

Forest Soil Carbon Management to Preserve Climate and Biodiversity

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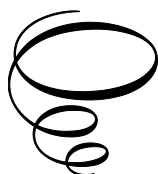
Cover. Example of reforestation following deforestation for intensive beef production at
Fazenda Santa Mônica, Embrapa Dairy Cattle, Rio de Janeiro State, Brazil. *Photo:* ©2025
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By

Lydie-Stella Koutika, Nicolas Marron,
Agustin Merino and Jean-Jacques Royer

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DEDICATION

Tribute to François Bartoli - by J. J. Royer

It was during a dull, rainy weekend in November 1992 that the Centre de Recherches Pétrographiques et Géochimiques (CRPG) opened its doors to the public to showcase its achievements. As leader of the Computer and Geosciences team, I had prepared a convection experiment to illustrate crustal magmatism and volcanism associated with mineralization—the origin of many industrial commodities. I also presented animated 3D topographic maps of mountain building, generated in real time using fractals. Visitors were captivated both by the physical processes and by the possibility of virtually modeling nature.

During my presentation, I noticed a colleague from the neighboring pedology laboratory waiting patiently. He introduced himself as a soil scientist interested in applying fractals to model soil porosity, as well as in our expertise in geostatistics and modeling. His name was François Bartoli.

This encounter marked the beginning of a fruitful collaboration between two laboratories separated by only fifty meters. François involved me in a national research program on fractals applied to soil characterization and invited me to co-supervise PhD students working on experimental data analysis. I introduced many of them to statistics, classification methods, principal component analysis (PCA), and fractal modeling. Several publications resulted from this collaboration.

It was during this program, in the late 1990s, that I first met Lydie Stella Koutika, who was preparing her PhD on the effects of deforestation on Brazilian soils. I recall helping her apply PCA to interpret soil properties before and after deforestation, and preparing her for her oral defense—a practice common in my team, though less so elsewhere. From the outset, I recognized Dr. Koutika's intellect, diligence, and determination, and remained in contact with her throughout her postdoctoral work.

Given her exceptional trajectory, I was pleased to advise her during the preparation of her habilitation, which she defended in early 2025 (Koutika, 2025). This collective book is one outcome of that effort. I have never regretted the time spent working with such a dedicated colleague.

None of this would have happened had François Bartoli not waited to speak with me about fractals on that November day in 1992. He sadly passed away on November 13, 2015 (Margaret, 2016). My thoughts remain with his memory and his family.

Nancy, Monday, 20 October 2025.

References

Margaret A. O. 2016. Tribute to François Bartoli. *European Journal of Soil Science*. 67(1), 22-22. DOI : 10.1111/ejss.12317.

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FOREWORD

Deforestation in tropical and subtropical regions poses a major threat to global biodiversity, climate stability, and ecosystem services. These regions host some of the world's most diverse and carbon-rich forests—such as those in the Amazon, the Congo Basin, and Southeast Asian—which are critical for climate regulation, carbon sequestration, and supporting local livelihoods. However, large-scale land conversion for agriculture (e.g., cattle ranching, palm oil, soy), logging, mining, wildfires, and infrastructure development continues to drive alarming rates of forest loss.

According to FAO (2020a), net global forest loss averaged 4.7 million hectares per year between 2010 and 2020. Net loss differs from true deforestation because it accounts for both forest loss and regrowth. Actual deforestation rates are much higher: FAO estimates that about 10 million hectares of forest are lost annually, with nearly 95% occurring in the tropics (Ritchie, 2021; 2021a).

Deforestation accelerates greenhouse gas emissions and contributes to habitat fragmentation, disruption of the water-cycle, and the erosion of Indigenous knowledge and cultural heritage. Urgent, coordinated action—including stronger governance, sustainable land-use planning, and investment in nature-based solutions—is essential to halt deforestation and support restoration in these ecologically critical regions.

Classical remediation of deforested lands focuses on restoring degraded soils and rebuilding ecosystem functions. Key strategies include afforestation, fallow systems, and plantation forestry using fast-growing species such as Acacia and Eucalyptus:

- Afforestation, the establishment of trees on previously non-forested land, supports carbon sequestration, biodiversity recovery, and soil improvement, especially when native species are used.
- Fallow systems, particularly those based on legumes, restore soil fertility between cropping cycles, enhance soil organic carbon (SOC), and improve nutrient cycling, offering sustainable alternatives to slash-and-burn agriculture.

