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Achieving sustainable management of tropical forests

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Preface

Professor Jürgen Blaser and Patrick Hardcastle have been friends and colleagues for more than 25 years. Their career paths have broad similarities and both have spent the majority of their professional lives working to improve the levels of interest, knowledge and capacity in tropical forests across the developing world.

In 1998, when Prof. Blaser was Senior Forestry Adviser in the World Bank, he organised a meeting that was held in the Appalachians to address the question: *Sustaining Tropical Forest: Can we do it, is it worth doing?* Patrick Hardcastle took on the role of facilitator and rapporteur. One output from the meeting was a definition for Conservation Forestry. This was defined as follows:

Conservation Forestry is the application of verifiable best practices for the management of forest resources, including woodland and trees, in ways that are ecologically sound, economically viable, socially responsible and environmentally acceptable and which do not reduce the potential of these resources to deliver multiple benefits now and in the future.

More than 20 years later, they have collaborated in editing this book, which aims to provide a reference work particularly for those who seek to apply SFM on the ground in their own tropical countries.

The Appalachian meeting gathered together a wide range of experts from all tropical regions and included a number of major figures in the tropical forestry world, one of whom, Jack Putz, has contributed to this book. Some are still with us today at a very advanced age, like Frank Wadsworth and Eberhard Brünig, others are sadly no longer with us. We would like to remember particularly, Alf Leslie, Duncan Poore, John Spears, and Tim Whitmore, all of whom had vast knowledge and were characterised by their great willingness to share that knowledge as widely as possible.

Introduction

While global rates of deforestation have started to decrease, deforestation rates remain alarmingly high in many tropical countries. The challenges faced by tropical forests highlight the importance of sustainable forest management (SFM). This collection summarises and reviews the wealth of research on tropical forests and how it can help make sustainable management of tropical forests a reality. Part 1 addresses the broader political, economic and environmental context in which tropical forests are situated. Chapters cover topics such as tropical forest ecology and climate change, global trade flows and land use, as well as the UN's Sustainable Development Goals and national governance.

Part 2 reviews the range of ecosystem services provided by tropical forests, from timber and non-timber products to carbon sequestration and biodiversity, as well as the way these services can be valued. Parts 3 and 4 build on this foundation by reviewing research on the management structures and techniques required for SFM. Chapters discuss operating standards in SFM, tenure and management rights and community-based forest management, as well as monitoring techniques and the role of agroforestry in SFM. Part 5 includes case studies of SFM of different tropical forest types.

Part 1 Challenges faced by tropical forests

Part 1 begins with an overview of tropical forest formations. The type of forest encountered on any specific site on the planet is the result of the interaction between abiotic factors and the living organisms that together make up the ecosystem. This interaction is then further complicated by a range of influences that may be human, biological such as pollinators, pests and diseases or mechanical, such as wind, storms and wildfires. Chapter 1 reviews environmental factors determining different types of tropical forest such as temperature, precipitation, sunlight, atmospheric and soil chemistry and mechanical factors. It then summarises key characteristics of different tropical forest formations such as moist evergreen forests/tropical rain forests, moist deciduous forests, tropical dry forests/monsoon forests and tropical conifer forests.

Chapter 2 addresses the pressures on tropical forests, focusing specifically on agriculture, trade and illegality. The chapter reviews some of the main pressures on tropical forests, starting with an overview of recent rates of deforestation. The drivers of this loss of tropical forests are summarised, and the main ones – clearance of forests for agriculture, often linked to global trade flows, and, to a lesser extent, logging for timber – are analysed in more detail. The key underlying problems of weakness in forest governance and law enforcement are discussed, and the chapter concludes with a summary of international efforts to tackle these and to eliminate deforestation from global supply chains.

