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Sustainable management of tropical forests

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Introduction

Tropical forests account for half of the world's forests, hold over half of all forest carbon and are home to more than 80% of terrestrial biodiversity. They also play a fundamental role in climate regulation on both regional and global scales, not to mention protecting soils from erosion, regulating water systems, lowering temperatures and providing countless products for local populations: meat, fruit, materials and medicinal plants. Unfortunately, tropical forests are disappearing at an alarming rate. Over the last thirty years, the planet has lost just over four hundred million hectares (400 Mha) of tropical forests, an average of 13 Mha per year. This total loss of forest cover is mainly due to the conversion of tropical forests to farmland, pasture or industrial plantations (oil palm, sugar cane, fast-growing trees). This deforestation is compounded by forest degradation which, in certain regions of the world such as Amazonia, affects as much land as deforestation. There is no single, universal definition of forest degradation. Generally speaking, it is a reduction in the forest's capacity to provide goods and services, due to human or natural disturbance. However, this definition does not take into account the temporal and quantitative aspects of degradation, which remain key elements. In fact, depending on the type, intensity and frequency of the disturbance suffered, the degradation will be more or less significant and long-lasting. The more intense and frequent the disturbance, the longer it will take for the forest ecosystem to recover its functions. In extreme cases, the disturbance is so severe that the ecosystem cannot regenerate and shifts to a different stable state, such as scrubland.

The two main causes of forest degradation are the uncontrolled, and usually illegal, exploitation of timber or firewood, and fragmentation, which is again linked to deforestation and exacerbated by the effects of climate change. Degradation causes varying degrees of disturbance depending on the causes and practices. The ability of a forest to recover, i.e. to return to a state comparable to its initial state, will depend essentially on the intensity and frequency of these disturbances.

As early as 1992, the United Nations Conference on Environment and Development warned of the need to preserve and conserve tropical forests for the good and survival of mankind; today, this issue has become an absolute priority. To achieve this goal, two complementary but often contrasted approaches exist. The first prioritizes strict conservation by creating protected areas, minimizing human exploitation of resources. In contrast, the second approach supports sustainable resource management, allowing controlled use for the benefit of local communities and society as a whole. Foresters chose the second method, based on the principle that a managed forest that provides goods and services for the population, the State and society will be protected and conserved.

Unfortunately, the reality on the ground continues to contradict this principle. Illegal logging, which is still widespread in many tropical countries, causes major damage to forest stands and diminishes their ability to regenerate and withstand the effects of climate change. Tropical countries and the international community are still slow to consider the problem of tropical forest degradation as an absolute emergency, in the same way as deforestation.

The aim of this essay is therefore to provide an overview, accessible to non-specialists, of the impact of timber harvesting on tropical forests. It also suggests ways in which timber harvesting can be made sustainable, thereby helping to conserve tropical forest ecosystems and improve the living conditions of millions of people who depend on them.

After a career spanning more than thirty years at the *Centre de coopération internationale en recherche agronomique pour le développement* (CIRAD), during which I travelled through the main tropical forest massifs to study the impact of logging on the capacity of tropical forests to recover, I decided to write this essay to share my experience with as many people as possible. Throughout my long career as a tropical forest ecologist, I have worked tirelessly to explain and convince people that selective logging of tropical forests can be an effective and complementary means of creating protected areas and conserving large areas of forest for the benefit of the people and countries of the global South.

Before diving into the heart of the matter, it is important to correct some misconceptions about tropical forests. They remain largely unknown to the Western public and are often idealized as a lost paradise—one where humans have no place, except as conservationists, as if they were incapable of living there without actively preserving them (Chapter 1). Yet, since the very beginning of humanity, humans have inhabited forests, whether temperate, boreal or tropical. Today, the 'indigenous' peoples, small-scale farmers and local populations are increasingly demanding the right to live in and from their forests, i.e. to use them while conserving them.

Timber harvesting, which is often blamed for all the harm done and considered to be the main source of deforestation, deserves to be objectively 'explained' rather than rehabilitated.

The aim of this essay is to clarify the principles of selective logging (Chapter 2), then to describe its real impact in a factual manner, and finally to lay the foundations for sustainable logging (Chapter 3). This exercise required a comparison of the realities on the ground with the results of the research and the recommendations arising from it. In the final chapter, therefore, I have tried to suggest ways of promoting and extending sustainable management practices, taking account of the environmental, social, economic and political dimensions. Finally, the conclusion looks at possible paths towards greater sustainability.

TROPICAL FORESTS

Tropical forests are found in a band on either side of the equator bounded by the Tropic of Cancer and the Tropic of Capricorn. The characteristics of this band are that in each of the tropics, the Sun appears at its zenith once a year, at the summer solstice in June for the Tropic of Cancer and at the winter solstice in December for the Tropic of Capricorn. Outside this zone, the Sun is never vertical to the ground. So when it is at its zenith over the Tropic of Cancer, it is summer in the northern hemisphere and winter in the southern hemisphere, and vice versa when it reaches its zenith over the Tropic of Capricorn. Between these two seasons, the Sun is at its zenith at the equator twice a year, on the equinoxes of March and September. In this vast bioclimatic zone, the average temperature in the coldest month rarely falls below 20°C, except occasionally at altitude. It is also the region of the planet that receives the highest light intensity.

A VAST DIVERSITY

The term ‘tropical forests’ covers a huge diversity of ecosystems, whose variation is mainly based on three factors: differences in rainfall within the tropical zone, altitude, which influences temperature, and the nature of the soil, which sometimes requires great adaptation by the trees (Figure 1).

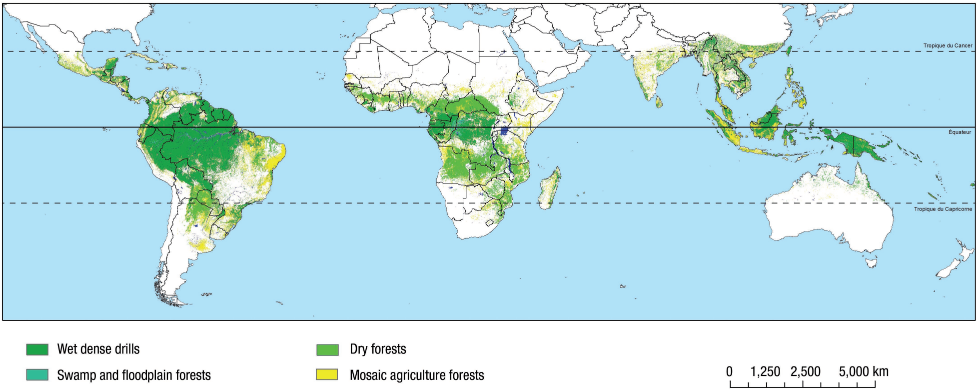

Figure 1. Distribution of the main types of tropical forest in the world (source: Global Forest Cover, *in* Sist *et al*., 2021).

Within the tropical region, the climate is not uniform. Rainfall is highest at the equator, often exceeding 2,000 to 2,500 mm/year, and the dry season is short (2–3 months). The further north or south one moves away from the equator, the longer the dry seasons and the lower the rainfall become. Tropical forest ecosystems have therefore adapted to this climatic variability. Near the equator, tropical rainforests dominate (Figure 2A). This type of tropical forest is often called ‘evergreen’, because the trees remain green all year round, although this does not mean that they do not lose their leaves but simply that new ones are being produced continuously. The air is saturated with moisture most of the time, and rainfall is abundant throughout the year, except for one or two months of respite during the dry season. These are the richest terrestrial ecosystems on Earth in terms of plant and animal species. More than 300 species of trees have been counted in a hectare of forest in the Peruvian Amazon at the foot of the Andes. The richest forests in France rarely have more than 20!

The largest and tallest trees in the tropics can also be found in evergreen tropical rainforests. The canopy (the roof of the forest) reaches between 35 and 60 m, and some trees go beyond this to reach heights of over 70 m. The height record belongs to a tree of the Dipterocarpaceae family in the forest of Borneo, a red meranti (*Shorea faguetiana*), measured at 100.8 m. This makes it the fourth tallest living tree in the world, with the Sequoia (*Sequoia sempervirens*) of the American West (115.7 m) in first place.

When rainfall decreases and the dry seasons extend in length and intensity, evergreen tropical rainforest gives way to semi-deciduous tropical forest, so called because some of the trees lose all their leaves during the dry season to better withstand the drought. It is from their leaves that the trees lose the most water, making them their weakest part during extreme periods of drought. This semi-deciduous forest develops under annual rainfall patterns between 1,500 and 2,000 mm. In terms of structure and biodiversity, it is very similar to evergreen tropical rainforests, and these two types of forest have many species in common.

Dry forests are found in regions with annual rainfall of between 800 and 1,200 mm. The trees are smaller and rarely reach 20 m in height, except along rivers, where a more luxuriant forest can develop. The longer and more intense the dry seasons, i.e. the further away from the equator, the less dense the forests. There is a gradual transition to wooded savannah. Trees are also more widely spaced, and most lose their leaves in the dry season. The vegetation is also adapted to frequent fire. Many tree species in the Brazilian Cerrado have developed thick bark to protect the living wood carrying the sap from fires.

In mountain environments, forest species must adapt to temperature and humidity conditions, which change considerably with altitude. These forests are often referred to as 'cloud forests' (Figure 2B). The air here is saturated with water, and as altitude increases, temperatures not only drop but also vary greatly between day and night. High in the mountains, above 2,000 m, the forests are home to many temperate climate plants such as rhododendrons, heathers and conifers.

Soil plays a crucial role in characterising tropical forest types. Hydromorphic soils, characterised by their poor drainage capacity, are frequently found near large rivers like the Amazon. These rivers experience constant or periodic flooding depending on the season, leading to the development of so-called 'flooded' forests, which can either experience periodic flooding during the rainy season or remain permanently flooded. (Figure 2C). In flooded forests, the trees have their feet in the water for a large part of the year. However, to ensure that their absorption functions properly, the roots need oxygen, which is in short supply in waterlogged marshy soils. To remedy this, many trees in flooded forests develop pneumatophores, portions of their roots that grow towards the surface of the water and then rise above both soil and water to capture the necessary oxygen.

Mangroves (Figure 2D) are special forests that should be distinguished from the other flooded forests mentioned above. They are found along coasts and estuaries, where they are influenced by the tides and develop in brackish water whose salinity varies considerably according to the tidal cycle. In addition to oxygen depletion during high tide, the soil is muddy and unstable. Mangroves, which reign supreme over these forests, have found a solution to ensure their stability on such a soft substrate: they grow on stilt roots, which form an often inextricable tangle. Many mangrove species are viviparous, meaning that the seed germinates in the fruit while it is still on the tree. Once the root is sufficiently developed, the fruit, which is not really a fruit anymore, but rather a 'propagule', falls and is planted in the mud

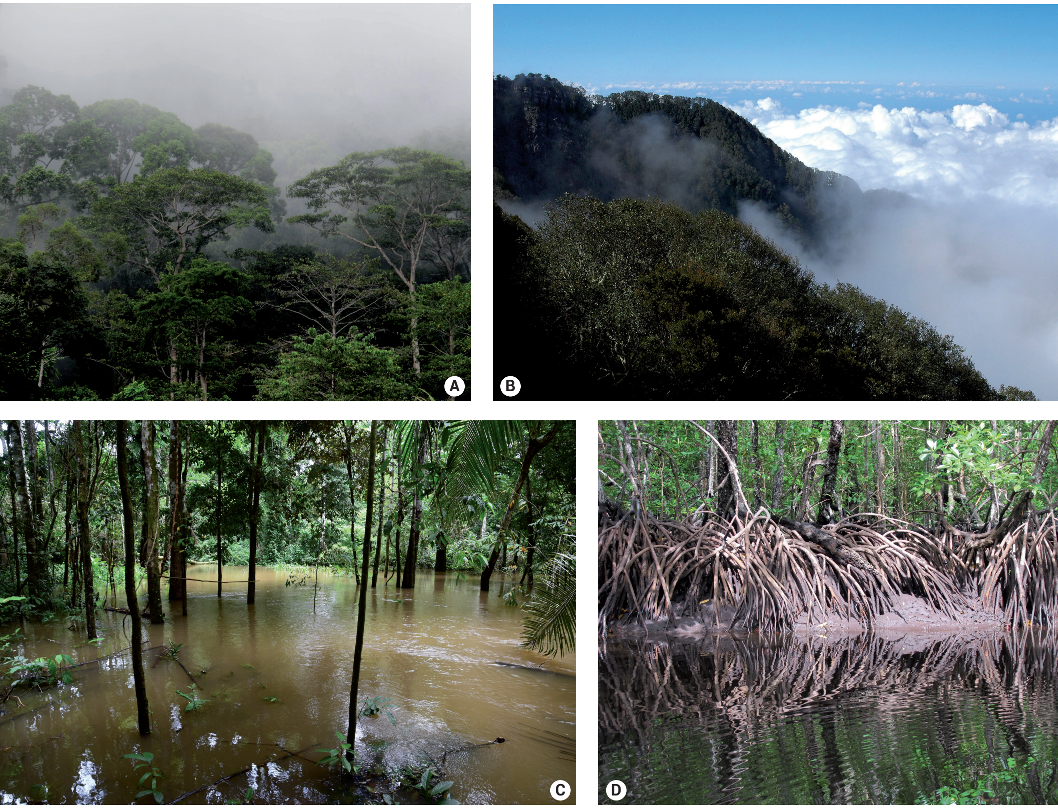

Figure 2. The different types of forest.
A) Tropical rainforest of Borneo, East Kalimantan, Indonesia (© Plinio Sist).
B) Mountain forest, Costa Rica (© Bruno Locatelli).
C) Tropical swamp forest, Amazonia (© Bruno Locatelli).
D) Mangrove forest of West Papua, Indonesia (© Manuel Boissière).

thanks to its already developed root. If the propagule falls at high tide, it floats. Depending on the currents and tides, it can travel a great distance before finally settling in the mud and giving rise to a new mangrove. Mangroves are true nurseries, as many species of fish, crustaceans and birds come here to reproduce.

MULTIPLE ROLES

Tropical forests provide invaluable environmental services. First and foremost, they are an unparalleled reservoir of biodiversity. It is estimated that they are home to 80% of terrestrial biodiversity. The Amazon rainforest contains some 390 billion trees representing 16,000 species, or 13% of the world's trees, and 50,000 plant species. Every year, biologists discover new plant and animal species in these forests that have never been described before.