- Plantations of *Acacia* and *Eucalyptus* enable rapid biomass accumulation, timber production, and soil improvement (e.g., nitrogen fixation by *Acacia*), but require careful management, as exotic species may cause water depletion, soil acidification, biodiversity loss, or invasiveness.

Effective remediation requires context-specific approaches that balance ecological restoration with social and economic needs. Prioritizing mixed-species plantings, native vegetation, and community-led agroforestry enhances long-term sustainability and resilience.

This book examines how deforestation and remediation strategies affect soil structure and properties, synthesizing three decades of research on soil organic carbon (SOC), a major component of soil organic matter (SOM) (Platteau et al., 2006). SOC dynamics are compared across major land-use changes and remediation strategies, including afforestation, fallow systems, and *Acacia-Eucalyptus* plantations. Soil management and conservation practices are presented as agroecological tools for building resilient ecosystems and advancing the Sustainable Development Goals (SDGs) in tropical regions. A comparative analysis of carbon sequestration in the Brazilian Amazon, the Congolese Coastal Plain, Cameroon, and Gabon provides a transcontinental perspective on sustainable soil management.

Chapter 1 introduces the deforestation-remediation framework through a literature review and selected case studies.

Chapter 2 addresses SOC storage in natural forest ecosystems (NFS) of the Brazilian Amazon.

Chapter 3 examines planted forest ecosystems (PES) in the Congolese Coastal Plains (Republic of the Congo).

Chapter 4 explores SOC dynamics across ecosystems and regions, with emphasis on biodiversity and species invasiveness.

Chapter 5 analyzes SOC storage in agroforestry and fallow systems of the Congo Basin.

Chapter 6 synthesizes key findings and outlines future research priorities.

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Photo 1. Two-year-old *Acacia mangium* on sandy soil in the Congolese coastal plains. Despite its benefits and increasing use, this species contributes to biodiversity loss due to its rapid and aggressive spread. *Photo:* © 2014 Koutika.

GENERAL INTRODUCTION

1. Context and challenges

The intensifying environmental crisis—driven by global warming, pollution, and biodiversity loss—has accelerated over the past five decades, posing a serious threat to human well-being, ecosystem vitality, and planetary health (source: <https://www.unep.org/geo/>; Kanakidou et al., 2022). Societies also face growing challenges such as land degradation, desertification, and food insecurity, exacerbated by continued population growth (Falk et al., 2022).

These interlinked crises have hindered global progress toward the seventeen (17) Sustainable Development Goals (SDGs) of the United Nations (UN) Agenda 2030 (THE 17 GOALS | Sustainable Development by un.org, Annex I). They have also slowed implementation of key international commitments, including the Paris Agreement—adopted by 196 parties at COP21 (UN Climate Conference, The Paris Agreement) (source: <https://unfccc.int/process-and-meetings/the-paris-agreement>), and are likely to affect the Post-2020 Targets of the Global Biodiversity Framework (UNEP, Kunming Montreal Global Biodiversity Framework, source: <https://www.unep.org/resources/kunming-montreal-global-biodiversity-framework>).

Soil organic carbon (SOC), a major component of soil organic matter (SOM) (Platteau et al., 2006), is closely linked to essential nutrients such as nitrogen (N), phosphorus (P), potassium (K), and sulfur (S) through stoichiometric relationships that regulate its cycling and storage (van Groningen et al., 2017; Tipping et al., 2016). SOC plays a central role in maintaining soil fertility, enhancing crop productivity, and mitigating climate change through CO₂ sequestration. It also supports the restoration of degraded lands, forests, and ecosystems (Lal, 2012, 2013, 2015; McBratney et al., 2014).

Recognizing the importance of SOC, the international community launched the “4 per 1000: Soils for Food Security and Climate” initiative at COP21 in December 2015, emphasizing that a 0.4% annual increase in global SOC stocks could significantly enhance food security and contribute to climate mitigation (www.4per1000.org).

In the same year, the UN adopted the 2030 Agenda for Sustainable Development, establishing the 17 Sustainable Development Goals (SDGs) as a universal framework for achieving economic, social, and environmental balance (<https://www.un.org/sustainabledevelopment/development-agenda/> (Annex I). This comprehensive approach supports human well-being and health while promoting alignment with the goals of the UN 2030 Agenda (THE 17 GOALS | Sustainable Development by un.org).