The next chapter focuses on the narratives on the Sustainable Development Goals (SDGs) and tropical forests. Chapter 3 explores the relevance of the UN's Sustainable Development Goals (SDGs) for tropical forests by identifying and assessing the three main narratives that characterize debate about the SDGs and forests. The chapter introduces each of these narratives, followed by a discussion of linkages and implications for tropical forests. It also examines the term 'narrative' and why this particular conceptual approach was used to discuss linkages between the SDGs and tropical forests, which is then followed by an introduction to the three narratives about the SDGs and forests. The chapter also explores linkages between the narratives and tropical forests, then concludes by addressing key issues relating to the way SDGs may affect tropical forests, including potential conflicts and trade-offs in reconciling particular SDGs and forest conservation.

Chapter 4 examines the key challenges of national governance and tropical forests. It reviews the status and trends of tropical forest governance, how it is manifested in SFM, and what can be done to improve it. The chapter starts by drawing attention to the development ambitions that provide a context for efforts to preserve or sustainably manage tropical forests. It then reviews a range of research on the state of governance in tropical forests, initiatives to strengthen governance, and evidence of progress or otherwise. It also discusses drivers behind favoured approaches to governance, as well as limitations to fulfilment of governance ambitions, including capacity constraints and lack of integration into the fabric of tropical societies. The chapter concludes by providing key messages on possible ways forward.

The final chapter of Part 1 reviews climate change and tropical forests. Climate change is a major global challenge. In recent decades, tropical forests have contributed to greenhouse gas emissions due to deforestation and forest degradation, but intact and recovering forests are taking up carbon and the contribution of tropical forests to the global carbon cycle is currently about neutral. This is likely to change in the near term, due to continued forest loss and the effects of climate change on tropical forests themselves. Tropical forests, and the human communities that depend on them, are diverse, with varying sensitivity and vulnerability to climate change. Chapter 5 provides an overview of the interactions between tropical forests and climate. It describes the role of tropical forests in the global carbon cycle, the relationship between forests and climate, the impacts of climate change on forests in different parts of the tropics and the options for future management of forests to adapt to climate change.

Part 2 Ecosystem services provided by tropical forests

The first chapter of Part 2 focuses on new types of products from tropical wood. Chapter 6 begins by discussing SFM practices in the tropics and highlights the main wood and biomass resources available. It then reviews the types of traditional and new products developed from these resources. It assesses current trends in terms of market development, possible applications and the challenges faced in the development of new products in light of the global need to mitigate climate change and produce low-carbon products.

The subject of Chapter 7 is non-timber forest products from tropical forests. Non-timber forest products (NTFPs) were hailed as a 'silver bullet' to provide the economic incentives to conserve standing forests, while contributing to local livelihoods. While the livelihood benefits of NTFPs have been widely acknowledged, the contribution of the NTFP sector to biodiversity conservation is less certain. Despite increasing scepticism of the ability of NTFPs to contribute to conservation, their promotion and development remains a readily implemented tool for many site level conservation projects. However, this chapter dispels certain assumptions related to NTFP sustainability and the links between NTFP extraction systems and conservation. The authors conclude that the links are generally tenuous to say the least and suggest that, despite the value of NTFP-based systems to rural livelihoods, our perceptions of the relative value of NTFPs in terms of biodiversity conservation need to be revised.

Chapter 8 examines the ecosystem services delivered by tropical forests, focusing specifically on the regulation of these services for climate and hydrological cycles. Global warming is significantly altering the environmental conditions under which forests grow at a global scale. At the local scale, the impact of global warming on forests depends heavily on current forest type and structure, soil conditions and water availability. Managing forests for the provision of ecosystem services requires anticipating how global warming might alter local environmental conditions and how this will affect the forests. Based on this anticipation, measures can be taken to reduce the risks and support forests in their adaption to those anticipated conditions. Such measures should take into account uncertainties and the effect that those measures themselves will have on climatic and other environmental conditions. The chapter summarises the current state of knowledge on the interactions between forest ecosystems and the climate system and the way in which forests influence the water cycle.