Tropical forests contain as yet undiscovered biologically active compounds that could meet humanity's future needs in the fight against emerging diseases. Around 70% of the plants identified as having anti-cancer properties by the US National Cancer Institute originate from tropical forests. Moreover, it is estimated that 25% of the drugs used in Western medicine are derived from chemical compounds produced by tropical plant species. However, the pharmaceutical potential of tropical forests remains largely undiscovered and deforestation is increasingly compromising our ability to discover the yet unknown medicinal properties of many tropical forest plant species. This was the case for calanolide A, a compound produced by a tree of the Clusiaceae family, *Calophyllum lanigerum* var. *austrocoriaceum*. This tree is found in the sandy forests known as 'kerangas' in Borneo. Samples taken in 1987 in Sarawak (the Malaysian state in the northwest of Borneo) revealed that this plant produced a compound active against HIV. A second expedition was then organised in 1992 to collect more material and isolate the active compound. Unfortunately, the tree could no longer be found there, leading the botanists to search for other specimens elsewhere. Some were eventually found in the Singapore Botanic

Garden, which possessed several plants collected by the British more than 100 years earlier. By collecting samples, it was finally possible to isolate the active compound: calanolide A.

Calanolide A is a powerful inhibitor of HIV reverse transcriptase, preventing the body's healthy T cells from becoming infected. Very soon after this discovery, Sarawak MediChem Pharmaceuticals developed and patented a synthesis process. Calanolide A and molecules in the same family remain experimental anti-HIV drugs and have not yet been approved for commercial pharmaceutical production. However, this example gives us food for thought about the yet unknown wealth of tropical forests, whose disappearance forever jeopardises the development of this pharmacological potential.

Indigenous forest populations have a very detailed ancestral knowledge of the pharmacopoeia of their forests, but this remains very poorly documented. This knowledge is also, unfortunately, tending to disappear due to deforestation, the expulsion of forest populations from their environments for exploitation purposes, urbanisation and the abandonment of the ancestral way of life by younger generations.

Tropical forests also provide a large number of more familiar food plants used throughout the world: manioc, cocoa, oil palm and coffee. These plant products are complemented by game, which is the main source of protein for many forest populations, particularly in rural areas of Central Africa.

Finally, the tropical forest is a source of materials such as wood, rattans, bamboo, resins and latex, the best known of which is undoubtedly rubber, which made the short-lived fortunes of the 'rubber barons' of Belém and Manaus in the Amazon.

The rise of rubber

Mass production of rubber, which began in the second half of the 19th century, started exclusively in Amazonia. This is the endemic region of the tree that produces it, *Hevea brasiliensis*, a member of the Euphorbiaceae family. Rubber is extracted from latex, which is different from sap: sap ensures the circulation of water, mineral salts and sugars and circulates in specialised vessels, whereas latex circulates in a separate network of vessels: the laticifer canals. Latex bleeds when the bark suffers a wound such as an incision, and when it dries it forms a protective barrier. The name '*caoutchouc*' for rubber comes from the Quechua *cao*, meaning 'wood', and *tchu*, meaning 'weeping': the weeping tree. The development of the rubber industry from the 1850s onwards, for the manufacture of boots and mackintoshes, then tyres for the first cars, generated a veritable 'rubber fever' in the countries of the Amazon. The peak was between 1879 and 1912, and colossal fortunes were built on the rubber trade. This led to the rise of Amazonian cities such as Manaus and Belém, whose splendour was reflected in the construction of sumptuous baroque-style palaces, such as the Amazonas Theatre in Manaus and the Peace Theatre in Belém, and in the early adoption of the latest technological discoveries of the time. Manaus was the first Brazilian city to install electric street lighting, in 1898. But the other side of the coin was darker: these fortunes, and the splendour that flowed from them, were based on the exploitation of harvesting workers, the *seringueiros*, who were kept in a state of semi-slavery and made to live like convicts. This splendour was short-lived, however, as rubber became the source of the first known example of modern international biopiracy. From the beginning of the 20th century, *Hevea brasiliensis* started to be intensively cultivated in other parts of the world, with the Amazon losing its exclusivity and global supremacy. As the demand for rubber continued to rise throughout the 19th century, the latex trade attracted growing interest from the British, who also intended to trade in it, but from their own empire. The aim was to introduce the plant to British colonies, particularly in Asia, so that it could be cultivated on plantations, thereby ensuring independent production that would compete with that coming from Amazonia. In 1876, Clements Markham, Secretary to the

Indian Office, asked an English adventurer, Henry Alexander Wickham, who had been living in Santarém in Brazil for several years, to send rubber tree seeds to London. Wickham accepted the challenge and collected 74,000 seeds—the equivalent of one tonne—which he took on board the steamship *Amazonas*, arriving in Liverpool on 10 June 1876. The seeds were sown on 16 June, but only 3.6% germinated. A year later, in 1877, eleven seedlings were sent to the Singapore Botanic Garden, and the seeds harvested from these plants in 1889 were used to grow rubber trees on a large scale, first in Malaysia and then throughout Southeast Asia. These original eleven plants are responsible for 90% of the rubber trees planted in the world today.

By 1910, plantation rubber production had supplanted that of Brazil, which collapsed. Today, 90% of the world's annual natural rubber production (14 Mt) comes from Asia. Thailand and Indonesia are the two biggest producers, with 4.9 Mt and 3.2 Mt respectively, or 60% of world production. Brazilian rubber now accounts for just 2% of the world's natural rubber production. Most of this is produced by small-scale farmers: 80% of production comes from family plantations ranging in size from 0.5 to 10 hectares. Worldwide, around 30 million people make their living from rubber cultivation.

Many of the active ingredients in medicinal plants from tropical forests, once identified and extracted, were very quickly chemically synthesised and then industrially produced by pharmaceutical laboratories, making it unnecessary to harvest the plants themselves. Most food plants from tropical forests have been domesticated and planted intensively to control and increase their production, while creating new markets on a global scale. These practices are responsible for some of the deforestation throughout the tropical world. The crops include cocoa, oil palm, banana and robusta coffee to name but a few.

In addition to the many material goods they provide, tropical forests play an essential role in the water cycle, both in terms of climate and in the protection and regulation of watercourses. The Amazon rainforest, for example, is a veritable sponge, absorbing the enormous quantities of rain that fall during the wet season. Tropical forests thus prevent soil erosion, which would otherwise be carried off into rivers, and reduce the risk of flooding by regulating watercourses. They are also generous, however, because some of this water is returned to the atmosphere through evapotranspiration produced by the transpiration of trees and vegetation as a whole. A large tree in the Amazon rainforest transpires up to 1,000 litres of water every day. It is estimated that the Amazon rainforest produces more than 20 billion tonnes of water daily in the form of water vapour, which escapes into the atmosphere. In comparison, the Amazon River discharges 17 billion tonnes of water into the ocean every day. The nickname 'flying rivers' given by researchers to this mass of atmospheric water is therefore quite apt. Once in the atmosphere, the moisture is transported by atmospheric currents. Above the forest, some of the moisture generates rain while capturing the transpiration of the trees. As these masses of moist air advance, they are blocked by the Andes mountain range and continue southwards. As they leave the forest, they cause rain and are the source of much of the precipitation in the western Amazon, southern Brazil, Uruguay, Paraguay and northern Argentina. This phenomenon is not specific to the Amazon but can also be observed over the Congo Basin forest and in Siberia.

Tropical forests contain more than half (55%, or 471 billion tonnes) of the world's forest carbon stock, the equivalent of around 40 years' worth of CO_2 emissions from human activities (fossil fuel use and cement production). Every year, forests absorb the equivalent of 15% of anthropogenic carbon emissions (fossil fuels and land-use change). On a global scale, tropical forests still act as carbon sinks, absorbing more CO_2 than they release; however, the effects of climate change, particularly longer and more intense periods of drought, are causing higher local tree mortality, which is no longer offset by the growth of surviving trees. This decline is particularly visible in Amazonia, where forests have been storing less carbon since 2000. In the 1990s, the Amazonian forest stored an average of 0.54 tC/ha/year, compared with just 0.38 tC/ha/year between 2000 and 2010, a drop of 30%. In Central Africa, on the other hand, this decline has only just begun, partly because of the low rate of deforestation, and partly because African tropical forests are better adapted to drought and high temperatures.

A LONG HISTORY OF RESOURCE EXPLOITATION

Forests have always been exploited by humans, and tropical forests are no exception. Through hunting, gathering and shifting agriculture, human populations have constantly modified and shaped forest ecosystems, including those in tropical regions. Tropical forests were long considered to be primary, i.e. free from any human presence or disturbance, but relatively recent archaeological studies have clearly uncovered evidence of human presence in the past. The Amazon is perhaps the most notorious example. For a very long time, human presence was ignored or underestimated, but thanks to recent archaeological studies using new detection tools, such as airborne Lidar by plane or drone, this presence is now increasingly well documented and detected. The earliest traces date back around 20,000 years, although it was not until 13,000 years ago that a stable and repeated human presence began to emerge, preceding the advent of agriculture. Before the arrival of the Europeans in 1492, the Amazonian Amerindian population was estimated at almost 10 million, and the total population of America at around 60 million. The diseases brought by the Europeans, to which the Amerindians had no immunity (influenza, smallpox, etc.), decimated 90% of the indigenous population over the following century. Today, the Amazonian Amerindian peoples number 1.2 million.

The Amerindians lived either in small semi-permanent villages or in permanent settlements covering up to 50 ha. Archaeological research in Amazonia developed considerably at the beginning of the 21st century, notably because of new laws requiring systematic excavations prior to the construction of major infrastructures. These excavations have revealed countless archaeological sites that were previously unsuspected. This human presence has inevitably left its mark on the environment. Recent botanical inventories show that the forests of the Amazon regions with the most archaeological sites recorded to date and, therefore, the most inhabited, are undeniably home to more species of domesticated plants than forests in less populated regions or regions with very few archaeological sites. This human influence on the floristic composition of the forests is noticeable within a 40 km radius of the ancient Amerindian villages. This concentration of useful plants can only be explained by human practices in the management of natural resources, favouring the growth of certain useful species while eliminating undesirable or competitive plants, the protection of useful trees during their development, the direct dispersal of seeds to prevent them being eaten on the ground by rodents, the selection of plants with certain sought-after properties, the cultivation of useful plants and, finally, the increase in soil fertility and structure, such as the creation of anthropogenic soils and earthworks. For example, the Kayapós in the southern Amazon have long practised biological control, using *Azteca* ants to repel leaf-cutting ants to prevent them from attacking the leaves of useful species. The Huaorani in the west and the Hotï in the north of the Amazon increase the abundance of several useful plant species by sparing and favouring the natural aggregations of certain species. It is not uncommon, for example, to come across 'patches' of Brazilian walnut (*Bertholletia excelsa*) in the Amazon rainforest that look completely natural but are probably the result of such practices. Today's indigenous and traditional populations attribute the aggregated distribution of useful perennials to the actions of their ancestors. It is also a criterion for choosing the location of a new village. For example, the Nukak people in the Colombian Amazon prefer to camp near sororoca plants (*Phenakospermum guyannense*), because they believe that these plants were brought by their ancestors. In turn, they themselves then sow large quantities of seeds around their temporary campsites to leave a trace of their passage. These management practices, which can be described as silvicultural, were long unsuspected but are still visible and detectable today, so much so that the composition of the flora and richness of palm trees could be a good indicator of the possible presence of hidden archaeological sites.

'Black earth' is another well-known example of a strong human presence prior to the arrival of the Europeans. The exceptional fertility of black earth is due to particularly high concentrations of charcoal, organic matter and nutrients (notably nitrogen, phosphorus, potassium and calcium). They also contain many fragments of pottery and food remains (fish, game, shellfish), testifying to their anthropogenic origin. Most specialists believe that these black earths were deliberately created by the Amerindians, by incorporating charcoal. This fuel plays a key role in retaining large quantities of water and nutrients.

The fertility of these soils means that, 500 years after they were abandoned, agricultural yields are still exceptional. However, a recent study of an archaeological site in the Amazon region of Brazil contests the purely anthropogenic origin of these soils, which could be mainly of natural origin (alluvial deposits).

On this site, the presence of human artefacts can be simply explained by the fact that the Amerindians recognised fertile land and settled there to practise agriculture.

The Amazon is far from being the only example of ancestral forest resource management practices. In fact, they are practised throughout the tropical world in ways and to intensities that are specific to each continent or region. There is a huge diversity of practices, ranging from very limited intervention in the forest, where certain plants are favoured over others without significantly altering the forest structure, to forests that are quite literally domesticated, with the dominance of a particular species, such as the dammar agroforests in Indonesia or the coffee agroforests in Ethiopia.

ECOSYSTEMS ON THE BRINK OF EXTINCTION

Until the end of the 19th century, deforestation occurred mainly in temperate countries, such as Europe, where it began in Antiquity and intensified during the Middle Ages. From 1920 onwards, the trend was reversed: deforestation decreased in temperate zones, particularly in Europe, where forests once again gained ground, and, on the contrary, deforestation was significant in tropical regions, amounting to around 200 Mha between 1920 and 1949 (6.6 Mha/year), whereas between 1700 and 1920 it had only accumulated an area of around 150 Mha (0.7 Mha/year). Between 1950 and 1979, tropical deforestation continued to increase, with a total deforested area of 310 Mha (10 Mha/year). Over the last thirty years (1990–2020), the gross loss of tropical forests has reached 420 Mha, an annual rate of 13 Mha.

The causes of deforestation are complex and vary from country to country, region to region and continent to continent, but agriculture is the main culprit (80%). Tropical forests are disappearing because they are being converted to pasture, farmland and industrial plantations of palm oil, soya, eucalyptus, cocoa and coffee. In many cases, deforestation has been orchestrated by governments for reasons of development and agrarian reform. This was the case, for example, in Indonesia and Brazil in the 1960s and 1970s, which respectively launched agrarian colonisation programmes in sparsely populated regions: the islands of Sumatra and Borneo in the case of Indonesia, and the Amazon in the case of Brazil. In Côte d'Ivoire, from the 1960s onwards, the government-led economic development policy was based on cocoa farming. Today, the country is the world's leading cocoa producer, but unfortunately this was at the expense of its forests, which have shrunk from 14 Mha in 1960 to just 2 Mha today. Côte d'Ivoire, which used to export wood, now has to import it for its own needs.

In addition to deforestation, forests are exploited for their timber and non-timber forest products. Depending on the techniques used, this exploitation can cause considerable damage. However, despite the damage and disruption caused, timber harvesting can be a means of conserving large areas of forest for the benefit of local communities. In theory, by giving an economic value to the forests, the stakeholders involved—forestry operators, processing industries and the State itself, which collects taxes on the timber harvested and processed—have good reasons to conserve the production forests that bring them benefits. In practice, however, the situation is far more complex, as most forestry stakeholders focus on immediate benefits and find it very difficult to think in terms of cycles lasting several decades that would be required for sustainable forestry.