Nature-based solutions (NbS), including agroforestry, afforestation, and bioengineering, have gained prominence as cost-effective strategies to address climate change, biodiversity loss, and land degradation. These approaches promote SOC accumulation in soils and biomass while providing multiple co-benefits, such as enhanced ecosystem services, improved water retention, and ecosystem restoration (Bremer et al., 2021; Miralles-Wilhelm, 2023; Rumpel et al., 2023).

Tropical rainforest systems, such as the Amazon (the largest), the Congo Basin (second largest), and Southeast Asia (third), have exceptional potential for sequestering atmospheric carbon in soils and biomass (Pan et al., 2011; Fernandez-Martínez et al., 2019; Hubau et al., 2020; Lescuyer et al., 2009; Paquette and Messier, 2010; Epron et al., 2013; Bauters et al., 2015; Penke, 2021; Eba’*a* Atyi et al., 2022) (Figure 1.1).

Sustainable soil management in these regions is essential for maintaining SOC stocks, particularly following land-use changes such as the conversion of natural forests to pastures or croplands (Choné et al., 1991). Mixed-species plantations can enhance biomass production, support the pulp industry, and improve rural livelihoods through fuelwood supply. Compared with monocultures, they increase soil carbon storage (to a depth of 25 cm) within a seven-year rotation (Tchichelle et al., 2017; Epron et al., 2013; Shure et al., 2012).

Nonetheless, human activities such as intensive agriculture, mining, and oil exploitation continue to threaten forest ecosystems and reduce their carbon storage capacity (Kissinger et al., 2012). Over the past decade, tropical rainforests in Southeast Asia have become net carbon sources, emitting more CO₂ than they absorb (approximately +0.49 Gt CO₂).

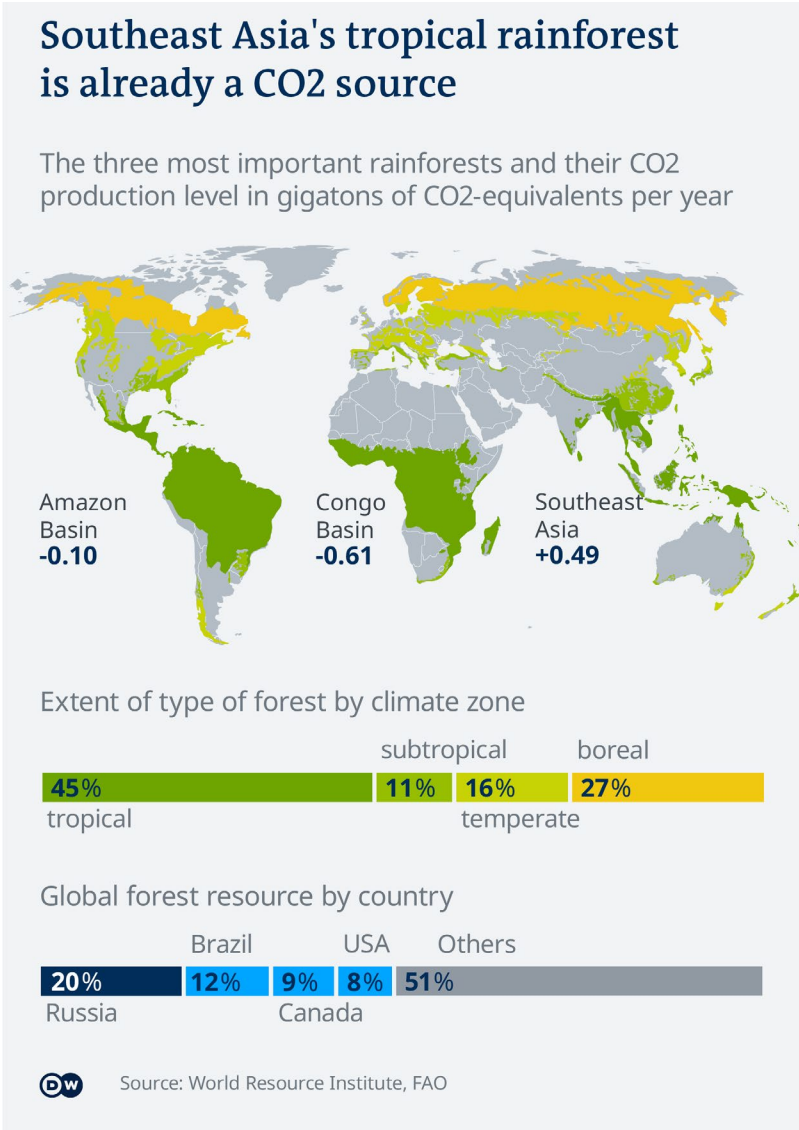


Figure 1.1. The three largest rainforest ecosystems (adapted from Penke, 2021).