Drawing on information previously discussed in Chapter 8, Chapter 9 moves on to examine biodiversity and ecosystem services in tropical forests, focusing on recent findings and their implications for sustainable forest management. Tropical forests are some of the most biologically rich areas on Earth. The biodiversity in tropical forests, specifically species and functional groups and the ecological processes resulting from species behaviours and interactions, underpins important ecosystem services. These ecosystem services are valuable locally as well as regionally and globally. It is biodiversity that provisions ecosystem services and at the same time supports or maintains tropical forest processes, which then provide other ecosystem services. An understanding of these interrelationships should be valuable to support SFM approaches. The chapter reviews research on species and functional groups that provide services in tropical forests and highlights areas in need of more research. An understanding of the linkages between tropical forests and surrounding agricultural landscapes may provide interesting new ways to frame SFM goals. This needs to be in the context of the state of urgency resulting from the rapid loss and transformation of tropical forests that is occurring today.

Part 2 of the book concludes with an analysis of amenity and recreation values in tropical forests from an ecosystem services perspective. Chapter 10 discusses the role of ecosystem services (ESS) in enhancing recreational and amenity services of tropical forests. It outlines the relationship between forests, recreation and tourism, including the concepts and issues involved in policy making. The chapter also discusses the challenges involved and gives examples of failures in managing ESS sustainably in relation to recreation to show how they might be better managed in the future.

Part 3 Management structures to support sustainable forest management (SFM)

Part 3 starts with a chapter that examines how to define sustainable forest management (SFM) in the tropics. Chapter 11 discusses definitions of SFM to promote clarity about the avoidable and unavoidable trade-offs associated with SFM. It begins with a discussion on the evolving concepts of sustainability, which is then followed by a section on the appropriate scales for assessment of SFM, specifically focusing on stand and landscape scales. The chapter also analyses the SFM trade-offs at different scales and provides a section on defining terms in SFM. Land-use types in SFM are also described. The chapter concludes by highlighting the potential challenges for SFM in tropical forests.

The subject of Chapter 12 is improving operating standards in sustainable forest management in tropical forests of Africa. Forests, if managed sustainably, are important for providing livelihood support to millions of people by delivering environmental, economic and social values. However, high rates of deforestation and forest degradation, undefined policies on land and forest tenure, and on associated benefit sharing, contribute to the unsustainable forest management in Africa. The chapter highlights some of the concepts of SFM as a way of presenting opportunities to stakeholders and communities, as well as contributing to sustainability of forest resources. Furthermore, opportunities for using SFM are highlighted using the Participatory Forest Management (PFM) approaches as a case study.

The next chapter examines the role of certification schemes in sustainable forest management of tropical forests. Forest certification and its impact has proved to be fertile ground for research and study, both political and technical, and a huge number of research articles, papers and books has accumulated. Chapter 13 seeks to offer an overview of this research, some of the main conclusions that have already been reached about the impact of forest certification, and how much it has been able to contribute to the goal of sustainable forest management. Finally, the chapter offers suggestions for modifications that could be made to the current structure of global and regional forest certification to ensure that it better achieves its goal.

Chapter 14 reviews tenure and management rights in tropical forests. Secure tenure rights are fundamental to the sustainable management of the world's tropical forests. By determining the depth of rights and the consequent decisions actors can make, tenure regimes allow present-day considerations of future values, thus incentivising investments in the sustainable use and management of forests, including their conservation and restoration. While legally recognised community forests tend to have lower rates of deforestation, store more carbon and benefit more people than forests managed by either public or private entities, over two-thirds of forestlands remain locked in the hands of governments—a significant portion of which is contested by the communities that traditionally use, govern and protect these ecosystems. Using longitudinal tenure data and analysis of global trends in forest ownership developed by the Rights and Resources Initiative, this chapter details the distribution of statutory forest rights across the world's most forested low- and middle-income countries in Asia, Africa and Latin America.