Timber harvesting mainly concerns evergreen and semi-deciduous tropical rainforests, which account for half of all tropical forests (964 Mha). Dry forests, on the other hand, are exploited for cooking wood, particularly in Africa, where wood remains the main source of energy for most households, as well as for wood for a variety of other uses and a host of other products (fodder, fruit, flour and gums). Dry forests provide many important and essential environmental functions for millions of people in regions that are subject to very severe constraints.

SELECTIVE LOGGING OF TROPICAL FORESTS

Forestry science is based on two major concepts that are worth remembering. The first is forest management, a kind of roadmap called a 'management plan' that defines the long-term management objectives for a forest, i.e. over several decades. These objectives can vary greatly from one manager, region or type of forest to another. Forest management therefore varies based on the managers' perceptions and the roles they assign to the forests.

The second major concept is silviculture, which is the set of practices used to achieve the objectives defined by the forest management plan in consultation with the stakeholders. For example, if a forest is designated exclusively for timber production, the silviculture practices put in place will prioritise the yield of a consistent quantity of timber across the various harvests throughout the production period, which covers several decades. On the other hand, if the management objective is to preserve the forest in a watershed used to produce drinking water, then silvicultural practices will strive to preserve the quantity and quality of the water produced by maintaining a healthy forest.

These concepts can be applied on a number of scales, from nationwide to forest management unit. On a national scale, a range of forest management and silvicultural practices need to be put in place to meet the country's objectives and needs. Forest management therefore involves the management of natural forests of different types (humid tropical, dry) and monospecific plantations (a single species, exotic or otherwise) or multispecific plantations (several species), depending on the management objectives. Silvicultural practices will also be highly varied and adapted to the types of forests and plantations and to the management objectives. As far as timber production is concerned, there are many uses for wood, including pulp and lumber. Each use involves a potentially different group of tree species. For example, fast-growing species such as planted eucalyptus are used exclusively for pulp. Tropical sawn timber, on the other hand, comes mainly from natural forests.

A BRIEF HISTORY OF TROPICAL FORESTRY

Modern tropical forestry emerged at the same time as the colonisation of tropical regions by European nations, notably France and Great Britain. The colonial powers' need for timber for their own economic development (industrial development at the end of the 19th and beginning of the 20th century, the rise of steam engines, wars) directed forest management towards objectives of sustained timber production. Tropical forestry was naturally inspired by temperate forestry, without really considering the specific characteristics of tropical forest ecosystems, whose complexity and species richness quickly became insurmountable obstacles for European foresters, who were used to managing much simpler forests that had been domesticated for several centuries. From the end of the 19th century to the early 1960s, before the independence of most colonised tropical countries, tropical forestry strove to 'simplify' tropical forest ecosystems by encouraging the regeneration and growth of a few species of commercial interest. The aim was to transform an ecosystem containing between 100 and 300 tree species per hectare into a forest containing just ten or so species, as is the case in European forests. This system is largely based on the high regular forest in temperate regions, which in the tropics is actually more like a plantation than a natural forest.

In reality, these silvicultural practices proved to be very poorly adapted to tropical forests and impossible to implement on a large scale. By eliminating the vast majority of non-commercial species, these practices considerably opened up the forest cover and encouraged the regeneration of invasive and extremely dynamic pioneer vegetation. This type of vegetation, made up of very light fast-growing tree species, mostly without any commercial interest, prevented the regeneration of the commercial species that were being promoted. Only regular clearing of this very dense secondary vegetation, often containing many lianas, made it possible to solve the problem, but the costs were far too high for these practices to be implemented over thousands of hectares, especially as natural forests were at the time a very cheap source of wood.

Over the decades, the objectives of tropical forest management have changed considerably. From simply sources of timber, natural tropical forests have become suppliers of many other goods (fruit, resins, medicinal plants) and services (soil and water conservation, biodiversity, carbon storage). Furthermore, the social dimension of forestry, largely ignored until the 1980s and 1990s, has continued to grow since then, with increasing demands from indigenous or local populations who oppose the outside exploitation of forest resources and claim the right to use them for their own benefit and according to their own vision.

PRINCIPLES OF SELECTIVE LOGGING

Complex silvicultural systems aimed at simplifying forest stands as much as possible to favour only a few species of commercial interest were replaced around 1960–1970 by a simpler and less costly model: selective logging.

Unlike more radical and intensive logging methods such as clear-cutting, selective logging aims to harvest only the largest mature trees of commercial interest. This maintains the natural regeneration ability of the forest. In theory, the aim of selective logging is to minimise disturbance to the forest ecosystem. By harvesting only certain trees, a greater diversity of plant and animal species is preserved, helping to maintain the ecological balance. Compared with clear-cutting, which means felling all the trees in an area, selective logging limits the damage caused to the soil, vegetation and natural habitats. By retaining a large part of the forest canopy and trees, the vital forest functions such as climate regulation, water filtration and soil preservation are maintained. To minimise the impact on the soil or watercourses and preserve the forest's capacity to regenerate, so-called 'low-impact' logging techniques are an essential approach.

The principle of selective logging is therefore to remove trees of commercial interest above a defined diameter, while preserving the rest of the forest ecosystem. Once the trees have been removed, a resting period, known as a 'harvest cycle', is established to allow the forest to regenerate (Figure 3). In the absence of data on growth and therefore on recovery rates of the timber volume, the length of the harvest cycle was defined so as not to compromise economic profitability, which is deemed to be negative beyond 25–30 years. As a result, most tropical countries have introduced harvest cycles of between 20 and 35 years.

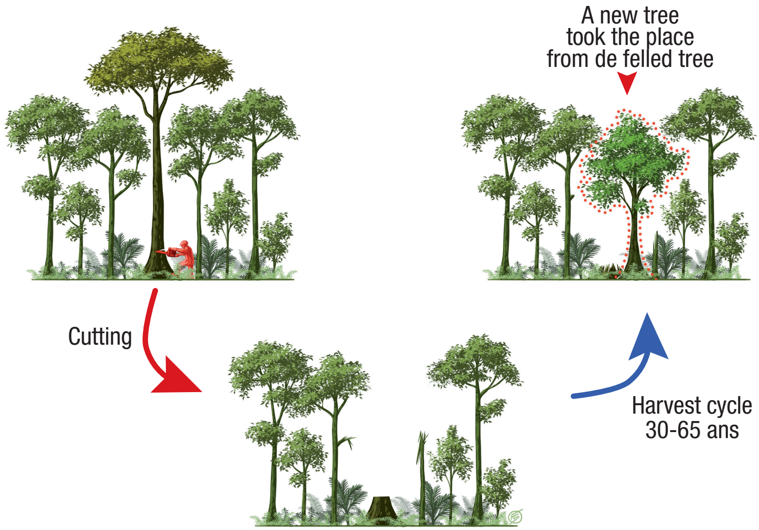

Figure 3. Schematic diagram of the principle of selective exploitation (source: Sist *et al.*, 2021).

A recent report by the World Resources Institute estimated that by 2022, 4.1 Mha of undisturbed natural tropical forests would be selectively logged, corresponding to an area the size of Switzerland. Potentially, the total area covered by tropical production forests, i.e. those already logged and those likely to be harvested over the coming decades, is estimated at around 680 Mha.

The different stages of selective exploitation

Selective logging, when it is legal, i.e. in compliance with the country's legislation and approved by the relevant forestry authorities, does not simply consist of cutting down the most valuable trees. There are many steps to be taken before felling can begin. The very first is to assess the resource over the entire management plan to delimit the cutting areas, but also to estimate the volumes of timber that will be produced by species, because the price of timber varies according to species. These inventories involve forestry engineers and technicians whose skills are constantly evolving and becoming more complex because of new technologies. Many of the harvesting inventories carried out prior to felling in the areas demarcated by a management plan are now carried out in the field in digital form, using tablets whose data is downloaded directly onto computers to generate tables and maps. The trees are no longer mapped on graph paper as in the past but geolocated by GPS. As well as generating essential information for the logger, forest inventories are essential to obtain felling permits from the forestry authorities. At the same time as the logging inventories, which are often made one or two years before harvesting, the first roads must be opened and first camps set up, some of which will be permanent and others temporary, for the duration of the annual cut. Given the length of the resting period and investment required for logging, only a large surface area can ensure profitable logging. In Central Africa, for example, where the logging intensity is one or two trees per hectare, profitability can only be guaranteed on concessions of several hundred thousand hectares. As can be seen, selective logging requires technical expertise and a major investment in professional personnel and equipment that is beyond the reach of smallholders or indigenous populations. These obstacles arise as early as the inventory stage, which must be run by professionals. Small farmers prefer to turn to private operators, who are often illegal or corrupt.

The periods of rest between two operating cycles, known as 'harvest cycles', extend over several decades and represent a threat to the sustainability of the system. Firstly, the duration of the operating licences is either less than or at best equal to the duration of the harvest cycle, with no certainty that these concessions or licence rights will be renewed. Since operators cannot be certain that they will be able to benefit from their current investments over several cycles, they are often very reluctant to invest for the long term. Furthermore, small holders with limited forested areas often choose to harvest the entire area at once to maximize profitability. Once logged, the forest will not yield any income for more than 30 years and will tend to be converted to other uses that are more lucrative in the short term such as pastures or industrial plantations, often developed with the profits generated by their own exploitation. This is the case, for example, in the Brazilian Amazon, where the Forestry Code requires at least half of every rural property to be left under forest cover. However, for small landowners who received 100 hectare plots, once the 50 hectares have been harvested, which will usually have been done by a contractor, their forest will earn them nothing for 35 years. The temptation is then to convert the logged area to pasture.

Selective logging concerns a very small number of trees, 7 to 12/ha in Southeast Asia, 4 to 7/ha in Amazonia, and rarely more than 2/ha in Central Africa. This represents barely 0.5 to 2.5% of the total density of trees present in 1 ha (100 m × 100 m) of tropical forest (an average of 500 trees with diameters greater than 10 cm). It is therefore easy to understand that, despite the damage caused by such logging, the disturbance remains moderate and rarely compromises the integrity of the ecosystem, except in the case of uncontrolled, repeated and totally illegal logging, which is unfortunately not uncommon.

The harvested tree species obviously vary greatly from continent to continent and region to region. Tropical and Southeast Asia in particular, are distinguished from other regions by the dominance of a family of trees known as the Dipterocarpaceae. This name derives from the Greek roots *di* (two), *pteron* (wings) and *carpos* (fruit), meaning ‘two-winged fruit’, a characteristic of the *Dipterocarpus* genus that gave the family its name. In the forests of Southeast Asia, 20–25% of trees over 10 cm in diameter and over 70% of canopy trees in the lowland and hill forests of Borneo belong to the Dipterocarpaceae family. In tropical Asia, there are more than 500 species of this family, more than half of which are found on the island of Borneo, which has the greatest diversity. This dominance of a single tree family, even though it is highly diverse in terms of species, is unique in the tropical world. Foresters refer to the region's forests as 'mixed Dipterocarp forests'. Because of this dominance, selective logging of these forests is limited to the largest trees (55 cm diameter and over) belonging to this family, which are mainly used for plywood. Most of the species harvested respond well to the opening of the forest canopy, as they react very quickly to the increase in light intensity created by these openings, unlike other species that need to remain in the shade of the undergrowth for longer before responding to the light. Selective logging, as long as it does not exceed a threshold of 7 to 8 trees per hectare, stimulates the growth of young trees of these species spared by logging. Above this threshold, pioneer species are favoured, which then slow down the regeneration of Dipterocarps.

SELECTIVE LOGGING IS NOT JUST ABOUT FELLING TREES

Timber harvesting can be complemented by silvicultural treatments before and after selective logging. Before harvesting, it is highly recommended to cut the vines around the trees to be harvested to facilitate directional felling of the tree, ensure the safety of the logger and limit damage to the neighbouring trees. Vine removal can also be done after harvesting around future crop trees—i.e. those for the next harvest—to stimulate their growth and limit the invasion of lianas that would prevent forest regeneration. For reasons of labour costs and logistics, vine removal is not widely applied in the field. However, it would be extremely useful in certain cases, as it is estimated that a quarter of exploited forests are subject to major invasions of lianas that prevent forest regeneration. In addition, monitoring of tree growth in Amazonia has shown that the removal of lianas from trees can increase their growth by more than 20%.

After logging, another possible silvicultural practice is devitalization. This consists of poisoning trees of no commercial value, either systematically or just around future crop trees. This practice eliminates competition between trees of no commercial interest and valuable timber species, thereby stimulating growth of the latter. Devitalization involves making notches all around the tree and depositing 5 ml of herbicide into each. This causes the gradual death of the unwanted tree, which rots in place without damaging neighbouring trees, unlike removal by felling. Because such practices require herbicides, they have never been applied operationally over large areas and are now banned by environmental legislation in most countries. The impact of the use of herbicides in natural forests, in very small quantities and applied only once every 30 years, is still unknown, as no serious study has yet been carried out on this subject.

One silvicultural practice that has been frequently tested by foresters, but very rarely applied on a large scale in the field, is the planting of commercial tree seedlings in the largest felling openings created by logging. These so-called 'enrichment' practices have a significant cost, in particular to produce seedlings, which requires the seeds to be harvested in the forest, for the construction of nurseries needed for the germination and production of seedlings, and for the preparation of the area to be planted, which is often cluttered with branches and trees swept away when the harvested tree falls. The benefits of these practices compared with natural regeneration over a period of 30–35 years are still highly debatable. In Indonesia, some forestry companies apply this enrichment systematically, along parallel paths cleared 3 m wide and 25 m apart. Seedlings belonging to 2–3 species of fast-growing Dipterocarps are planted every 3 m along these strips. This strategy is based on a highly productivist vision of the forest, which is seen solely as a source of timber. However, by planting timber species at such a high density, we are creating a future situation where intensive logging will be necessary, which will cause such extensive damage that it will be impossible to maintain a functional forest structure. In reality, this is nothing short of transforming a natural forest into a plantation of just a few timber species.

HARVESTING TIMBER AND NON-TIMBER FOREST PRODUCTS

In Amazonia and Central Africa, timber species belong to very different families and are used mainly for sawing and peeling (plywood). In Central Africa, minimum cutting diameters are generally above 60 or 70 cm and vary according to species. In Amazonia, the minimum cutting diameter is the same for all species and is set at 55 cm, as in Southeast Asia. Many of the timber species also provide other goods, known as 'non-timber forest products', such as fruits, resins and active ingredients with pharmacological properties extracted from leaves or bark (Figure 4). In Amazonia, it is estimated that these uses concern around a third of the 300 timber species.