In contrast, the Amazon has shown modest carbon uptake (-0.1 Gt), while the Congo Basin has recorded the highest absorption (-0.61 Gt) (Hubau et al., 2020; Penke, 2021; Eba'a Atyi et al., 2022) (Figure 1.1). Despite this, Congo Basin rainforest ecosystems face severe pressure from high deforestation rates and intensive wood use (Eba'a Atyi et al., 2022). In the Democratic Republic of the Congo, Cameroon, and the Republic of the Congo, over 90% of households rely on wood for fuel (Shure et al., 2012). Agricultural practices such as slash-and-burn further degrade forests, reduce canopy cover, and increase air pollution, biodiversity loss, and health risks for both humans and the environment (Nzila et al., 2002; Kissinger et al., 2012).

Nature-based solutions (NbS), particularly those incorporating native tree species, are essential for conserving natural forests, restoring degraded lands, supplying fuelwood to rural communities, and sustaining ecosystem services (Shure et al., 2012; Koutika et al., 2022; Eba'a Atyi et al., 2009, 2022). In southern Cameroon, legume-based fallows combining trees and herbaceous vegetation have proven effective in sequestering carbon and improving soil organic matter (SOM), particularly nitrogen and associated nutrients (Koutika et al., 2001a, 2002, 2004a, b). Similarly, mixed Acacia-Eucalyptus plantations in the Congolese coastal plains have increased biomass production (Epron et al., 2013), supporting the pulp industry and rural livelihoods while enhancing SOC storage and soil fertility, especially nitrogen levels.

Globally, NbS represent a promising pathway to address environmental challenges (Mbow et al., 2014; Cardinael et al., 2021; Debele et al., 2023). Based on 547 case studies, mainly from Europe (60%), Debele et al. (2023) found that 33% of NbS (e.g., urban green spaces, parks, green roofs, and green walls) provide multiple co-benefits, including temperature regulation, improved rainfall infiltration, and reduced air pollution. NbS also play a key role in restoring and conserving biodiversity, offering essential strategies to counter its alarming decline caused by human activities (Read et al., 2022; Petrosillo et al., 2023).

The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) warns that biodiversity loss jeopardizes progress toward the Sustainable Development Goals (SDGs) of the UN Agenda 2030, undermining advances in health, poverty reduction, food security, water management, urban sustainability, and climate action (source: <https://www.unep.org/news-and-stories/speech/triple-planetary-crisis-forging-new-relationship-between-people-and-earth>).

Biodiversity loss can also result from the introduction of exotic species during afforestation, land restoration, or agroforestry (Beekmann et al.,

2024). To minimize risks and maintain healthy soils and ecosystems, comprehensive risk assessments should precede any introduction of new species, with priority given to native ones (Koutika and Richardson, 2019). Degraded lands and forests negatively affect terrestrial biodiversity (Adla et al., 2022), increasing human-wildlife interactions that facilitate zoonotic disease transmission and competition with invasive species. These effects are largely driven by human activities, such as climate change, illegal hunting, and habitat loss, that act as vectors for disease spread (Adla et al., 2022). Additional drivers of soil degradation include climate, topography, deforestation, land-use change, erosion, and nutrient depletion (Lal, 2015).

The United Nations has underscored the urgency of global conservation and land restoration, aiming to achieve land degradation neutrality under Agenda 2030 and related international frameworks. To address climate change, pollution, and biodiversity loss, nature-based solutions (NbS), including regenerative agriculture, afforestation, reforestation, and agroforestry, serve as effective tools for preventing and reversing land degradation and desertification, particularly in tropical regions (Mbow et al., 2014). Tree establishment on degraded lands has proven effective in enhancing soil and ecosystem carbon pools, thereby supporting ecological restoration (Goodman and Herold, 2014).