The final chapter of Part 3 assesses community-based management of tropical forests. Community-based forest management (CBFM), also known as community forestry, social forestry, joint forest management or participatory forestry, has emerged in response to the concern that centralised forest ownership in most developing countries has failed to promote sustainable forest management SFM. Chapter 15 provides an overview of CBFM in the tropics. It first discusses the origins and evolution of CBFM, followed by an analysis of governance issues relating to CBFM, the factors affecting the success (and failure) of CBFM, the design and implementation of CBFM, and CBFM in international forest policy and management.

Part 4 Monitoring and management techniques in sustainable forest management (SFM)

The first chapter of Part 4 discusses new techniques for assessing and mapping tropical forests. Chapter 16 reviews these recent developments by discussing the planning of inventories, assessment procedures and statistical evaluation. It then examines the use of remote sensing techniques to identify changes in land use such logging and deforestation. It also looks at the role of *in-situ* assessment and how this data can be integrated with remote sensing data. Particular attention is paid to cost efficiency and quantification of uncertainty in inventories. The chapter concludes by providing information on potential future trends in research on the subject.

The next chapter focuses on advances in monitoring and reporting emissions from tropical forests in the context of the United Nations Framework Convention on Climate Change (UNFCCC). Chapter 17 provides an update on advances in monitoring and reporting emissions from, mostly tropical, forests in the context of the UNFCCC. The world's forests store vast amounts of carbon and sustainable forest management is therefore intimately linked to monitoring and reporting on greenhouse-gas (GHG) emissions. Many countries are making progress in developing National Strategies and/or Action Plans for Reducing Emissions from Deforestation and Forest Degradation (REDD+), developing and submitting REDD+ Forest Reference (Emission) Levels (FREL/FRLs) and REDD+ results to the UNFCCC. This chapter illustrates the choices countries have made when constructing their FREL/FRLs and areas for improvement identified during technical assessments. Such information can help countries to learn from each other's experiences and thus facilitate South–South knowledge exchange on REDD+. The chapter concludes with an outlook on expected future advancements in measuring, reporting and verifying REDD+.

Chapter 18 emphasises the importance of understanding and exploiting the genetics of tropical tree species for the restoration of tropical forests. The development of sound conservation and regeneration strategies depends on the exploitation of genetic variation of tropical trees. Patterns of genetic variation have been assessed in field trials but at the molecular marker level, only for a few main plantation species in the tropics, such as eucalypts. Preliminary evidence points towards considerable genetic diversity and complex spatial structures for most tropical tree species. The chapter provides examples to illustrate the use of field trials and molecular tools in order to clarify genetic relationships within species-rich taxa, such as dipterocarps, and to identify superior genotypes for plantation establishment.

Moving on from Chapter 18, the next chapter analyses the pathogens in tropical forests in terms of diversity and management. Plants in tropical forests are subject to attack by a wide range of pathogenic organisms, including fungi, bacteria, viruses and parasitic plants, which reduce productivity. In natural forests, pathogens are normal components, arguably driving evolution through attacking susceptible individual trees, so that the following generations of plants are from more resistant parents. Chapter 19 begins by highlighting root diseases in trees, such as root decay fungi. It then examines other diseases, such as stem and wilt diseases, and goes on to analyse foliage pathogens and virus diseases. A discussion on nematodes and algae parasitic plants is also provided before the chapter concludes with a section on disease management.

The final chapter of Part 4 examines the role of agroforestry in sustainable forest management of tropical forests. Chapter 20 reviews to what extent agroforests that are classified as forests are in line with the objectives of sustainable forest management, focusing on biodiversity conservation, supply of forest products and carbon capture. The authors use shifting cultivation as a case study, given its pantropical distribution and the paucity of data on agri-silvicultural systems. The chapter then highlights the limitations to and threats from system intensification to delivery of these goods and services. It concludes with a section of potential sources for further information on the subject.

