaries of the farms they planted hedgerows with species that cattle can eat, like calliandra, gliricidia, leucaena, with timber trees like teak and pine every six metres. If you look, you can still see a few of the teak trees. But people didn’t like the hedgerows, because they had to be pruned all the time and – since they’re all spread out – it took too long to collect the leaves for fodder. And then there were the mice …”

“I can still remember them squeaking as I walked along our hedgerow,” interrupts Mary.

“… If you read the report,” continues Rose, “it explains how in the end they had to recommend not sowing maize seed too close to the hedgerows, because the mice would eat it all. After the project, everyone grubbed out the hedges. The timber trees have been cut down one-by-one over the years. They’ve been quite useful, but no one has planted any new ones.

"They tried alley cropping too. They knew that here the soils are quite poor and that most people can't afford fertilizer, so that was the solution, they said. They brought in some workers to plant gliricidia in rows in some of the fields. They were supposed to pump up the nutrients from below. There were four metres between the rows, and people planted their maize in the alleys. Every three months they were supposed to prune back the trees and leave the foliage to decompose, like green manure. But the maize didn't grow any faster, and the trees took up space that we used for crops before. The report doesn't say what happened in the end, but everyone says they mostly had to poison the trees to get rid of them.

"Then, on the hilly pastures, they said it was important that the cattle had some shade, and that trees could also help to prevent the grass from drying out so much in the dry season. So, people planted some trees – I think they got them from South America – and they had to protect them with little stockades around the groups of trees until they were too tall for the cattle to reach the leaves. To be fair, the trees were very fast growing, and after just one growing season they were almost two metres tall. So, they said that the people could remove the stockades to put the cattle in. I think that everybody knew what would happen. The cows couldn't reach the leaves, but they liked to scratch themselves on the trunks of the trees, and they soon pushed most of them over and broke the stems."

How the principles were misapplied or ignored: What went wrong?

"I think I can answer that question quite quickly," says Rose. "You know, the report talks a lot about participatory methods. But I think they thought that participation was just about asking people questions. Also, if you look at some of their tables of results, you can see that most of the people they talked to were men. I think that the women would have given them another story. So, this wasn't really a **farmer-centred process**, because either they didn't talk to the real farmers, or they didn't listen. As for the **principle of aptness** – as you can see, it is quite dry here and, as I have said, the soils are poor. That means that we can't have trees here that are going to take the nutrients and water that the crops need. Solutions that work elsewhere won't work here. You know that photo I mentioned, of Mary with the eucalypt tree? Well, you know, that tree is still there. It is because someone planted it in a very dry and rocky place that is not good for anything else. Almost all the others are gone.

"As for **synergy**, these systems were synergistic in theory, but in practice the different components were not connected, except negatively. The hedgerows competed with the maize and provided habitat for mice, the gliricidia just took up space, and the trees in the pastures were a bit of a waste of time."

Rose smiles. "So, nought out of three. You know, we are lucky. We've had the chance to learn from these kinds of mistakes."

Scientific names of species and genera

abaca: *Musa textilis*

acacia: Acacia species, especially A. *mangium*

açaí: *Euterpe oleracea*

African mahogany: *Khaya* species

agoho: *Casuarina equisetifolia*

alder: *Alnus* species

andiroba: *Carapa guianensis*

annatto: *Bixa orellana*

arrowroot: *Maranta arundinacea*

avocado: *Persea americana*

bananas: *Musa x paradisiaca* species

beans: *Phaseolus* species, especially *P. vulgaris*

beet: *Beta vulgaris*

black pepper: *Piper nigrum*

cacao: *Theobroma cacao*

calliandra: *Calliandra calothyrsus*

cassava: *Manihot esculenta*

casuarina: *Casuarina* species

centro: *Centrosema* species

chard: *Beta vulgaris*

chilli peppers: *Capsicum* species

durian: *Durio* species

erythrina: *Erythrina* species

eucalypt: *Eucalyptus* and *Corymbia* species

falcata (Moluccan albizia): *Falcataria falcata*

ginger: *Zingiber officinale*

gliricidia: *Gliricidia sepium*

hog plum: *Spondias mombin*

imperata: *Imperata* species

inga: *Inga* species, especially *I. edulis*

ipê: *Handroanthus* species

kudzu: *Pueraria* species

laurel: *Cordia alliodora*

lazones: *Lansium domesticum*

leucaena: *Leucaena leucocephala*

mango: *Mangifera indica*

Mexican sunflower: *Tithonia diversifolia*

musizi: *Maesopsis eminii*

napier grass: *Pennisetum purpureum*

narra: *Pterocarpus indicus*

panic grass: *Panicum* spp.

pigeon pea: *Cajanus cajan*

pine: *Pinus*

stylo: *Stylosanthes* species

sugarcane: *Saccharum officinarum*

taperebá: *Spondias mombin*

taro: *Colocasia esculenta*

tea: *Camellia sinensis*

teak: *Tectona grandis*

turmeric: *Curcuma longa*

vanilla: *Vanilla planifolia*

Vetiver grass: *Chrysopogon zizanioides*

yam: *Dioscorea* species

Glossary

The glossary includes only terms not defined in the main text.