Andiroba (*Carapa guianensis*) is an interesting example, as it demonstrates the possibility of combining the exploitation of timber and a non-timber forest product from the same species. Andiroba belongs to the large Meliaceae family, i.e. the mahogany family. However, its wood is of lesser quality than the 'true' American mahogany, *Swietenia macrophylla*. Andiroba is also very famous for its seeds, from which an oil is extracted that has multiple benefits. This oil contains natural compounds with anti-inflammatory and analgesic properties. It can be applied to the skin to relieve muscle and joint pain, or skin inflammation. This oil is a natural insect repellent, particularly against mosquitoes, ticks and chiggers, which are very common in the Amazon rainforest. Because of its antibacterial properties, it is also used to disinfect minor cuts and scrapes. A small bottle of andiroba oil is a must-have in your rucksack for trips into the Amazon rainforest. Andiroba oil is also used in candles for its insect-repellent properties, and in soaps and shampoos for its cosmetic benefits. Studies monitoring the fruit production of this species showed that trees above 60 cm diameter produce less than trees between 30 and 59 cm diameter. On average, one tree produces 6 kg of seeds, which yield around 75 cl of oil. To reconcile timber and oil production, it is recommended to only cut the largest trees for timber: those with a diameter greater than 60 cm rather than the 50 cm stipulated by law. As andiroba is a heliophilous species, i.e. it needs a substantial amount of light to grow and reach the sub-canopy, logging will stimulate the growth of the remaining trees by creating openings. This example shows that multiple uses of forest resources (timber and non-timber forest products) are entirely possible if we understand the biology of the species and their ecological requirements.

The harvesting of non-timber products can provide a regular source of additional income during harvest cycles. In practice, only forest communities or small farmers organised into cooperatives are interested in producing non-timber forest products. Unfortunately, these markets are often very limited and dominated by a few processing companies that set their own prices and conditions. Moreover, the production of such products, particularly those dependent on fruit, is often irregular and of very variable quality depending on the region and the year. It also requires the creation of cooperatives to pool production across a territory or region in order to offer sufficient quantities to interested companies. It is clear that in practice, adding value to non-timber forest products is not as straightforward as it seems in theory.

Figure 4. Some examples of non-timber forest products.
A) Bottles of andiroba oil at a local Amazonian market, Santarém (© Plinio Sist).
B) Handcrafted jewellery made from seeds, Belém (© Plinio Sist).
C) Coloured jewellery made from the seeds of the Amazonian palm *Phytelephas macrocarpa*, Belém (© Plinio Sist).
D) Caterpillars highly prized in Central Africa, harvested from the sapelli tree *Entandrophragma cylindricum*, a member of the African mahogany family (© Charles Doumenge).

STATUS OF TROPICAL PRODUCTION FORESTS WORLDWIDE

In its latest report on the state of the world's forests in 2020, the Food and Agriculture Organization of the United Nations (FAO) estimated that around 30% of the world's forests are being used for production of timber, fibre, wood energy or non-wood forest products. Selective logging potentially concerns more than 680 Mha of tropical rainforests, i.e. around a third of the world's tropical forests. Only 11% of the world's forests are designated for biodiversity conservation. The surface area of forests within protected areas represents 18% of the world's forest cover. In South America, this proportion exceeds 30%, particularly in Brazil (42% of the Brazilian Amazon is protected to varying degrees), Peru and Venezuela. In West and Central Africa, forests in protected areas cover an area of 61 Mha, or 21% of the region's forests.

According to the same report, 73% of the world's forests belong to governments, although there are major disparities between regions. In Europe, excluding Russia, privately-owned forests account for the majority, with 54% of the region's total forest area. In Central and West Africa, 93% of the forests are state-owned and most of them are under concession by private operators. In Southeast Asia, governments are also the main forest owners, with 88% of the forests. In South America, the proportion of privately-owned forests is 37%, and in Central America it is the majority, with 63% of forests belonging to private owners.

Timber harvesting in tropical regions mainly concerns natural forests, as plantations are still very much in the minority and mainly exploited for pulp production. According to the FAO, planted forests account for 7% of the world's forest area, or 294 million hectares. Europe, excluding Russia, accounts for the largest proportion, where 30% of the forest areas are planted. In

Central and West Africa, planted forests account for just 1% of the region's total forest area, while in Southeast Asia and the Caribbean, this proportion rises to 11% of forest cover. South and Central America only have very modest planted areas, accounting for barely 2% of their forest cover.

The scale of illegal logging is difficult to assess objectively, accurately and rigorously because of the very nature of this activity. A 2011 report by the United Nations Environment Programme (UNEP) and Interpol showed that, depending on the country, between 50% and 90% of tropical timber is produced illegally. More recent figures from the Brazilian Amazon estimate that around half of all timber harvesting is illegal. This illegality takes a wide variety of forms, often highly complex, to circumvent the rules of forestry legislation in the countries concerned. It remains a major obstacle to the sustainable management of tropical forests, as it represents unfair competition and is highly discouraging for operators who want to comply with the forestry regulations in force.

TROPICAL WOODS AND THEIR PRODUCTS ON THE INTERNATIONAL MARKET

In 2021, production of tropical industrial roundwood ('logs') reached 322 million cubic metres (Mm^3), just 16% of global production, estimated at 2 billion m^3, with Indonesia, India, Vietnam, Brazil and Thailand accounting for around 74% of production. By 2022, the top two exporters of tropical logs were Papua New Guinea (2.5 million m^3) and Brazil (2.3 million m^3). Cameroon (849,000 m^3), the Republic of Congo (596,000 m^3) and Mozambique (490,000 m^3) rank third, fourth and fifth, with much lower log export volumes. The global trade in tropical logs remains centred on the Asia-Pacific region, with three main markets: China, India and Vietnam, which imported 89% of tropical roundwood in 2021. China is by far the biggest importer of tropical logs, with an import volume of around 6 million m^3 in 2022, accounting for almost 65% of all tropical wood imports. Other importing countries are India (1.4 million m^3), Portugal (1.3 million m^3) and Vietnam (1.1 million m^3).

Many tropical countries ban the export of logs in order to develop their own processing industries. The main products are plywood, sawn timber and veneer. In 2021, tropical production of these products accounted for 14.5%, 50.6% and 38.3% of world production, respectively. As with logs, the market for these products remains very much centred in Asia, with China being the main importer.

Regarding imports from the twenty-seven countries of the European Union, a recent IDH report indicates that in 2018, Europe imported 1.47 Mt of tropical wood and wood products (logs, sawnwood, plywood veneer). These imports represented 12% of total exports of tropical wood and wood products from producing countries, the remaining 88% being exported mainly to China, India and Vietnam. Most European imports come from Africa (56%), followed by Asia (25%) and Latin America (19%). Over the past decade, the value of the tropical timber market in Europe has fallen considerably, from almost €7 billion in 2007 to €4.5 billion in 2018.

To sum up, tropical woods and products still account for a minority share of world production and markets, except for veneers. Exports are mainly to China and a number of Asian countries, with Europe accounting for only a very small proportion of imports. As a result, until the Asian market adopts the same stringent production source requirements as the EU, the EU regulations governing the certification or legality of tropical woods and wood products will have little impact on upstream changes in producer countries towards more sustainable and legal logging practices.

ECONOMICS OF THE FORESTRY SECTOR IN TROPICAL COUNTRIES

The forestry sector plays an important role in the economies of many tropical countries, as it is a source of income and employment, as well as generating revenue for the State through the taxation of forestry products and concession contracts. In Cameroon, for example, the forestry sector contributes 5% of the GDP (2021 figures), and generates over 200,000 jobs, including 15,000 in the industrial forestry sector (9,000 in industry and 6,000 in logging), 40,000 in the small-scale sawmilling sector and 150,000 indirect jobs. In Gabon, it contributes 3.6% of the GDP, while hydrocarbon production is the main contributor, accounting for around 50% of the GDP, 60% of tax revenue and 80% of exports. However, the timber sector accounts for 13% of exports and 60% of non-oil export revenues. After the government, it is the country's largest employer, accounting for 28% of the workforce.

In Brazil, the forestry sector contributes 4% of GDP and 8% of exports, while collecting more than €570 million in taxes per year and generating 2 million direct and indirect jobs. The timber sector is the largest employer in the Amazon, responsible for 127,000 direct jobs and 105,000 indirect jobs in the region, as well as 120,000 indirect jobs outside the region. Of course, Brazil's forestry sector is not confined to the Amazon, which produces only a third of the country's total log production. The south of the country, in particular, has over 5 Mha of industrial eucalyptus plantations for the pulp and paper industry.

THE IMPACT OF TIMBER HARVESTING

When foresters took an interest in the damage caused by mechanised logging, they quickly realised that this seemingly minor impact could, depending on the intensity and techniques used, affect up to half of the forest stand—including trees uprooted or topped during felling operations, trees uprooted during log extraction by tractors or left injured, etc. This is particularly the case in Southeast Asia, where logging intensities can exceed 10 trees per hectare. Based on the assumption that the lower the damage to the forest stand, the faster the forest will recover, foresters from the early 1990s onwards have been testing so-called 'reduced-impact' logging techniques aimed at minimising damage. At the dawn of the 21st century, these techniques quickly became one of the basic requirements for forest certification.

REDUCED IMPACT LOGGING

The fundamental principle of reduced impact logging (RIL) is the planning of all operations. First and foremost, RIL places particular importance on the opening, engineering and maintenance of main and secondary roads providing access to harvesting areas. Roads have a significant impact on forest stands and soil. The RIL therefore strives to limit their footprint by planning their routes according to the topography and configuration of the area's water network (watercourses and marshy areas). The aim is to minimise soil erosion and limit the opening up of the canopy and road network development as much as possible. The roads are built by specially trained teams led by civil engineers who are aware of the need to minimise soil disturbance, ensure proper drainage and avoid crossing watercourses as far as possible.

Annual forest cutting inventories, which vary in size from a few thousand hectares in the Amazon or Asia to several tens of thousands in Central Africa, are a key stage in the RIL process. During these inventories, all harvestable trees of commercial interest are identified, measured, located and mapped, i.e. those that have reached the minimum cutting diameter and, according to the technicians responsible for the inventories, have a well-shaped trunk. As we saw in the previous chapter, these inventories provide key data for very precise planning of all harvesting and annual production. The maps generated by these inventories are used by the loggers during felling. They enable them to plan their daily operations according to the topography and size of the tree. For each tree marked as harvestable, the logger and their assistant carry out a final assessment to decide whether it should be felled. The decision depends on several criteria. Firstly, the logger makes a final assessment of the shape of the bole and may have a different opinion from the one made during the inventory. Secondly, if there are too many lianas around the tree, the logger may not want to fell it, as this could represent a danger to himself and his assistant. In tropical forests, the tops of trees are often linked by lianas, which can drag other trees down during felling, and even change the direction of fall originally planned by the logger. Finally, just before felling, the logger tests for hollows by pushing the chainsaw blade perpendicular to the trunk. If the hollow is deemed too large, the tree is left standing, as it will provide very little timber, but can live for decades and contribute to the regeneration of the species by producing seeds. The link between the presence of such hollows and genetic inheritance has never been demonstrated, as there are many factors involved in the occurrence of wood rot that are independent of an individual tree's genetic background. During felling, the logger applies specific techniques known as 'directional felling' so that the fall of the tree does not damage young neighbouring trees, i.e. those that will make up the next harvest.

Once the felling has been completed, the logger indicates the direction of felling on the map. It is then time to extract the logs left in the forest by the felling teams. This is done by machines called 'skidders', used to open 'skidtrails' to access the logs. The RIL strategy is to plan the network of skidtrails according to the position of the felled trees, and of course the topography, with the objective of minimising this network and, therefore, the damage caused to the stand. Indeed, without this planning, which indicates to the machine driver the route to follow and the exact location of the logs to be extracted, the skidtrails would multiply and cause much unnecessary damage. In addition, in areas with steep terrains, it is essential to plan the skidtrails in such a way as to limit the impact on the soil, especially as the heavy rainfall in humid tropical climates is a major factor in soil erosion on slopes where the vegetation has been partially removed (Figure 5).

Finally, once the logs have been extracted from the forest, they are stored in timber yards that receive logs from a predefined area. For several thousand hectares of cut forest, there are naturally many timber yards. These are completely cleared areas whose size varies greatly from one operation to another and according to the volumes extracted per cut area but usually cover about 2,000 to 5,000 m^2. By systematically planning timber

Figure 5. Skidding route for an unplanned logging operation (A) and a low-impact logging operation (B) in Indonesia, East Kalimantan.

yards, RIL aims to reduce their number and size. One of the recommendations is to limit the size to 2,000 m^2, which is roughly a 60 × 30 rectangle, for example. Other objectives of timber yard planning are to ensure the safety and protection of personnel and equipment working in or near the yard, and to protect watercourses and groundwater from sediment and pollutants. Here, the logs are measured, sorted and then transported to the sawmill or other destination. A great deal of machinery travels through the yard: skidders arriving from the forest, log loaders and log trucks. It's a busy place, with loggers cutting up the biggest logs for transport, and inventory teams measuring the logs to calculate their volume. These are very busy and dangerous places.

Reduced impact logging is often seen as a very costly process for operators but, in reality, leads to greater efficiency. For roads, for example, it avoids unnecessary road opening costs and reduces road maintenance costs, which can be very high if the logging company does not use appropriate road engineering techniques during construction. Well-planned roads and skidtrails also considerably reduce fuel consumption by machinery.

Reduced impact logging not only reduces damage to the stand and soil, but also includes other kinds of impacts, such as the storage of engine oil and staff working conditions. Forest managers also ensure constant surveillance of entry points to the forest management units using barriers and check points managed by a security company. The adoption of RIL by operators reflects a clear commitment to long-term sustainable management.

IMMEDIATE IMPACT ON THE FOREST STAND

The different stages of logging have specific impacts on the forest stand, which we will briefly describe here by explaining the main factors involved.

Forest roads are undoubtedly the most visible traces of logging, although their average spatial footprint represents less than 2% of the area logged. Despite this, their impact on soil erosion, particularly in high relief areas, and on drainage when they cross rivers or swamp areas can be very significant if basic civil engineering rules are not followed. For example, watercourses are often crossed by simply filling them in with earth, when a drainage culvert should be installed. By obstructing river flow, swamp areas of varying size form on either side of the road, depending on the size of the watercourse, resulting in massive mortality of trees that are not adapted to these very specific water conditions. Roads also provide forest access to hunters and itinerant farmers, allowing rapid colonisation of previously untouched areas.