Part 5 Sustainable forest management (SFM) of different types of tropical forest

The final part of the book begins with Chapter 21, which reviews the restoration of tropical forests, focusing specifically on forest landscape restoration (FLR). It begins by addressing the importance of implementing forest landscape restoration and provides an overview of different guides and tools for FLR. It also provides two case studies, the first being a 3-year project on FLR in Madagascar by the WWF and the second being an analysis of the political process called the 'Bonn Challenge on FLR'. The chapter then reviews the challenges and opportunities in taking forest landscape restoration forward and concludes by highlighting how it has changed since it was first defined 20 years ago.

Chapter 22 focuses on sustainable management of tropical plantation forests. Global forest plantation areas increased from 17.8 million hectares in 1980 to 278.0 million hectares in 2015, an increase of almost 1500% within 35 years. The tropical region recorded the highest increase of 8% between 2010 and 2015. Forest plantations contribute significantly in meeting the world's growing demand for wood products and other ecosystem services. Despite their small extent (7% of the global forest area), about 50% of global industrial wood is sourced from planted forests. The chapter examines key sustainability issues in tropical forest plantations to provide a more holistic and multi-dimensional understanding of sustainability of the ecosystem. It also discusses measures to improve sustainable management of tropical forest plantations.

The next chapter examines sustainable forest management of tropical moist forests in the Congo Basin, which is the second largest expanse of tropical forest on the planet. Chapter 23 discusses the recent history and implementational challenges to sustainable forest management across the basin. It shows that, while the most modern SFM ideas and concepts have shaped the current forest legal framework, their translation into effective actions and implementation on the ground remains wanting. The chapter also looks at issues such as logging concessions, land zones and the processes and institutions required to implement effectively SFM policies.

Chapter 24, similarly to Chapter 23, reviews sustainable forest management of tropical moist forests but focuses on the Brazilian Amazon. The chapter presents an overview of forest management practices and regulations in the Brazilian Amazon. This is then followed by a discussion of the benefits and challenges of legal forest management in the region, from private to community-based enterprises. The chapter concludes by summarising the way ahead to ensure the sustainable management of Amazonian rainforest.

The penultimate chapter of the book focuses on the sustainable management of African dry forests. Dry forests constitute the bulk of African tropical forests. They support a wealth of human, animal and plant life. They are important to climate change mitigation and adaptation, and support virtually all sectors of national economies. Chapter 25 discusses the characteristics and distribution of dry forests in Africa. It also reviews key issues in managing sustainably these dry forests. It concludes by providing key sources for further information.

Chapter 26 summarises the key findings from the chapters written by subject specialists from around the world for *Achieving sustainable management of tropical forests*, providing a synopsis of current knowledge and thinking about different aspects of Sustainable Forest Management (SFM) to help those who are responsible for its achievement. As one of the main renewable natural resources, forests will be expected to help mitigate climate change, protect soil and water, provide clean air, conserve biodiversity, help maintain the mental and emotional health of humans who live in them and who visit them to find space and calmness. Concurrently, these forests will also be required to produce wood fibre and other products. This is a tall order but with adequate recognition, finance and human resources made available, it can be achieved through adoption of the principles and practice of SFM.

Part 1

Challenges faced by tropical forests

Chapter 1

An overview of tropical forest formations

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1 Introduction

The type of forest encountered on any specific site on the planet is the result of the interaction between abiotic factors and the living organisms that together make up the ecosystem. This interaction is then further complicated by a range of influences that may be human; biological such as pollinators, pests and diseases; or mechanical such as wind, storms and wildfires. These influences operate over different scales, the largest of which is climate. However, climatic effects are themselves also modified by various effects and the scale of their variation. For the purposes of this chapter, we provide here a brief summary of the overarching complexity within which tropical forests may lie. Deliberately, the present chapter focusses on the biome 'tropical forest' and not the anthrome but being aware that the species *homo sapiens* has altered the biome tropical forests fundamentally over the past decades.