In conclusion, NbS are essential for maintaining healthy soils that underpin sustainable food systems, food security, and ecosystem services (Mbow et al., 2014; Eba'a Atyi et al., 2009, 2022; Bremer et al., 2021). As an estimated 95% of food originates from soil (Weigelt et al., 2015; FAO, 2015), soil health is fundamental to primary production and the supply of high-quality, nutritious food for humans and animals. Soil condition directly influences food quality, quantity, and ultimately human health (Brevik and Burgess, 2014).

Within this framework, the objectives of this research were defined. The overarching goal, pursued across diverse ecosystems worldwide, including the Congo Basin, is to enhance human well-being within a healthy environment while promoting sustainable development. This research spans more than three decades, from the late 1990s to the 2020s.

The state of the art and key findings from national and international collaborations are summarized in Chapter 1 (General Introduction). Chapter 2 presents results on soil organic matter (SOM) management in forest and pasture ecosystems of the Brazilian Amazon. Chapter 3 examines soil organic carbon (SOC) management in forest plantations of the Congolese coastal plains, in collaboration with international institutions such as the Centre de Coopération Internationale en Recherche Agrono-

mique pour le Développement (CIRAD). Chapter 4 explores SOC management across diverse ecosystems and regions, while Chapter 5 focuses on agroforestry and fallow systems in the Congo Basin. Chapter 6 concludes with key findings and future perspectives.

2. Managing Ecosystems through Soil Organic Carbon Storage as an Agroecological Tool

Research on carbon stocks in natural forests and pastures aged 7, 12, and 17 years in the Brazilian Amazon (Paragominas, Pará State) showed higher carbon storage (to 1 m depth) in the oldest pasture compared with forests (Koutika et al., 1997). Similarly, greater carbon stocks (0-25 cm) were recorded at the end of a 7-year rotation in mixed-species plantations than in monocultures in the Congolese coastal plains (Koutika et al., 2014; Tchichelle, 2016; Tchichelle et al., 2017; Koutika, 2021). However, in some cases, soil structural and physicochemical properties deteriorated, accompanied by a decline in easily mineralizable carbon in the 0-10 cm topsoil of the Amazon (Koutika et al., 1999b, 2000). A reduction in SOM (C and N) was also observed in the 0-5 cm layer of Congolese soils five years into the second rotation.

Sustainable forest management, implemented through nature-based solutions (NbS), supports the restoration of soil and ecosystem health (Figure 1.2). This figure synthesizes collaborative studies across diverse natural and managed ecosystems, addressing challenges such as species invasiveness and key ecological processes. As illustrated, managing SOC at ecosystem, species, and soil microbial levels aligns with specific SDGs, highlighting the strong link between soil science and sustainable development policies.

Combining legume-based fallows with organic and inorganic fertilizers is essential to meet farmers' nutrient requirements (Koutika et al., 2002). Species often regarded as weeds (Koutika and Rainey, 2010) may, in fact, provide agronomic benefits in certain regions (Koutika et al., 2006; Koutika and Rainey, 2010). Sustainable cropping system management is therefore critical for improving yields through the optimization of key nutrients.

After nitrogen (N), phosphorus (P) is one of the most limiting nutrients in tropical ecosystems due to its immobilization by aluminum (Al) and iron (Fe) oxides in highly weathered soils (Bünemann et al., 2004; Laclau et al., 2010; Mareschal et al., 2011).