Agrobiodiversity: biological diversity on farms, including, but not limited to species and varieties of domesticated plants and livestock

Agroecological services: positive contributions of one component of an agroforestry system (or other agroecosystem) to the growth, productivity or sustainability of other components (for example, shade, nitrogen-fixation)

(Agroforestry) intervention: any action or set of actions aimed at promoting or improving the practice of agroforestry

Alley cropping: an agroforestry practice in which crops are grown in "alleys" between rows of trees. The trees are regularly coppiced to produce nutrient-rich mulch

Biomass: plant or animal material, including dead and decomposing material

Climate change adaptation: in the agroforestry context, refers to actions taken to enable farming families to cope better with the effects of climate change

Climate change mitigation: actions taken to reduce current or future greenhouse gas emissions, or to reduce existing greenhouse gas concentrations

Climate-smart agriculture: agriculture that is adapted to, or that mitigates climate change

Domestication: the processes by which farmers or scientists change the genetic characteristics of wild plants and animals so that they are more useful for agriculture

Ecosystem services: the benefits environmental assets such as land, water, vegetation and atmosphere provide to people, especially in the form of essential goods and services (for example, clean air, water and food)

Enabling environment: factors, other than sound agroforestry practice and the natural environment, that determine whether a given agroforestry intervention is likely to be feasible or successful: for example, government policies, the availability of credit, or the quality of extension services (Enabling environments can be favourable or unfavourable.)

Flagship species: the main species (one or more) in an agroforestry system: that is, the crop, livestock, or tree species that the farmer considers the most important component

Flotilla species: species (usually trees or other plants) included in an agroforestry system primarily for the agroecological services they provide to the system and to the flagship species

Habitat connectivity: the degree to which animals, pollen and seeds are able to move between larger blocks of habitat, particularly via smaller habitat "bridges" (for example, riparian corridors) or "stepping-stones" (for example, scattered copses or individual trees)

Keystone species: a species that plays a very important ecological role due to other species' dependence on it

Landscape: a sizeable area of land (of the order to tens to hundreds of square kilometres) in which humans and natural ecosystems interact. (The interactions often drive changes in land cover, land use, livelihoods and demographics.)

Microsymbiont: a microorganism that forms a mutually beneficial relationship with another organism

Modern variety: relatively recent varieties of staple crops, particularly the dwarf varieties associated with the major yield increases of the "Green Revolution"

Monoculture: a crop field, orchard or forestry plantation consisting of only one species

Mulch: material used to cover the ground in order to control weed growth and maintain soil moisture. (In agroforestry, the term refers especially to dead leaves and branches, although other organic and inorganic materials can also be used.)

Multistrata system: an agroforestry system with distinct layers (strata) formed by the crowns of trees and understorey components.

Organic matter: animal and plant material (mostly dead or decomposing) in the soil

Photosynthesis: the process by which plants use light energy to make carbohydrates

Rotation length: in forestry, the number of years between regeneration and final harvesting of a stand of trees

Sequential system: see Successional system

Successional system: an agroforestry system, usually multistrata, that changes in a planned way over time as components reach the end of their life cycles or are shaded out by other components.

Technological package: a predetermined, standard set of cultivation practices for a given species or product, particularly one that growers are obliged to follow as a condition for receiving credit, subsidies or technical support

Traditional varieties: varieties of crops and trees, genetically differing from their wild relatives, that have been developed over long periods of time by farmers, and that are well suited to local conditions and farming practices

Taungya: the practice of growing staple crops in young timber plantations, typically as a means of plantation establishment

AGROFORESTRY:
A PRIMER

Conventional agriculture is very productive. But high productivity comes at a cost: soil that is depleted or eroded, watercourses that are polluted or drying up, and a food system that produces 20–40% of greenhouse gas emissions. Many people now agree that we urgently need to transform the food system, including agriculture. Agroforestry, as a nature-based approach to production and land use, will play an important role in this transformation. Agroforestry is not new; farmers have practised it for thousands of years, and scientists have recognized it since the 1970s as a productive and ecologically sustainable form of agriculture and land use. But now agroforestry is suddenly at centre stage; it is promoted as a land-use strategy to support climate change mitigation and climate change adaptation, biodiversity conservation, sustainable agriculture and other goals. Many organizations recommend or use it as a tool for restoring ecosystems – not only agricultural ones, but also forest landscapes.

Although not a cure-all, agroforestry has great potential to contribute to all the goals mentioned above. However, agroforestry is not just a matter of adding trees to farms. To realize its potential, practitioners need to understand its principles. *Agroforestry: A primer* is a guide to agroforestry principles and concepts – and how to use them effectively.

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