2 The tropics: defining the enabling conditions for tropical forests

The tropics are geographically defined as the region on the Earth's surface between 23°27′N (tropic of Cancer) and 23°27′S latitude (tropic of Capricorn). More accurately the tropics are defined in terms of climatic periodicity, including temperature, light (solar radiation) and hydrological periodicity. In the tropics,

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the daily temperature fluctuations are higher than annual fluctuations. According to Troll (1961, cited in Lamprecht, 1990) the limits of the tropics are formed by the line of equilibrium between the daily and annual temperature variations. With respect to light periodicity, there is relatively little fluctuation in the duration of day and night. At the equator, day and night last 12 hours each throughout the year, and at the two tropics the longest day lasts 13.5 hours and the shortest 10.5 hours. In terms of hydrological periodicity there is no unique characteristic distinguishable for the tropics. As the sun lies directly overhead with high levels of solar energy, the tropics experience increased water evaporation as compared to temperate regions. Near the equator rising warm air is subjected to adiabatic cooling and daily rainfall occurs (Thomas and Baltzer, 2002). Varying climatic systems make the Earth's equatorial zone both warm and wet, thereby supporting the characteristic diverse flora and fauna of the tropical rainforest.

The relevant environmental site factors in the tropics relate to (i) temperature, (ii) precipitation, (iii) sunlight, (iv) atmospheric and soil chemistry and (v) mechanical factors.

2.1 Temperature

The low seasonal fluctuations are a characteristic of the tropics as a whole, including lowland (hot) tropics, mountainous areas (cold tropics) and also, although to a lesser extent, the dry tropics. What creates the particular condition for tree/plant growth and diversity is the constancy of the mean annual temperature over the year, independent of the temperature. In contrast, daily fluctuation of temperature can be important. For example, in Bogor, Indonesia, the difference between the warmest month (25.9°C) and the coldest month (24.9°C) is 1°C, while typical daily temperature fluctuation is 10°C from 23°C at 0600 hours to 33°C at 1400 hours. At higher elevations, the daily fluctuation increases further.

The high energy flux means the relationship between insolation and temperature is different in tropical and temperate regions. Locations in the temperate zone may have a similar mean temperature to a location in the tropics, but the annual temperature variation is much less in the tropics and the solar energy received is much greater. Consequently, the tropics experience increased water evaporation compared with temperate regions. The climate cycle is presented in more detail in Chapter 5, but, in essence, rising warm air is subjected to adiabatic cooling leading to rainfall.

2.2 Precipitation

The patterns of tropical precipitation are derived from the circulation of the air masses regulated by the position of the sun between the tropics of Cancer and Capricorn. At the equator, the sun is in a zenithal position twice a year (March and September). This is the time when the extreme hot and moist air rises in the atmosphere and cools off, creating convective clouds and zenithal rains. The clouds then travel southbound or northbound at high altitudes and descend at 30–40° latitude in the subtropical anticyclone and return to the equatorial cyclonic zone as the so-called trade winds. The intertropical convergence zone, which follows the sun being directly overhead, results in the trade wind patterns, and the moisture-laden air rising over land masses is subject to adiabatic cooling and consequent rainfall. Depending on latitude and topography the tropical belt experiences a perhumid climate essentially around the equator where rainfall exceeds evapotranspiration throughout the year, with some additional influence from soil depth and water storage capacity as well as topography on this.

The outlined process is fundamentally altered by the monsoon winds, in particular, on the southern and eastern borders of tropical Asia. During the northern summer, in latitudes between about 10°N and 23°N, this region is dominated by rain-bringing winds blowing into the equatorial cyclone that has shifted during the northern summer as far as to the northern part of India. The northeast trade winds blow only in winter when the pressure distribution is inverted.