Felling a tree causes often fatal damage to neighbouring trees. The felled tree drags other trees down with it, uprooting or topping them, or damaging the crowns of neighbouring trees.

Damage to crowns affects the growth and survival of damaged trees. If a tree is deprived of part of its crown, it also loses a large proportion of its leaves, i.e. its photosynthesis factory. Broken branches also encourage pathogen entry which, in the medium term, can lead to death of the tree. Studies have shown that trees injured by logging have a mortality rate two to three times higher in the 4 to 5 years following logging than intact trees. The felling techniques of RIL are designed to minimise damage to neighbouring trees, particularly future trees, are therefore fundamental.

Felling creates openings in the forest canopy that provide light wells for the remaining trees and regeneration. However, the larger the opening, the more likely it is that pioneer species will appear, competing with species less attracted to light. The soil contains many dormant seeds of pioneer species. If the light level remains that of the undergrowth, i.e. low, nothing happens, but if a large gap is created, the light that penetrates it breaks the dormancy of these seeds, which germinate rapidly. Pioneer species, which are generally of no commercial interest, will occupy more space than commercially valuable species. Large gaps also create greater vulnerability to strong winds, which tend to uproot trees on their edges, thus enlarging such gaps. Finally, gaps are prone to invasion by creepers or bamboo, particularly in Asia, which literally suffocate natural regeneration. For all these reasons, it is preferable to limit the size of gaps.

As they clear a path to extract the logs, the skidders uproot small trees in order to move forward. They also sometimes injure larger trees as they pass. Although the trees are not destroyed, the injuries are generally more or less deep cuts in the trunk, which can nevertheless have harmful consequences in the medium term because they leave an entry point for pathogens.

After felling, secondary roads and skidtrails are no longer used and are quickly colonised by the surrounding vegetation, to the point where they become invisible on satellite images after a few years (3 to 5 years).

The extent of damage to forest stands during felling and skidding depends essentially on two factors: the intensity and the harvesting technique. Impacts associated with roads and timber yards are more directly related to harvesting techniques. Studies comparing stand damage caused by unplanned logging, often referred to as 'conventional' logging, with that caused by RIL clearly show that, for the same extraction intensity, RIL halves the damage caused by felling and skidding. Interestingly, research carried out in Indonesia in the 1990s showed that, above a threshold of eight trees felled per hectare, the damage caused by RIL was comparable to that of conventional logging. Reduced impact logging therefore has its own limitations, which need to be recognised and taken into account.

LONG-TERM IMPACT

Importance of research and experimental monitoring sites

We have described the immediate impact of logging on the forest stand. However, it is also essential to understand the long-term effects on the reconstitution of several essential functions of forest ecosystems, in particular biomass, timber volume and biodiversity. Research institutes interested in tropical production forests have set up experimental sites of permanent sample plots for monitoring forest dynamics before and after logging. Monitoring forest dynamics means following the growth and mortality of the trees that make up the stand, as well as the recruitment of young trees, generally over an area of one hectare (100 m × 100 m). In practice, this involves measuring all the trees above a chosen diameter, generally 10 cm at breast height, periodically, ideally every year or two. New trees that have reached the inventory diameter of 10 cm are also measured and included in the database. Finally, trees that die between two measurement campaigns are listed, noting the cause of death (died in place, uprooted, broken by topping by another tree). As you can see, these studies take time and patience, because trees grow slowly, and the first effects of silviculture only become apparent after several years. They also require substantial investment over the very long term, as regular measurements and an almost permanent human presence are needed to prevent illegal poaching or logging. These measurements enable us to understand the effects of the intensity of logging techniques, silvicultural treatments and environmental conditions (soil, rainfall, extreme climatic events) on the forest stand and the recovery of biomass, commercial volume and biodiversity.

The TmFO network

There are several sites around the world monitoring forest dynamics after logging, which are grouped under the Tropical Managed Forests Observatory (TmFO*), a network coordinated by CIRAD.

The TmFO observatory currently comprises 30 experimental sites in 12 countries (Argentina, Bolivia, Brazil, Côte d'Ivoire, Gabon, Guyana, French Guiana, Indonesia, Malaysia, Peru, Central African Republic and Surinam), with a total of 657 forest plots representing a total inventoried area of 1,276 ha. It focuses on the resilience of exploited tropical forests with the aim of formulating recommendations for sustainable forestry, an urgent challenge in a context of biodiversity erosion and climate change. All these experimental sites have been monitoring forest dynamics after logging and silvicultural interventions for several decades. The aim is to gain both a regional and pantropical view of the resilience of these forests. For example, the forests in the northeast of the Amazon do not react in the same way to logging as those in the south of the same forest basin. The observatory's data, put in a regional context, has a greater impact when it comes to adapting recommendations for sustainable logging. This data, accumulated over several decades, can also be used to develop predictive models for the regeneration of timber volume or biomass.

Some of these sites, such as Paracou in French Guiana and Mbaïki in the Central African Republic, have been monitoring the growth, mortality and regeneration of all trees with a diameter of 10 cm or more for over 40 years. Maintaining them requires perseverance, funding and a great deal of patience. Nonetheless, today these systems are of inestimable scientific value as they provide a better understanding of how forests regenerate after logging, and consequently a better prediction of the reconstruction of the volume of timber extracted, the biomass and biodiversity.

Figure 6. Location of TmFO experimental sites (source: https://www.tmfo.org/).

[*] https://www.tmfo.org/

Impact on the regeneration of timber volume, biomass and biodiversity

Studies carried out on the monitoring of forest dynamics (tree growth, mortality and recruitment) clearly indicate that the intensity of logging, and thus the associated damage, is a determining factor in the processes and speed of recovery of three key services: timber volume, biomass and biodiversity.

Regarding the regeneration of the volume of commercial timber harvested, simulation models indicate that, in most cases, the current harvesting regimes, i.e. the intensity and duration of harvest cycles, cannot maintain constant timber production in the long term. This is because the first logging is usually carried out in old, mature forests that have developed over several centuries and therefore contain trees that are several hundred years old. It would be unrealistic to expect to regenerate the volume extracted during this first harvest, accumulated over centuries, after just another 25 or 35 years, as recommended by most forestry legislations in tropical countries. In reality, data from forest dynamics monitoring shows that only half of the volume harvested is recovered. The missing half is what foresters call the 'mature forest premium'. This is the part of the logged volume that accumulated over the centuries prior to any logging. In Indonesia, for example, the volumes extracted from mature forests when they are first harvested average 80 m^3/ha, although in some areas they can reach 140 m^3/ha. Simulation models based on monitoring data indicate that future harvest volumes will be 40 m^3 every 40 years. In this way, the stock of commercial volume and production would remain constant at the end of each cycle. Unfortunately, these recommendations made in the early 2000s have never been considered or applied.

In the Brazilian Amazon, the same premium mature forest phenomenon can be observed. Initial harvesting volumes are of the order of 20–30 m^3/ha, and simulation models recommend harvests of 10 m^3/ha in future cycles, spaced every 60 years. In this region, the sustainability of timber production requires not only a 50% reduction in the volumes to be extracted by future harvests compared with those extracted in the very first, but also a doubling of the harvest cycle provided for by most Amazonian legislation (30 years).

Finally, in Central Africa, logging intensity is extremely low (less than 2 trees/ha), so the commercial volume generally recovers over 30-year cycles. However, this situation remains very specific and will no doubt evolve towards greater diversification of species with commercial value on the market. If the harvesting intensity was to increase in Central Africa, the problem of recovering the commercial volume would undoubtedly arise in the same way as for the other two tropical forest regions, Amazonia and Southeast Asia.

Biomass recovers much more quickly than timber volume, and in most cases during the resting period between 25 and 35 years. This is because, unlike timber volume, whose recovery depends directly on the growth of commercially valuable trees with a large diameter, biomass recovery benefits from the growth and recruitment of all trees with a diameter of 10 cm or more. As with volume, the rate at which biomass is recovered depends directly on the intensity of logging and the damage caused. In general, the higher the intensity, the longer it takes for the biomass to recover.

What biomass is and how it is measured

Forest biomass refers to the quantity of organic matter (such as trees, treelets, leaves, branches, etc.) found in a given forest or woodland area. This biomass can include living trees, standing dead trees, plant debris on the ground, stumps and other organic material present in the forest ecosystem. Most often, we measure the standing living biomass of a forest, i.e. the living, aerial parts of trees (trunk, branches and leaves) above a certain tree diameter. Forest biomass is an important indicator of the condition and health of a forest. In the field, biomass is not measured directly but is calculated using allometric equations that relate biomass to easily measured characteristics such as tree diameter (Figure 7). By measuring the diameter of each tree and identifying its species to obtain the value of its wood density, these allometric equations can be used to calculate the biomass of each tree without having to fell and weigh it. It should be emphasised that these allometric equations were developed using actual biomass measurements, which involved felling trees a section at a time, then drying and weighing samples of each part of the tree (trunk, branch and leaves). This is a gigantic task, taking a very long time and requiring a large number of staff and much equipment.

Non-destructive biomass assessment techniques are now available using terrestrial Lidar. This is a device mounted on a tripod that emits a laser light beam and records the distance to the point where this meets a solid object (the trunk of a tree, for example). By sending out thousands of laser light beams from several different angles, the device produces a three-dimensional image of the aerial part of the tree. This image provides very precise data on the size of the tree and its volume. By combining this data with the wood density of each tree, it is then possible to calculate its biomass. This technique requires time and sophisticated equipment to measure and analyse the data. Over large areas, increasingly accurate satellite remote sensing tools are now used to estimate forest biomass based on density, height and the vegetation observed. However, to make this technique possible, field data are essential to calibrate the remote sensing biomass estimation models.

Figure 7. Measurement of permanent plots in Amazonia (A), Indonesia (B) and Africa (C) (A, B: © Plinio Sist; C: © Émilien Dubiez).

Studies on the long-term impact on biodiversity cover a wide range of biodiversity compartments, including insects and vertebrates (reptiles, birds, mammals), forest stands (trees) and tree genetic diversity. Analyses of the scientific literature on the subject show that logging itself has very little impact on biodiversity in general, and that logged forests retain more than 80% of their original biodiversity prior to logging. Compared with other land uses, and in terms of species diversity, selectively logged forests remain the closest ecosystems to undisturbed mature forests. For example, they are far richer in plant species than agroforests. Furthermore, they are not subject to the introduction of exotic species, as is often the case with the latter. These data clearly demonstrate the value of exploited tropical forests in terms of biodiversity conservation.

Little is known about the long-term impact on the diversity of the forest stand, as this requires data spanning several decades. This is nonetheless beginning to become available thanks to the experimental schemes set up in the 1980s. The diversity of tree species (sometimes more than 200 tree species/ha) and the difficulty of identifying all the individuals, which are usually sterile in the case of young trees, mean that these studies take time and require numerous botanical samples to be collected to identify the species. The term 'restoration' for biodiversity is a misnomer because, whatever the disturbance, whether human or natural, the diversity and composition of species in a forest cannot be restored identically. The aim here is not simply to calculate a quantity such as volume or biomass. Instead, we compare the species composition and richness of logged and unlogged forest stands, or the initial state before logging with that observed a few years after logging. However, the differences observed and their consequences for the functioning of the forest and the services provided remain difficult to assess. Indeed, we need to ask whether a forest with a different composition and species richness would function differently and provide fundamentally different services from an unharvested forest. The available results once again show that intensity is a determining factor in the process of reconstituting stand biodiversity. By creating large and numerous openings in the forest canopy, high intensity logging encourages the regeneration and growth of so-called 'pioneer' species, stimulated by the large amount of light. These are often species with low wood density and a short lifespan (25–30 years), which rapidly reconstitute a low forest cover, allowing the regeneration of species that are less demanding in terms of light for their development. By occupying space, the colonisation of large openings by pioneer species actually lengthens the direct regeneration of the slower-growing species that make up the forest canopy. Conversely, intermediate disturbances caused by low-impact logging, by creating gaps of varying sizes and, hence, diverse and contrasting environmental conditions, encourage the regeneration of a wide variety of tree species with different light requirements, and thus contribute to greater diversity in the forest stand. It is therefore common to find, after a few years, a greater diversity of tree species in forests that have undergone moderate logging intensity than in intact forests.

Impact on wildlife

New roads are key routes for forest penetration, giving access to previously uninhabited areas for hunting and all manner of illegal exploitation of timber or mining resources (particularly gold). Moreover, once the timber has been extracted, the forest loses its immediate economic value and tends to be converted to more lucrative agricultural or pastoral uses. Forest roads facilitate this conversion by providing quick and easy access to exploited forest areas. Roads are therefore frequently accused of various evils, particularly for their alleged role in deforestation and degradation. In reality, they are simply essential tools for forestry activity and the economic development of a region.

Provided that poaching is kept under control, the direct impact of logging on wildlife through canopy disturbance and the removal of certain large trees is generally low and diminishes over time. Such disturbances do not actually lead to a radical change in the ecosystem, which remains wooded and similar to that of an intact natural forest. However, here again, logging intensity is key. A recent study shows that below an intensity of 10 m^3/ha, the diversity of mammal species in a logged forest is greater than in an intact forest. However, as the intensity increases, the number of mammal species decreases and, once it reaches 38 m^3/ha, is reduced to half of the species recorded in an intact forest.

While logging intensity is an important factor for wildlife, its impact varies considerably from one species of animal to another. Highly specialised species, for example those with a specific diet dependent on just a few plant species, will naturally be more vulnerable than more generalist species. It is also important to consider the ability of animals to adapt to disturbance, which will be easier if the disturbance is small. For example, extracting the largest trees can temporarily change the availability of food resources and, in particular, reduce the availability of fruit for some fauna. Studies carried out on the Malay Peninsula on two species of monkey, the white-handed gibbon (*Hylobates lar*) and Sumatran semnopithecus *(Presbytis melalophos*), showed that individuals living in logged forests consumed more leaves and less fruit than their neighbours in intact forests. This can no doubt be explained by a temporary lower abundance of fruit and higher leaf production in certain juvenile trees exposed to light, whose growth is stimulated by a greater input of this light energy.

The most significant impact on wildlife is undoubtedly the hunting carried out by loggers and local residents, who take advantage of the roads to enter the forest. Hunting pressure is particularly high in Central Africa, where wildlife is the main source of protein for rural households. The sale of game is also an important source of cash income for many rural families, giving them access to services and basic necessities.