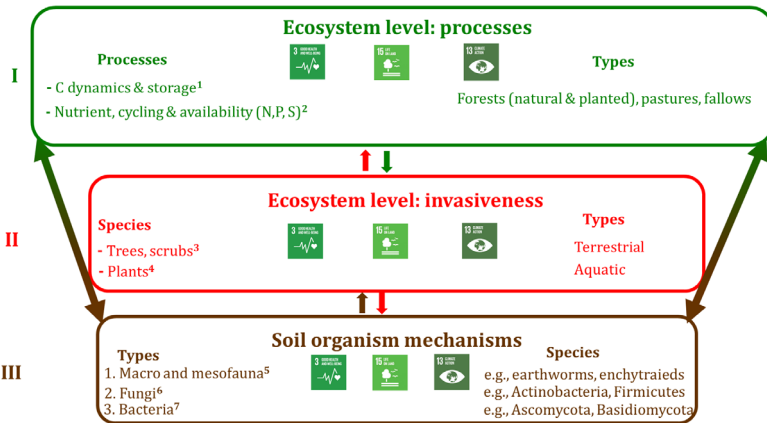


Figure 1.2. Management of soil organic carbon across multiple levels—from ecosystem processes (I) and invasiveness (II) to soil organism mechanisms (III)—in support of specific Sustainable Development Goals (SDGs) of the UN Agenda 2030. Sources: ¹Koutika et al. (1997, 1999 a, b, 2000, 2001a, 2002, 2005); ²Koutika et al. (2001a, 2004a,b, 2020a); ³Koutika et al. (2007, 2008); Koutika and Richardson (2019); ⁴Koutika et al. (2011a, b); Koutika and Rainey (2015); ⁵Koutika et al. (2001b, 2013); ⁶Koutika et al. (2023); and ⁷Koutika et al. (2020b).

In high-P soils of Kenya, available phosphorus (P) in microbial biomass increased following combined applications of organic and inorganic fertilizers (Ayaga et al., 2006; Koutika et al., 2013, 2017b). This integrated approach promotes the gradual release of P during plant growth and restores degraded, nutrient-poor soils by improving their physical, chemical, and biological fertility, as well as water retention.

In grasslands near Wageningen, the Netherlands, soil health improved through earthworm activity, which, together with enchytraeids, stimulated the humification of soil organic matter (SOM) (Koutika et al., 2001b). Soil biota enhance nutrient cycling and carbon (C) sequestration in both soil and biomass. Similar outcomes have been observed in Acacia and Eucalyptus plantations in the Congolese coastal plains of the Congo Basin and in Itatinga, São Paulo, Brazil (Epron et al., 2013; Tchichelle et al., 2017; Koutika et al., 2021b). Comparable benefits have also been reported in planted fallow systems in southern Cameroon (Koutika et al., 2004a) and in cropping systems combining manure with inorganic fertilizers in Kenya (Koutika et al., 2013).

Nature-based solutions (NbS) enhance soil fertility and productivity while supporting ecosystem services and conserving natural resources

such as forests and grasslands (Nyika and Dinka, 2022). As discussed in Section 2.3, these approaches also mitigate climate change by promoting carbon sequestration in soils and biomass and advancing reforestation.

3. Building the Resilience (System and People): Adoption of Appropriate Nature-Based Solutions Regarding the Agroecological Zone

Some of the research findings presented in this book align with the UN Sustainable Development Goals (SDGs) of the UN Agenda 2030 (Figure 1.3), demonstrating that these studies contribute not only to scientific knowledge but also to global priorities such as poverty reduction, food security, and climate change mitigation. The research directly or indirectly supports several SDGs, including SDG 1 (“No Poverty”), SDG 2 (“Zero Hunger”), SDG 3 (“Good Health and Well-being”), SDG 12 (“Responsible Consumption and Production”), SDG 13 (“Climate Action”), and SDG 15 (“Life on Land”) (Figure 1.3; Annex I).

Soils are a major reservoir of global biodiversity, hosting complex communities of microorganisms, flora, and fauna. They contain over 25% of Earth’s total biodiversity, with more than 40,000 organisms found in a single gram of soil¹ (FAO, ITPS, GSBI, CBD, and EC, 2020). This biodiversity plays a fundamental role in sustaining soil functions. In forest plantations of the Congolese coastal plains (Republic of the Congo), bacterial communities are dominated by four main phyla-Actinobacteria, Proteobacteria, Firmicutes, and Acidobacteria-which together represent over 90% of all phyla in Acacia stands and 89% in Eucalyptus monocultures (Koutika et al., 2020b).

Although based on correlations, the prevalence of Actinobacteria, which are sensitive to sulfur, may be linked to H₂S deposition from oil exploitation in the area since the late 1960s (Koutika, 2022). Long-term hydrogen sulfide emissions may negatively affect soil and ecosystem health (Koutika, 2025, 2025a). Sulfur is strongly associated with fungal communities, showing the highest correlations, exceeding those of phosphorus (P) and nitrogen (N), and highlighting its key role in shaping microbial structure (Koutika et al., 2024).