From the equatorial belt the climate becomes increasingly seasonal and this seasonality is also affected by topography. Important alterations in the hydrological regime also occur locally and regionally due to a whole array of factors. Moisture-laden winds crossing high relief hold less moisture afterwards, and leeward areas will be progressively drier. The intensity of the resulting dry season is progressively amplified as the two peaks of the bimodal rainfall pattern of the equatorial zone merge into a single peak beyond around 10° latitude. The effect of altitude can overlay this simple model as the temperature drops with increasing altitude, and moisture is deposited by direct condensation as well as rainfall. The presence of cold ocean streams influences coastal vegetation (Peruvian Pacific coast). Another well-known regional effect has been well described in the case of Brazilian Amazon, where it was described that nearly half of the precipitation of the Amazonia originates from the evaporation of the forests in this area. The other half is from the Atlantic Ocean (Salati et al., 1978).

2.3 Light

As there is a relatively limited length of daylight throughout the tropics, tropical plants are adapted as short to medium day plants. This is also the main reason that temperate or boreal species cannot flower or fructify properly in tropical climates. Although there is intensive insolation due to the high position of the sun throughout the year, clouds and high humidity restrain the amount of light reaching the forest canopy. In the forests only the trees reaching the canopy layer and the emergent trees receive the full sunlight available. Light intensity can fall to 1% in the understorey (Lamprecht, 1990). Trees in that layer have a shade habit, including broad, loose crowns, horizontal branches and soft and large leaves.

Particularly in the humid tropical forest types, light is the main ecological factor. Most of the tree and plant species in the forest canopy are adapted to receive only limited sunlight. Regeneration of forests, however, needs horizontal opening of the canopy layer, and regeneration happens in the gaps of the forest canopy, large or small scale. When mature trees die and fall, the gap created allows increased light at the ground level and stimulates the growth of suppressed seedlings and saplings. If the gap is large, then it will be colonised by more light-demanding species and the succession process will retreat to an earlier stage. Where disturbance levels are low, few gaps will be created other than by occasional falling trees. The stable forests growing in such conditions are predominantly linked to hotspots of forest biodiversity (Whitmore, 1998).

2.4 Atmospheric and soil chemistry

While the chemical conditions of the air (atmospheric conditions) are relatively uniform worldwide, the properties of tropical soils differ essentially from the soil characteristics in temperate or boreal zones.

Tropical forest soils are generally old, not disturbed by major climatic changes in the past, with year-round high temperature and precipitation that has led to intensive weathering and leaching of nutriments, particularly in the humid tropics. Moist tropical soils have virtually no regenerative power. They lack essential minerals for plant growth and are generally composed of iron and aluminium oxides. The typical clay minerals of such ferralitic soils are kaolinites with low cation exchange capacities. In a largely undisturbed humid tropical forest, the exchange capacity is assumed by the humic substances, a fine organic compound and components of the humus layer. The humic substances are part of the thin layer, only a few centimetre-thick layer of humus which is produced by the litter mineralised within a few months. This system reinforced by the presence of mycorrhiza is adequate to maintain soil fertility in largely undisturbed or sustainably managed natural tropical forests.

Due to the extremely low fertility of tropical soils overall, tropical climax forests apply a series of strategies to protect themselves from nutrient loss. One of the core strategies is their diversity and the multi-storey structure of the forest stands. The specific forest structure intercepts nutrients from the air and rain. Also, the root system works as a filter through a web of fine roots. Mycorrhizae assure the complete uptake of the nutrients released in the process of humus mineralisation. As Lamprecht (1990) pointed out, in the humid tropics, 'the soils are maintained by the forests and not the forests by the soils'.

At the local and regional level, throughout the tropics, there are a number of areas with predominance of 'young' tropical soils, with high levels of nutriments, including volcanic andosols and alluvial soils in inundation areas of tropical Whitewater rivers, which bring a constant supply of minerals from young mountain ranges (such as the Andean mountain chain in the upper Eastern part of the Amazon or in the Mekong river basin on SE Asia). Tropical mountain areas also have more favourable soils with respect to nutrient contents. In the drier tropics, the soils are often nutrient rich (depending on the bedrock), but the limiting factor for both dry forests and agriculture is the availability of water.