By reducing or eliminating certain mammal populations, hunting then has an impact on the functioning of the forest ecosystem. The vast majority of trees in tropical forests depend on mammals and birds for their dispersal. Animals therefore play an essential role in the tree regeneration process. The fruit and seeds of over 80% of Latin American tree species are eaten and dispersed by animals. Large mammals such as primates and wild ungulates disperse large seeds. Numerous studies have shown that seed predation is concentrated at the foot of fruiting trees, as this is where they are most numerous and, therefore, most available. Dispersal then allows a certain proportion to escape this predation while ensuring the spatial dispersal of the species. The increasing scarcity of large mammals could, in the long term, lead to the disappearance of tree species with large seeds in favour of species with smaller seeds, dispersed by small animals that are generally not hunted. The functioning of the tropical forest ecosystem in fact depends on the sometimes very subtle balance of animal populations. Predators such as felines regulate the populations of herbivorous and frugivorous mammals. The scarcity of these predators can lead to a surplus of these mammals, which in turn will lead to greater predation on the seeds, because although these mammals disperse the seeds, they also consume a large proportion of them. This is the price plants have to pay to ensure their reproduction and mobility.

All these effects only manifest themselves over the long term, and an intact forest with a deficit of large mammals may falsely appear to be in perfect condition. This is what specialists call the 'empty forest syndrome'. Our knowledge of the long-term effects of defaunation on the regeneration processes of tropical forests is still very limited, due to the need to monitor these effects over several decades. They affect primarily reproduction and regeneration processes and, therefore, very young seedlings whose future role in the structure and composition of the flora will not be visible for several decades. The possible effects of the absence of wildlife can manifest themselves in various ways in the forest. First of all, dense-wood trees, which form the roof of the forest and are often emergent, are species that are generally dispersed by animals, particularly mammals and birds, except for Dipterocarps whose seeds are mainly wind dispersed. The absence or scarcity of these larger animals can considerably disrupt dispersal and regeneration processes and, in the long term, compromise the regeneration of dense-wood tree species. Trees with lower-density wood, whose seeds are often dispersed by the wind or small mammals like bats—less hunted than larger animals—will be less affected and, without competition, will come to dominate the forest. The consequences would then be a forest with a different structure and floristic composition and a lower biomass, given the dominance of species with lower density wood and, therefore, lower biomass.

SOCIAL IMPACT

Timber forest management tends to develop in isolated regions with a low level of economic development, where the presence of the State is generally weak and the infrastructure network is limited to that developed by the operations themselves. In this context, the social impacts can be considerable in both the short and long term. Many forest concessions are inhabited by indigenous populations (Amerindians, Pygmies, Punan and Dayak) who are often among the most politically and socially marginalised. These communities tend to be poorly informed about the social obligations that forestry companies and authorities must provide to them as compensation for the disturbance caused by the exploitation of their ancestral lands. Furthermore, the forestry industry is very male dominated, which raises many questions about gender relations and gender equity, both in terms of employment and health, safety and the wider effects of logging operations on local communities, including prostitution, alcoholism and substance abuse.

Forest frontiers are typically areas where justice is poorly administered due to the weak presence of the State. This creates *de facto* lawless situations, where local populations are the poorest and most vulnerable. Finally, in these isolated forest regions, very different economic systems, cultures and visions of the world come face to face. Logging exacerbates these differences and accelerates the socioeconomic and environmental changes for which local communities are not always ready. The pace and scale of these changes often lead to social and cultural fragmentation, conflict and increased local inequalities.

The forestry sector is generally presented as a major contributor to national and local economies and development through incomes, job creation and the provision of road infrastructure and other basic services. Indeed, the forestry sector is expected to contribute to alleviating local poverty. The question of whether this actually happens remains crucial and difficult to prove objectively, as in reality there is a large gap between the promise of such positive social impacts, potential or perceived, and their materialisation for local communities living from logging activities. In most Central African countries, for example, logging companies managing concessions of several hundred thousand hectares are legally required to make payments to local communities based on concession area and volume extracted, as well as monetary compensation for damage to local property, usually agricultural crops. However, these payments, which are initially collected by the state and then redistributed to the communities, rarely reach local populations, as they are often monopolised by the elites at all levels.

In theory, the jobs created by all forest management-related activities represent a potential contribution to local economies and individual households. In the remote areas where logging operations are often located, the forestry sector remains the largest employer in the formal non-state sector. However, in many cases, the jobs offered to local or indigenous people are temporary and low-skilled, with longer-term positions of responsibility (engineers, foremen) generally reserved for the logging company's permanent managers, who rarely originate from the region itself.

Forestry operations generate a large amount of infrastructure, such as roads and ports, which directly benefit the regions. Within the concessions, the companies build housing with electricity and running water for their employees. Some concessions operate completely independently, like small towns, with their own schools, clinics and grocery shops.

As well as the economic aspects, logging can also affect the relationship that local people have with the forest and the uses they make of it, which may be incompatible with logging practices. For example, many tree species exploited for their timber by loggers are also essential sources of food for local populations, particularly their fruit. Logging the largest trees can lead to a drop in fruit production or force people to travel greater distances to find fruit-producing trees.

It would be impossible to cover all the social impacts of farming here, as they are so many and vary so much from one region to another, and the subject is broad enough to fill an entire essay of its own.

SUSTAINABILITY IN PRACTICE

Sustainable forest management is far from being a new concept. As early as the 14th century in France, Philip VI of Valois, aware of the need to conserve and manage forest resources in a sustainable way, introduced the first Forestry Code and laid the foundations for the concept of sustainability, as illustrated by this extract from the Brunoy Ordinance issued on 29 May 1346: “The masters of the waters and forests will survey and visit all the forests and woods and sell them so that the said forests can be perpetually maintained in good condition”.

Almost seven centuries later, the definition of sustainable forest management adopted by the European Union in Helsinki in 1993 is as follows: “The stewardship and use of forests and forest lands in a way, and at a rate, that maintains their biodiversity, productivity, regeneration capacity, vitality and their potential to fulfil, now and in the future, relevant ecological, economic and social functions, at local, national, and global levels, and that does not cause damage to other ecosystems”. Whatever the objective of management, therefore, sustainability aims to find compromises between the production of goods or services in the long term and the preservation of the integrity of the forest ecosystem, i.e. enabling it to retain its capacity for regeneration and reconstitution as well as its productive capacity for future generations. Sustainability is simultaneously environmental, economic and social, and these three pillars cannot be dissociated from one another.

The very nature of the concept of sustainability changes according to the role that society assigns to the forest. If the forest is perceived essentially as a timber resource, then the criteria for measuring and assessing whether sustainability has been achieved will essentially be in terms of timber production. The aim will be to achieve sustained and constant timber production over time and over the course of harvest cycles. Of course, the impact of silviculture on the other functions of the forest will also have to be assessed, but this will ultimately remain fairly secondary, since the primary objective is sustained timber production. On the other hand, if the primary objective is to preserve a catchment area for the production of good quality drinking water for neighbouring towns, then the criteria for assessing sustainability will focus on the structure and floristic composition of the forest, the quality of its soils and its biodiversity, all of which guarantee the proper functioning of the ecosystem, which is essential if it is to act as a water filter.

SUSTAINABILITY OF TIMBER PRODUCTION

The forest is still mainly perceived as a source of timber production, so we will assess the conditions for its sustainability. In the previous chapter, we saw how studies monitoring forest dynamics show that the exploitation regimes introduced over 40 years ago are not sustainable in the long term. At this rate, the stock of timber volume will continue to fall and forest structure will change considerably. The very few examples of second harvesting show that, in order to harvest the same quantity of timber as in the first, it was necessary either to extract new species, i.e. species that were not of commercial interest and which become so for want of anything better, or to lower the minimum harvesting diameter. This means that the second harvest draws once again on the forest stock accumulated over centuries, and not on the volume that is recovered between two harvests. Sustainability is therefore clearly called into question. Simulations based on data from forest dynamics monitoring after logging indicate that logging regimes need to be decreased. In Southeast Asia, the intensity of logging, which can exceed 80 m^3/ha during the first logging, should be limited to 40 m^3/ha every 40 years for the next, which is already a remarkable productivity for a natural tropical forest.

In Amazonia, the current authorised regime of 20 m^3/ha every 30 or 35 years, depending on the country's legislation, needs to be completely overhauled by halving the intensity (to 10 m^3/ha) and almost doubling the length of the cycle, which would increase to 60 years. In addition, the number of commercial species needs to be considerably diversified in order to improve the rate of recovery of the commercial volume. The current demand for timber in the Brazilian Amazon is 10 Mm^3 per year. This production comes mainly from natural forests on private estates, concessions (1.6 Mha) and legal and illegal deforestation. In this region, which covers an area of around 400 Mha (eight times the size of mainland France), selective logging concerns 460,000 ha every year, at an intensity of more than 20 m^3/ha. To ensure this level of annual production over the long term on a sustainable basis, applying a regime of 10 m^3/ha every 60 years, it would be necessary to set aside around 100 Mha of natural production forests for timber, an area equivalent to twice the size of mainland France. In Central Africa, logging intensity remains very low, generally below 2 trees/ha. This explains why forest concessions in the region cover very large areas, often exceeding 500,000 ha. However, monitoring of experimental permanent plots in the Central African Republic, where a logging intensity gradient was tested in the 1980s, shows that above an intensity of 4 trees/ha, the commercial volume is barely restored to 40% after 35 years, which suggests that the productivity of Central African forests remains very low, and that this will undoubtedly pose sustainability problems in the future if the intensity increases.

It is therefore imperative to review the current logging regimes in force in most countries. State forestry departments and logging companies have shown little interest in changing the rules for the time being, as they go against the fundamentals they took for granted. By increasing the harvest cycle period to 60 years instead of 35, the Amazon will have to face many opponents who are convinced that it would be impossible for logging to be economically profitable over such a long period. This argument is perfectly valid under the current system, but not if we agree to radically change the forest management system.

As well as reducing the intensity of logging, particularly in Amazonia and Southeast Asia, the sustainability of logging depends directly on the number of timber species that can be sold on the market. In fact, a greater diversity of species will lead to a better recovery of timber volume because of the diversity of behaviour of these species, particularly their abundance and growth. In fact, the logging of a few timber species with high wood density, slow growth and often low numbers of individuals per hectare prevents rapid timber volume recovery. Tropical timber markets are still very poorly diversified, and only a few flagship species are actually sold. These markets also offer very few product outlets, and the wood industry contents itself with supplying basic products such as plywood or sawn timber. Under these conditions, the timber industry in tropical countries remains antiquated and undiversified. As a result, yields are very low, rarely exceeding 30%, meaning that 70% of the logs are burnt. A higher yield would undoubtedly help to reduce harvesting intensity.

DIVERSIFYING THE SUSTAINABILITY OF THE CONCESSION SYSTEM

The state forest concession system managed by private companies remains the most widespread management model in tropical regions. Under this model, the State transfers to a private company the right to manage large areas of land that can exceed several hundred thousand hectares, and sometimes more than a million. In most cases, these concessions are in remote regions with very little infrastructure and very limited government presence. In this context, the logging companies at the head of these concessions become the region's main employer and economic engine. They also take the place of the state in building infrastructure such as roads, staff transport, and sometimes schools and health centres. As we saw in the previous chapter, the social impact of such a situation can be very negative for local people, who are entirely dependent on the forestry company. Although certified operations offer their staff very high standards of working conditions (pay, safety measures) and living conditions (housing for families, schools and medical clinics within the concession), they are still in the minority in the tropical world. Moreover, certification does nothing to change the concession system itself, which remains a very rigid and hierarchical framework that offers little scope for the emancipation of local populations.

The economic constraints on forestry companies are an intrinsic obstacle that has always called into question the economic sustainability of the activity and forced these companies to make decisions that are hardly compatible with the long-term sustainability of logging. Firstly, the permits granted by the State for management of a concession never exceed the harvest cycle period set by law and are very often shorter. Under these conditions, the forestry company does not have the guarantee of being able to operate beyond the first exploitation. This then restricts their investment choices, which they cannot plan beyond 20–30 years. The risk of non-renewal of such permits is all the greater when the political situation in a country is unstable, which can have the effect of changing not only the leaders, but the rules put in place by their predecessors. The length of the harvest cycles, generally between 25 and 35 years, remains a major obstacle to the economic profitability of the business, as it is extremely difficult to project over several decades without the guarantee of being able to keep the usufruct of the concession. Any proposal to extend this period is generally frowned upon and strongly opposed by the forestry sector. In this context, the forestry companies in charge of managing the concessions aim above all to maximize profits generated by logging during the term of their contracts. They are therefore very reluctant to invest in large-scale silvicultural treatments, for example, for fear of not reaping the benefits during the second harvest.

This concession system could be improved through active monitoring and greater accountability by the State, which, after all, owns these vast forest regions. The State should assume responsibility for ensuring the long-term sustainability of the concession systems through greater involvement, not just by setting the management rules, but also by investing in infrastructure such as road networks and ensuring that pre-harvest inventories are carried out by the relevant State services (forestry service, forestry department, regional forestry agencies). In this way, the State would remain the true project manager and guarantor of the management of its forests and would limit the role of private companies to that of forest operators responsible for harvesting, rather than for forest management and its sustainability.

PROMOTING SOCIAL FORESTRY

The concession system remains almost exclusively accessible to private companies with strong investment capacities and access to credit to develop their activities. It therefore excludes many other potential stakeholders, such as small farmers and forest communities. The future of sustainable tropical forest management and its long-term survival will depend on the ability of governments to offer operating systems that enable these stakeholders to manage their forests for their own benefit. Admittedly, there will be a long and difficult road ahead before local populations can manage their forests autonomously and sustainably, but this obstacle must be overcome. Forest communities and small farmers generally have little means of investment and, above all, very little technical knowledge of modern forest management, which requires a high level of engineering in a wide range of fields. In addition to the technical skills they need to acquire, they also need to know the markets and develop current accounting management skills. Unlike private companies, these populations do not have access to credit to invest in forestry activities. Finally, land tenure and use rights for the land occupied by these populations are for the most part non-existent or informal, which naturally constitutes a major obstacle to long-term investment.