The impact of H₂S on vegetation remains complex: high concentrations can inhibit plant growth, whereas subtoxic levels may supply sulfur for plant nutrition, potentially disrupting sulfur homeostasis. Its overall role in plant growth therefore remains debated (Ausma and De Kok, 2019).

¹ See the list of abbreviations at the end of the book.

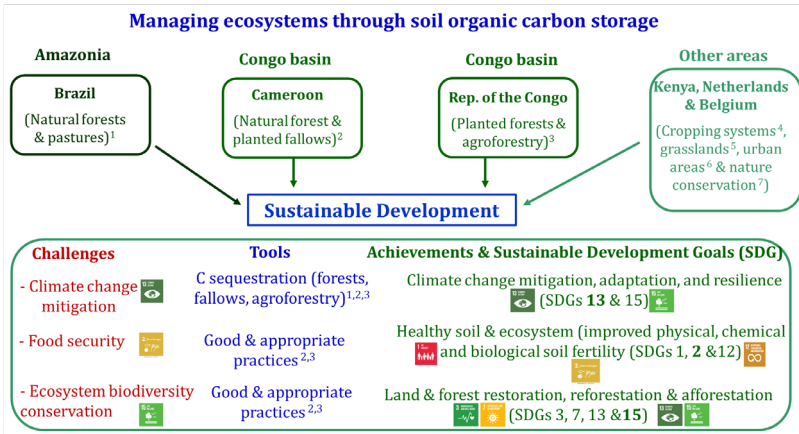


Figure 1.3. Managing ecosystems through soil organic carbon storage to address selected Sustainable Development Goals (SDGs) of the UN Agenda 2030. Arrows indicate the links between practices and SOC. Sources: Koutika et al. (1997, 1999a, b, 2000, 2001a, 2002, 2005); Koutika et al. (2004a, b, 2007a, 2008; 2011, 2013); Koutika and Mareschal, 2017, 2021); Koutika and Richardson (2019, 2020b).

Alterations in bacterial and fungal communities, and their relationships with carbon (C), nitrogen (N), phosphorus (P), and sulfur (S), highlight the intricate links between soil biota, nutrient cycling, and ecosystem functioning (Barrios, 2007; Koutika et al., 2021a). Soil biota regulate key processes that sustain ecosystem services and broader biodiversity, including earthworms, birds, amphibians, and reptiles (Zhang et al., 2021).

Caution is warranted when introducing exotic species, as they may become invasive and threaten biodiversity and natural resource conservation (Rai and Singh, 2020). Such invasiveness can disrupt ecosystem integrity and local livelihoods, as observed in central Belgium (Koutika et al., 2007, 2008). Similar risks occur in fast-growing plantations and agroforestry systems in the Republic of the Congo and the Democratic Republic of the Congo (Koutika and Richardson, 2019), as well as in regenerating forests of southern Cameroon (Koutika et al., 2004a, b; Koutika and Rainey, 2010).

Research priorities derived from two decades of studies on planted forests in the Congolese coastal plains (Republic of the Congo) (Koutika et al., 2022) can be extended to regions with similar soils, vegetation, and climates, including the Batéké Plateau (Democratic Republic of the Congo) and agricultural areas in Gabon (Koutika et al., 2022b). Inter-

cropping leguminous and non-leguminous species in fallow lands, forests, and agroforestry systems across these regions has consistently improved soil health, increased crop yields through biological nitrogen (N₂) fixation (Koutika et al., 2001a, 2002, 2004a, b, 2014, 2016, 2017; Koutika and Mareschal, 2017; Tchichelle, 2016; Tchichelle et al., 2017; Koutika et al., 2019, 2020a, b), and enhanced carbon (C) sequestration in soils and biomass (Epron et al., 2013; Koutika, 2021; Koutika et al., 2021a, b).

The outcomes of this research, achieved through national, regional, and international collaboration, benefit not only the Congolese coastal plains (RoC) and the Batéké Plateau (DRC) but also apply to comparable ecosystems covering approximately 6 million hectares of the Congo Basin (Schwartz and Namri, 2002; Koutika et al., 2021, 2022b). These results highlight the value of multilevel collaboration, from local to international scales (Koutika, 2025a), and demonstrate how such efforts advance human well-being and sustainable development, particularly in countries such as the Republic of the Congo.