Overall, about two-thirds (73%) of the soils in the tropical area are nutrient poor, including ferralitic and heavily weathered and leached soils, shallow as well as sandy soils (podzols), and about one-third of the soils have sufficient uptake of minerals, including fertile tropical black soils, alluvial soils and soils in semi-arid peripheral tropics (Weischet, 1980, modified).

2.5 Mechanical factors

Winds and storms (cyclones, typhoons and hurricanes), volcanic eruptions, lightning, forest fire, inundation and earthquakes influence the development of tropical forests. While some of these factors are unforeseen and considered as an 'unexpected' occurrence or 'surprise', today, increased vulnerability has been observed due to the effect of climate change, particularly the frequency and intensity of storms and forest fires.

Tropical storms can destroy intact natural forests, and there have been many cases over the past centuries that forests are destroyed before reaching climax, for example, 'hurricane' forests in the Caribbean and Central America or storm forests in Malaysia. Mangroves that naturally build a wall against flooding after storms or earthquakes/Tsunami have been increasingly threatened and partly destroyed over the past decades (e.g. Myanmar, Indonesia).

Lightning strikes are frequent in equatorial zones throughout the tropics, and they play a role in creating small gaps in tropical moist forests, generally favouring the regeneration of forests. Lightning strikes are also common in the subtropical belt.

Hail can be a problem in that it damages foliage and may facilitate disease damage by allowing fungi to colonise open wounds. Hail is infrequent at low elevations in the tropics, but at higher elevations, cooling in updraughts within cumulonimbus clouds is sufficiently severe for hail to reach the ground. The map in Cecil and Blankenship (2012) clearly shows the link between hail and attitude, with only high altitudes affected in tropical regions. Most literature on hail damage relates to plantations in the subtropics, such as Wingfield and Swart (1994).

Forest and landscape fires are of major significance as an ecological factor in all tropical forests, dry, semi-arid, semi-humid and today even rainforests, as, due to changing precipitation patterns and prolonged dry periods, the risk of vegetation fire has increased over the past 10–20 years. Some forest areas are considered as 'fire climaxes' (e.g. the lowland conifer forests in Central America and the extensive woodland savannas of East and Southern Africa) that have developed over many centuries due to repeated fires. In many areas throughout the tropics, the species compositions of moist and dry deciduous forests have altered due to frequent fires. While natural phenomena occur, most of the fires, today and in the past, are the result of direct human interventions, due to either uncontrolled agricultural burning, hunting carelessly or wilful infractions.

Results from the Ndola (Zambia) fire management plots started in the 1930s concluded that, while fire exclusion in *Miombo* woodland was infeasible over large areas, controlled early burning reduced the frequency and severity of fires. Until the 1980s, this practice was widespread in savanna woodland in Africa, both north and south of the equator. It subsequently fell into disuse as forest departments were increasingly inadequately funded, but its value is beginning to be recognised again (e.g. Hollingsworth et al., 2015).

3 Classifying tropical forest formations

3.1 Overview of the major tropical forest formations

The vast climatic variation and the specific conditions in the tropics result in a large variety of forest types, differing in their diversity, species composition and stand structure. There is no consistent, exact and universal definition of 'tropical forest', as changes are usually continuous and without sharp boundaries, depending on physical (climatic, edaphic, orographic) and biological conditions. The lack of a uniform classification of tropical forest formations is unfortunate because diverging definitions of forest types complicate comparisons between countries and continents (Corlett, 2016).

Tropical forests reach from moist deciduous forests (generally called tropical rain forests) to moist and dry deciduous forests, to subtropical, savanna and woodland, as well as into mountain ecosystems and specific edaphic forest ecosystems (e.g. peat swamp forests, heath forests, mangroves and tropical conifer forests). Table 1 gives an overview of the forest formations in the tropics, based mainly on climatic and particular soil characteristics.

Occasionally there may be an apparent mismatch between species composition and climate. One good example is the Nkhata Bay lakeshore in Malawi. The forest structure here most closely approximates tropical moist