Involving local communities

To illustrate the importance of involving local populations in forest resource management, the Brazilian Amazon offers an interesting example. In this region, the Brazilian Forestry Code requires the preservation of a forest reserve covering 50–80% of the surface area of each property. It authorises timber harvesting provided that a management plan is approved by the relevant local institutions. However, the approval criteria are much better suited to large-scale mechanised logging by specialist companies than to small-scale forestry. The latter only has small areas of forest (50–80 ha) and low investment capacity, exacerbated by the lack of forestry credits. In addition, they are unfamiliar with forestry and business management techniques. To make a profit from their forest reserves and remain within the law, small farmers are forced to sell standing trees, usually at low prices, to loggers, most of whom are illegal and use logging techniques that are highly damaging to the forest. The loggers sign contracts with several farmers each year, so that they have enough land to make a profit from their activities. The area varies between 500 and 1,000 ha, representing between 10 and 20 individual contracts. These practices are detrimental not only to the farmers, who earn little income from their forest reserves and bear the legal responsibility for this illegal trade, but also to the forest ecosystem, whose regeneration capacity is compromised by the extensive damage caused by logging operations that do not generally apply low-impact logging techniques. Establishing specific legislation for the management of forest reserves on rural estates, by defining precise specifications to ensure the sustainability of logging, and by ensuring the fairness of contracts through fixed prices per cubic metre, would create a framework favourable to the development of small-scale forestry and the legal accountability of forestry operators.

Unfortunately, this type of partnership is still underdeveloped, as the government tends to favour 'autonomous' peasant forestry systems, i.e. ones set up and managed by the farmers themselves. However, this requires a high level of technical and financial support from the State, which has yet to materialise. The development of farm forestry would also require the opening of specific forestry credit lines for small farms, in the same way as those made available for agricultural activities. These credits could be used by farmers' cooperatives wishing to make the most of their forest reserves and to finance the forest inventorying stage, which is essential to determine the precise volume that can be exploited by species. The cooperatives would thus retain considerable autonomous control over the main management decisions (annual felling area, species to be harvested) and would be able to negotiate harvesting contracts more easily. Inventory costs are estimated at around 13–20% of total management costs, which is within the norm for credits granted to family farming.

Although the annual incomes generated by such partnerships remain modest compared with that from agriculture, the amounts received by farmers after timber harvesting constitute capital that can vary from 5,000 to 30,000 dollars depending on the species harvested and the volume extracted. The forestry revenues generated could be reinvested in setting up ecologically intensive farming and stockbreeding systems on land that has already been cleared, thus avoiding any further deforestation. Finally, the areas involved are considerable, as the forest reserves of rural properties in Amazonia cover around 650,000 km^2 (65 Mha).

The development of private forestry could no doubt take inspiration from the institutional aspects of the French system. Indeed, 75% of France's forest is privately owned (12 million ha) by more than 3 million people. The average property size is just 3.5 ha, and forest owners use forestry companies. The *Centre National de la Propriété Forestière* (CNPF), a public administrative body, and its 11 regional delegations, the *Centres Régionaux de la Propriété Forestière*, are at the heart of the private forest management system. They are at the service of forest owners. However, small properties of less than 4 hectares are rarely put to use, as they are considered too small to be profitable. If taken together though, these small holdings account for 30% of the total forest area in mainland France, or 6.8 million hectares. In France, as in Brazil, the agglomeration of small private forest areas is a challenge.

Community management

Another alternative to a forest concession managed by a private company would be a concession system managed by communities or associations of villagers, in other words, community forest management. For several decades now, local populations, particularly indigenous peoples, have been demanding their right to manage their forests themselves and for their own benefit. While economic profitability is a key factor in enabling them to make a living from logging and improve their living conditions, it is not the only reason for becoming involved and claiming the right to manage the forest resources on their concessions or land. Communities also see it as a way of reclaiming the land of their ancestors and perpetuating a way of life that harmonises tradition and modernity. In most cases, community forest management is a means of conserving large areas of forest and deterring illegal logging or deforestation, as forests inhabited and used by local communities tend to be actively protected by them. However, few countries fully exploit the potential of community forest management, and there are many obstacles to its effective implementation. The system is still fragile and does not always deliver the expected results due to both internal constraints (legislation ill-suited to the community model, weak and fragile social organisation of communities) and external constraints (no access to funding, unstable markets). In addition, it is difficult to assess the success of community forest management schemes in a comprehensive way, because they are extremely diverse from all points of view—environmental, social, economic and political—and because of the perceptions of the people involved. Some consider environmental protection and the recognition of local people's rights to manage their forest resources to be the main criteria for success, while others focus primarily on the benefits generated by forest management.

Research carried out over the last 40 years on the conditions necessary for the successful implementation of community management systems points to several essential factors to be considered. The first is state recognition of the land rights of communities wishing to manage their forests. These rights can be recognised either through the granting of concessions for a period at least equal to the harvest cycle set by law, or through the granting of property rights, which in the latter case is particularly well suited to village or peasant forest management. Without this security of harvesting over several decades and in all legality of the forest resources of an area legally demarcated and recognised by the State, no community or village management system is possible in the long term. In many tropical countries, land tenure rights are still very nebulous, and the forests, although in most cases state-owned, are inhabited and exploited by local people informally and frequently illegally, as they have no rights recognised by the State.

In most tropical countries, government-imposed forestry regulations are the second major obstacle to the development of community forest management systems. The procedures are numerous, extremely complex and rarely adapted to the context of community forest management. These regulations, often designed for systems of concessions or large private forest estates, require in-depth knowledge of forestry laws. Private operators finance experts specialised in procedures and have offices in major towns, giving them easy and regular access to state forestry agencies. Forest communities and villagers, on the other hand, have little knowledge of forestry regulations and lack the logistical resources of large private operators. Obtaining a felling permit can sometimes take years and involve very high transaction costs. All too often, these efforts fail, discouraging project leaders and reinforcing their sense of powerlessness to establish community forest management.

The success of a community management system depends heavily on strong, well-established governance between the members of the community, which may comprise several villages, themselves made up of families. Governance that defines the rules of operation, in particular the way in which the whole community is represented, is a key element in the success of a forestry development project. Solid governance means the full and active participation of local communities and other stakeholders, transparency in the decision-making process and accountability. It is also associated with effective and efficient management of natural, human and financial resources, as well as fair and equitable distribution of benefits to community members. Conversely, weak governance will lead to a lack of transparency, which could result in an inequitable distribution of income to the benefit of certain elites in the community, and a risk of corruption. Numerous studies show that the development of solid governance does not happen by itself and requires regular support over many years from non-governmental organisations (NGOs), research players and the support of international cooperation with governments.

Strengthening forest communities' technical knowledge of forestry is an essential element in the success of community management. Although in many situations certain operations can be entrusted to external operators, it is important to understand the basic principles in order to negotiate the best possible service contracts.

Difficult access to markets and insufficient knowledge of how they work are major obstacles to the economic success of community management. In addition, community or smallholder enterprises need time to respond to the constraints of the market, which demands a fixed quantity and quality of products over time. Communities and smallholders need to gain considerable knowledge to assess the markets and adapt their products to these requirements. Associations representing communities and smallholders can play an important role by acting as intermediaries between their members and market information, and by advocating market and regulatory reform, as forest owners' associations do in Europe, for example.

Unfortunately, one of the main constraints on community management, particularly entrepreneurial management, is financing. There is no credit available for communities, because the risks are too great for the banks. The only solution is therefore to obtain financial aid from the State or from international cooperation. In other words, the development of community and social forestry in general will not happen without subsidies from governments or international development aid. Agriculture is heavily subsidised and so have agrarian reform programmes in Amazonia and Indonesia, with the environmental consequences of deforestation and massive forest degradation well known to all. Funding community forest management projects, on the other hand, would make it possible to safeguard millions of hectares of forest, to the benefit not only of communities, but also of our planet. The best example of this is the Maya Biosphere Reserve in Guatemala, which is managed by communities descended from the Mayas and which today constitutes a forest massif of more than 2 million hectares, representing 40% of the country's forest cover.

A successful example of community forest management

> In 1990, in order to stem deforestation and forest degradation in Guatemala, the government created the Maya Biosphere Reserve (MBR) with the support of international organisations. The MBR covers 20% of Guatemala's area. In the 1990s, the country introduced a policy of forest concessions. Within the MBR, agreements were signed between the government and 12 community organisations. They obtained 12 forest concessions and grouped together to form the Association of Forest Communities of Petén (ACoFoP). This association now has around 15,000 direct community beneficiaries.
>
> Forest concessions have played, and continue to play, a key role in maintaining the country's forest cover, by slowing the advance of the agricultural frontier and curbing deforestation and the degradation of natural forest ecosystems within the MBR. The annual rate of deforestation within the concessions is estimated at 0.4%, compared with rates three times higher for the country as a whole: 1.27% between 1990 and 2000, 1.22% between 2000 and 2010, and 0.54% between 2010 and 2020.
>
> In addition, these concessions generate considerable income, providing better living conditions for the families involved, who receive higher incomes, better housing conditions, better access to healthcare and educational opportunities, and natural resource strategies that are more consistent with the conservation philosophy than non-member families. This income has enabled families to ensure the education of the younger generation, which is now reflected in the training of young forest engineers from families involved in forest management. Once trained, these young engineers return to work for the community concessions.

After more than 25 years, the ACoFoP has been internationally recognised as a pioneer and an example of successful forest management. In fact, all the concession contracts have recently been renewed, between 2021 and 2023, for a further 25 years.

The formalisation and implementation of the model mainly benefited from international support and backing from development banks. This financial aid took the form of support for public institutions and concessionaires. It has also focused on health, education, community employment, strengthening the rights of indigenous populations, product certification and technical assistance to communities in the areas of sustainable forest management, setting up community businesses, fire protection and developing value chains for associated products.

Relationships on the ground between forestry services and communities are crucial to the success of community forest management. In many cases, forestry officials are reluctant to accept the fact that forests are no longer managed by the state but by communities, villages or small farmers' cooperatives, even though they are obliged to do so under the regulatory framework. This resistance on the ground is sometimes a greater obstacle than the land rights mentioned above. For example, forest service officials may have to move from directive forest management, which consists of applying or enforcing state-defined management rules, to participatory forest management, in which they must instead help and support smallholders and communities to manage forests for their own multiple benefits. This implies a fundamental change in the agencies' organisational culture, which is very difficult to achieve. Such changes in attitude and approach cannot be imposed by decree and always require significant support. In Mexico in the 1970s and 1980s, although communities were recognised by the state as the true owners of the forests, government institutions continued to exercise direct control over these resources and, in some cases, appropriated most of the benefits. A similar situation was reported in Nepal, where an analysis of case studies in the country's main ecological zones revealed that, although local rights of access and use were guaranteed by national policies and laws, government officials on the ground had great difficulty in fully transferring rights to communities.

Even if all the basic conditions mentioned above are met, it takes a long time for a community to achieve its management objectives because it must necessarily go through a long process of learning and adaptation, which is essential if it is to improve its governance and achieve the desired results.

CHALLENGES OF RESTORING FOREST LANDSCAPES

The research results clearly show that the remaining natural tropical forests alone will not be able to meet the growing demand for timber. It is therefore essential to develop alternative sources of timber production. Deforestation in tropical regions over the last fifty years has created millions of hectares of degraded, unproductive land. It is estimated that this degraded land covers more than 2 billion hectares worldwide. This observation has given rise to international initiatives to promote the restoration of forest landscapes.

Definition of forest landscape restoration

Forest landscape restoration is a relatively recent approach inspired by scientific research on the ecological restoration of ecosystems. While there are many definitions, that of the World Wildlife Fund and the International Union for Conservation of

Nature is doubtless the most concise and clear: “An ongoing process of regaining ecological functionality and enhancing human well-being across deforested or degraded forest landscapes”. The first novel aspect of forest landscape restoration lies in its integrative landscape and territorial approach to different land uses, naturally taking into account forest cover, but also the agricultural land, pastures or industrial oil palm or rubber plantations within an area or region. The second distinctive feature is that its actions must improve the living conditions, particularly the incomes, of the people living in the area in question. The third characteristic is that, unlike the ecological restoration of ecosystems, the restoration of forest landscapes does not necessarily seek to restore ecosystems to their original state, but rather to restore the ecological functions of these ecosystems. In this way, an agroforest fulfils ecological functions comparable to those of an ‘intact’ forest, such as preserving soil and rivers and maintaining a relatively high level of biodiversity. Naturally, an agroforest will not harbour the same level of biodiversity as an intact forest, but it could, for example, act as a buffer on the edge of a protected area or play a key role in connectivity between forest ecosystems within a fragmented landscape, while providing income for farmers through the sale of products from these agroforests.

Promised figures, but a more complex reality

Over the last twenty years or so, the restoration of forest landscapes has received considerable attention from governments, donors and NGOs. Numerous international and regional initiatives bringing together these different players have been launched, and many countries, particularly in Africa and South America, have set themselves very ambitious targets. This is the case for the 34 African countries that are part of the AFR100 initiative, which is committed to restoring 100 Mha of deforested and degraded landscapes in Africa by 2030, and the Latin American countries that are part of the 20×20 initiative, aiming to restore 20 Mha by 2020. None of these targets have been met, but countries are still committed to them.

Apart from the publicity effect, highly prized by the political world, these quantified commitments give the impression that forest restoration is simply a matter of planting trees. Yet setting numerical targets—whether by area or number of trees—misses the point, because forest restoration is not limited to planting trees on cleared land. In some cases, doing so may even be useless or counterproductive.

In reality, the success of restoration is decided well before the final planting stage and includes a wide range of actions that do not necessarily involve planting trees. Above all, it depends on planning and full consultation with local stakeholders. It is these stakeholders who must decide on the future of their area and inform the decision-makers of their needs and their vision for the decades to come. Stakeholder involvement is vital because, for a tree to grow, it needs men and women who care for it. It therefore needs people who are aware that the restoration programme they have helped to draw up will meet their needs and improve their living conditions now and in the future. So it is important to clearly define the restoration objectives with the stakeholders, as these will determine the actions to be taken. For example, if the main objective is to restore biodiversity, the actions to be undertaken will seek to reconstruct natural ecosystems as much as possible and to strengthen connectivity between forest blocks to allow the movement of species and gene flow. In reality, there are many different objectives and the complexity lies in finding a compromise between restoring the environmental services provided by forest ecosystems (soil and water protection, preservation and conservation of biodiversity) and the production of goods (timber, agricultural products) within an area or region. Finally, planning also serves to identify the priority areas for restoration, based on their location, their state of degradation and the objectives set by the stakeholders. This prioritisation is vital, because restoration involves a cost that needs to be estimated and optimised.