MANAGEMENT OF SOIL ORGANIC CARBON STORAGE IN NATURAL FOREST ECOSYSTEMS IN BRAZILIAN AMAZON

1. Introduction

Agriculture is one of the largest sources of human-induced greenhouse gas emissions globally (Penke, 2021). The largest share arises from land-use change (Land Use, Land-Use Change and Forestry, LULUCF; UNFCCC). Between 2010 and 2019, AFOLU (Agriculture, Forestry, and Other Land Use) contributed 13-21% of total anthropogenic emissions, with deforestation accounting for about 45% of AFOLU emissions (UNFCCC).

Oceans are the planet's primary life-support system and its largest carbon sink (Terhaar et al., 2022). They produce about half of Earth's oxygen and absorb roughly 90% of the excess heat from CO₂ emissions. By sequestering approximately 25% of global CO₂ emissions, oceans exceed forests, which account for about 15% (Penke, 2021). Nearly half of the world's forested area is concentrated in four countries: Russia (20%), Brazil (12%), Canada (9%), and the United States (8%) (Penke, 2021; Figure 1.1).

Sustainable forest management remains a critical nature-based solution (NbS), especially for countries in the Global South, to mitigate climate change and promote sustainable development (UN, THE 17 GOALS | Sustainable Development (un.org); Pan et al., 2011). The capacity of forests to store and sequester carbon (C) is well established (Thompson et al., 2009; Pan et al., 2011; Hubau et al., 2020). In 2015, forest biomass-above- and below-ground- was estimated to contain about 296 Gt of carbon (73 t ha⁻¹) (FAO, 2015). Pan et al. (2011) reported even higher total carbon stocks of nearly 471 Gt (116 t ha⁻¹) in tropical forest ecosystems, including living vegetation, soil, and necromass (Figure 2.4).

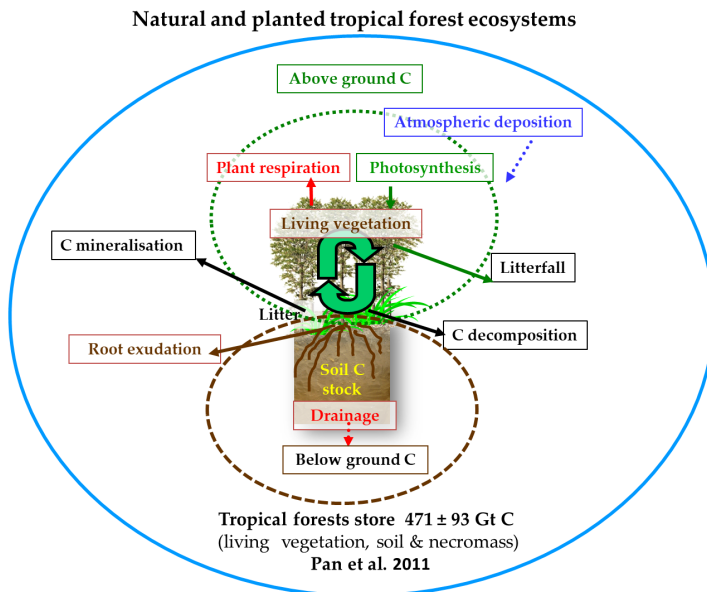


Figure 2.4. Carbon storage potential of tropical forest ecosystems (natural and planted) (adapted from Pan et al., 2011; Koutika, 2022).

The conversion of tropical forests to agricultural land, which disrupts ecosystem dynamics and services, is a major driver of global environmental change. From the late 1970s to the mid-2000s, deforestation in the Amazon, particularly in Brazil, was primarily driven by cattle ranching for beef production and soy cultivation to meet growing demand from developed countries, especially in North America. Additional factors included land clearing for dam construction, mineral extraction, and urban development (Butler, 2020).

Agriculture accounts for the largest share of deforestation in many countries. According to the FAO, agricultural expansion drives nearly 90% of global deforestation (FAO, COP26). While urban and infrastructure development are the main drivers in Europe, agriculture remains the primary cause in most countries of the Southern Hemisphere (COP26). Beef, soy, and palm oil production alone account for about 60% of tropical deforestation (Ritchie et al., 2021; 2021a). Such land-use changes have significant negative impacts on soil and ecosystem health (Yee et al., 2020), including increased SOC decomposition following forest-to-pasture conversion (Koutika et al., 1999a).