Forest restoration does not necessarily mean planting trees on deforested land. In fact, there are two main forms of restoration. The first, known as 'active restoration', involves either planting trees or helping forest ecosystems to recover through silvicultural operations. The second, known as 'passive restoration', relies on the capacity of forest ecosystems to regenerate on their own, i.e. without human intervention. These two approaches do not conflict but complement each other. Depending on the state of the forest cover to be restored and the objectives set, one of the two types of restoration may be favoured, or they may be combined. In areas where the forest cover is still very present, with many trees producing fruit and seeds, it is easier, less costly and, from an environmental point of view, more effective to allow natural regeneration to take place. It should be remembered that 87% of French forests today are the result of natural regeneration, i.e. trees that have reseeded themselves, possibly with the help of foresters. So it is not plantations that shape the bulk of French forests. Active restoration is mainly justified in areas where forest cover is very low and degraded. This is particularly true of former mining sites, where restoration generally requires human intervention. Such cases are referred to more as rehabilitation than as restoration.

An opportunity to promote multi-species forestry

Forest landscape restoration represents an opportunity to promote another kind of silviculture that diversifies wood production sources according to market demands, such as wood energy, pulp and paper and, of course, timber. In most tropical landscapes, forest cover is heterogeneous, consisting of intact, logged and degraded forests, as well as secondary forests, which develop on formerly deforested and abandoned land. Unfortunately, none of these forests are considered to be of economic value anymore, putting them in danger of being converted to other uses, such as agriculture, grazing or oil palm, cocoa or rubber plantations. Their main raison d'être lies in the need to leave cultivated land fallow to replenish soil fertility. Unfortunately, after a few years, they are destined to be converted back into farmland. However, by allowing these forests to regenerate, over time they accumulate a high potential for timber production. These secondary forests therefore deserve the full attention of foresters and government departments with a view to their rehabilitation for timber production, while still providing many environmental services. Timber production from these forests would reduce the pressure on older natural forests, while generating profits for the areas or regions concerned.

In addition to the rehabilitation of degraded and secondary forests, agroforests and forest plantations can also play an important role in forest landscape restoration programmes. They can contribute to the production functions of forest restoration, reduce pressure on 'natural' forests and contribute to strategies to combat deforestation. Restoring the production functions of the forest cover remains essential to meet the very principles of forest landscape restoration, particularly to generate sustainable income for the populations involved. Restoring production functions also means meeting the expectations of local stakeholders, with a particular focus on small-scale or village production.

THE ROLE OF INTERNATIONAL BODIES

In today's globalised world, international bodies can play a decisive role in promoting the sustainable management of tropical forests. However, as states are sovereign, the extent to which they are involved in implementing public policies to encourage the sustainable management of their forests remains crucial and is entirely their responsibility. International aid cannot be effective without the cooperation and motivation of the States themselves to promote sustainable practices.

International standards

International standards, such as certification, are necessary tools to guide consumers and encourage them to buy products from legal and 'sustainable' forest lands. However, it must be admitted that certification systems have a very limited impact on either logging methods or markets. In fact, only 6.5% of managed natural tropical forests receive a certification label, which is a very low rate that should be significantly increased. One of the main reasons for a logger to sign up to a certification process is economic. However, world trade in tropical logs is still centred on two major markets—China and India—where certification systems have no hold. Only the European Union market actively promotes certified products in a substantial and voluntary manner, yet it only accounts for 12% of global imports of tropical timber and products. These figures therefore clearly demonstrate that regulations requiring sustainability or legality certificates will have very little impact on the adoption of sustainable practices in producer countries as long as requirements regarding the legal origin of timber and its sustainability are not generalised and similar in all markets. These requirements should also be enforced in producer countries and at the regional level, and consumers must be made aware of them. For example, the adoption of sustainability standards by the Brazilian market, which consumes over 80% of the timber produced in the Amazon, would undoubtedly have a much greater direct impact on promoting sustainable management systems and combating illegal logging than a boycott of Amazonian timber on the European market.

As part of its new regulations against imported deforestation, Europe also wants to play a major role in the fight against forest degradation and illegal logging. Aware that its imports of raw materials are responsible for around 10% of deforestation in tropical regions, from 1 January 2026, Europe will be adopting regulations only authorising companies to sell their products within its borders if their suppliers publish a declaration confirming that the imported products do not result from deforestation or forest degradation that occurred after 1 January 2021. The commodities concerned are palm oil, soya, wood, cocoa, coffee, livestock, coal and derivatives. The regulation was passed in June 2023, and companies will have 18 months to comply and stop sourcing from locations that contribute to deforestation. Europe has undertaken to cooperate with producer countries to strengthen their policies to combat deforestation and degradation, so that they can export their products legally. This commitment is still theoretical but remains essential if this new regulation is to have a real impact and make a genuine contribution to the fight against deforestation, forest degradation and illegal logging. Otherwise, there is every chance that producing countries will turn en masse to other markets, particularly in Asia.

Carbon markets remain inefficient

Following the Rio Summit in 1992, carbon markets were set up to finance reforestation or forest conservation projects by governments, local communities or private individuals. Demand for carbon credits on the voluntary market has exploded, mainly due to the interest shown by businesses. In 2021, the volume of carbon credits traded on voluntary markets increased by 89%. However, the average price of forestry carbon credits in 2021 was between $4.7 and $15 per tonne of CO_2, well below the price needed to meet the Paris Agreement target of limiting global warming to 1.5°C. Overall, the contribution of carbon market remains minor compared with other sources of green financing. It must be said, therefore, that these payment mechanisms based on the tonne of CO_2 captured or preserved per unit of time have not had the expected impact on forest conservation and restoration.

The main problem with carbon markets is that they consider forests solely as carbon sinks and often lead people to believe that all we have to do to offset our greenhouse gas (GHG) emissions is to stop deforestation and plant trees. It is estimated that forests capture an average of 15.6 billion tonnes of CO_2 per year and that deforestation emits just over 8 billion tonnes, giving a net balance of 7.6 billion tonnes of CO_2, or around 20% of GHG emissions linked to human activities. These figures clearly show that forests alone cannot offset all the GHG emissions linked to human activities. It therefore remains urgent and essential to significantly reduce our CO_2 emissions, in other words to radically and profoundly change our capitalist lifestyle model. This reduction is even more urgent given that increasing emissions would result in more intense periods of drought and higher risks of megafires. Forests will be even more threatened, and their capacity to absorb

CO_2 will be more limited. The effects of climate change on the CO_2 absorption capacity of forests have been felt for several years now. In France, for example, the latest forest inventory data shows that between 2015 and 2019, forests stored half as much CO_2 (30 Mt CO_2/year) as during the previous five-year period (2010–2015, 60 Mt CO_2 stored). In the Amazon, there was also a 30% drop in CO_2 stored between 2000 and 2010 compared with 1990–2000. While conserving forests and promoting forest restoration can contribute to mitigating climate change, this can and must only be done if, on the one hand, we combat deforestation and forest degradation and, on the other, we urgently establish a proactive and ambitious policy to reduce our emissions on a global scale.

Conclusion

Tropical forestry is undoubtedly at a key turning point in its history. The sustainability of selective logging requires, on the one hand, revising the logging regimes laid down by forestry legislation (intensity and length of harvest cycle) and, on the other, diversifying the number of timber species. Natural tropical forests will not be able to meet the demand for timber on a sustainable basis, so there is an urgent need to develop and promote other production systems. Tropical forestry, still very much focused on natural forests, urgently needs to change its paradigm by diversifying production systems. This means taking an interest in the silviculture of so-called 'degraded' forests, secondary forests, agroforests and plantations. It also means investing in forest restoration initiatives at regional and local levels. It is important to stress the absolute necessity of involving local populations in tropical forest management and in any forest restoration initiative at a very early stage in the process. The days of massive reforestation imposed by forestry agencies are over, and it is now time to work with the stakeholders to plan the restoration actions from which they will be the main beneficiaries. The major challenge for foresters in the field of restoration is to identify the species that will be best adapted to the climatic conditions of the coming decades. Temperate countries have been looking at this issue for a long time, and numerous research programmes have been launched, particularly in genetic improvement. In tropical regions, this work has to start from zero.

For a long time, foresters saw forests as a source of timber or energy. This perception has changed, however, because today they are also recognised for the many environmental services they provide to society. Tropical forests are, of course, no exception. On the contrary, with their diversity of plant and animal species, their lushness and remarkably large trees, they represent a real challenge for foresters to implement practices that reconcile production with environmental services. Today, sustainable forest management is therefore intended to be multifaceted, seeking compromises between the production of goods and the environmental services provided by forest ecosystems. This often means limiting the production of goods so as not to compromise the long-term integrity of the ecosystem. However, it should be acknowledged that timber is still the main product from which income can be earned. Unfortunately, sustainable forest management practices that preserve the integrity of the functioning of tropical forest ecosystems are slow to be reflected in a higher price that would reward these good practices. It is high time for markets to offer prices that recognise the value of tropical timber from sustainably managed forests. It is also time to reserve tropical timber from centuries-old natural forests for high value uses, worthy of their unique properties and characteristics, leaving less valuable timber from plantations, agroforests or secondary forests to be used for purposes that do not require special qualities.

The state forest concession system, managed by private companies, still dominate in tropical regions. The State cannot delegate its entire responsibility to the private sector; it must itself guarantee the introduction of good practices and long-term sustainable management. The system put in place by the Brazilian Forest Service for granting and monitoring concessions can serve as an example for other countries. However, it remains very cumbersome and time-consuming to implement, given that in 17 years the concessions granted have only covered a total area of 1.6 Mha, whereas the potential area is close to 35 Mha.

Access to forest management by communities and small-scale farmers is a major challenge for the conservation of the millions of hectares of forest owned by local populations, which are currently unused and therefore in danger of being converted to other uses. The development of social forestry in tropical regions requires both the help of governments, through the creation of forestry legislation adapted to the context of community and small-scale forest management, and substantial financial support. This is the price to pay for conserving these millions of hectares of forest while generating benefits for rural populations. This social forestry could also be particularly well suited to multiple management combining the production of timber and non-timber forest products, ecotourism and payments for environmental services.

Sustainable management of tropical forests cannot become widespread or become the norm without a determined fight against illegal logging, which still accounts for a significant proportion of logging (between 40 and 50%). This fight must be waged through proactive policies by the governments themselves, with the help of international cooperation. It is a fight that can be won, because today remote sensing tools exist to identify illegal logging, but they will remain powerless unless accompanied by repressive measures on the part of governments.

For more than 40 years, tropical forests have garnered the world's attention. The entire international community recognises the importance and urgency of conserving and enhancing them, and of halting their deforestation and degradation. However, it should be emphasised that deforestation is no longer confined to tropical regions but is becoming more widespread due to the effects of climate change. For more than a century, temperate countries have seen their forest cover expand, as has France's forest area, which has doubled in just over a hundred years, but the effects of climate change are jeopardising this expansion. Some of France's forests are dying because of long periods of drought, making certain tree species vulnerable to attack by pathogens such as bark beetles, which are responsible for the decline of spruce forests. Initially triggered in the Grand-Est region, the bark beetle epidemic has now spread to almost all spruce forests, from the northern half of France (Bourgogne-Franche-Comté, Hauts-de-France, Normandy) to Auvergne Rhône-Alpes. Data from the latest national forest inventory, carried out in 2023, shows that the average tree mortality rate in French forests has risen by 80% in ten years. Temperate forests are also more vulnerable to fire, whose spread is accelerated by long periods of drought and drier, more flammable vegetation. In 2022, forest fires in France destroyed more than 60,000 ha, much of which was in the Landes forest. That same year, across Europe, 785,000 ha of forest burnt. This is more than double the average between 2006 and 2021. Finally, in 2023, fires in Canada ravaged around 18 Mha, an area twice the size of Portugal. As a result of climate change, deforestation is spreading across the planet. Temperate countries are therefore also affected by the problems of deforestation and degradation, albeit for different reasons, but ones that are just as worrying.

In tropical regions, climate change is exacerbating the effects of forest degradation caused by unsustainable illegal logging. However, very little is known about these effects to date, as research about the recovery of tropical forests after logging takes very little account of the different climate scenarios. A recent study carried out at Paracou, in French Guiana, modelled the reconstruction of the forest after logging according to different climate scenarios. The results suggest that an increase of 1.5°C by 2100 would have little impact on timber production, whereas an increase of 4.5°C by 2100 would lead to a 40% drop in timber production.

The road to sustainable selective logging of tropical forests is still strewn with seemingly insurmountable obstacles. Over the last 50 years, research in this field has produced countless results. While some of these results require us to change our vision of tropical forestry, many of them, confirmed by experimentation and modelling, could be applied in the field today. To achieve sustainable selective logging, governments will need to have the courage to combat illegal logging, review logging regimes and launch ambitious forest restoration programmes. Without this political will, tropical forests will continue to deteriorate under the effects of both predatory and illegal logging practices and climate change. Climate change is likely to accelerate the loss of tropical forest cover.

In a world in the throes of climate change, the effects of which are being felt more keenly every day, forests have never been so crucial to our survival. We need to learn to respect and care for them. This means using them in a way that supports their capacity to recover. Agreeing to reduce the intensity of logging and to extend logging cycles is certainly a difficult choice to make, as it goes against the silvicultural dogmas established half a century ago. There are solutions, however, such as those outlined in this essay. These need to be put in place quickly, because the life cycle of trees spans several human generations. So the time to act is now—especially as the urgency of climate change grows clearer by the day.

Finally, we all recognise that forests are not just machines for producing wood, they are also crucial to safeguarding a viable and habitable environment for all humanity. Let's take care of our forests and ensure that humans finally become their guardians rather than their gravediggers.

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Over the last thirty years, more than four hundred million hectares of tropical forest have been destroyed. Alongside this deforestation comes forest degradation, which in some regions of the world, such as the Amazon, affects an area just as large as deforestation. Safeguarding tropical forests has therefore become nothing less than a priority for the survival of humanity.

One way forward involves setting aside forests as protected areas, thereby limiting the use of their resources by humans. The other is to manage them sustainably, so that they continue to provide vital goods and services to local communities and society as a whole. Foresters favour this second method, based on the idea that a forest that is valued for the goods and services it provides to populations, the State and society will be protected and conserved.

Yet reality on the ground tells a different story. Illegal logging, which is still widespread in many tropical countries, causes significant damage to forest stands, undermining their ability to regenerate and withstand the effects of climate change. Timber harvesting is thus often blamed for a host of ills and widely regarded as the main driver of deforestation.

This book does not set out to justify logging. Instead, it offers a clear, factual and accessible account of its true environmental impacts. More importantly, it reveals how timber harvesting, rather than being an enemy, could become a powerful ally in the fight to conserve the world's tropical rainforests.

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