

Review

# Sustaining Forest Plantations for the United Nations' 2030 Agenda for Sustainable Development

Lydie-Stella Koutika <sup>1,\*</sup>, Rosalie Matondo <sup>2</sup>, André Mabiala-Ngoma <sup>1</sup>, Viviane Sogni Tchichelle <sup>1,3</sup>,  
Mélanie Toto <sup>1</sup>, Jean-Claude Madzoumbou <sup>1</sup>, Juste Armand Akana <sup>1</sup>, Hugues Y. Gomat <sup>1,4</sup>, François Mankessi <sup>2</sup>,  
Armél Thongo Mbou <sup>5</sup>, Tiburce Matsoumbou <sup>1</sup>, Alpiche Diamesso <sup>1</sup>, Aubin Rachel Saya <sup>1</sup> and Jean de Dieu Nzila <sup>4</sup>

<sup>1</sup> Research Centre on the Durability and the Productivity of Industrial Plantations (CRDPI),  
Pointe-Noire P.O. Box 1291, Congo

<sup>2</sup> Ecole Nationale Supérieure d'Agronomie et de Foresterie (ENSAF), Université Marien N'gouabi,  
Brazzaville, Congo

<sup>3</sup> Horizon International Sarl, Pointe-Noire, Congo

<sup>4</sup> Ecole Normale Supérieure (ENS), Université Marien N'gouabi, Brazzaville, Congo

<sup>5</sup> Institut de Formation et de Conseil Agricole (IFCA), 97470 Saint Benoit, France

\* Correspondence: ls\_koutika@yahoo.com; Tel.: +242-068-133-452

**Abstract:** Located in the hearth of Africa, the Congo basin is the world's second largest rainforest ecosystem, spanning over nine countries including the Republic of the Congo. Nature-based solutions, i.e., afforestation, reforestation or agroforestry supplying wood energy, halting food insecurity, restoring land desertification and fostering mitigation and adaptation to climate warming, have been increasingly used in the past decades. Within this framework, Congolese coastal plains have been afforested using fast growing trees since the early 1950s. Due to the low forest productivity and soil fertility, sustainable management of these forest ecosystems (trees, soils and environment) have been performed. Improved germplasms, increased stand wood biomass and healthier soils have the potential to enhance wood and fuel wood energy supply, mitigation and adaptation to climate change, food security, restoration of land and ecosystem biodiversity. This meets ten out of the seventeen sustainable development goals (SDG #), specifically goals related to alleviating poverty (1) and hunger (2), improving health (3), education (4), sanitation and access to clean water (6). Other goals include providing affordable clean energy (7), sustainable production and consumption (12), action on climate change (13), life on land (15), and partnerships for goals (17). Nature-based solutions help to face important societal challenges meeting more than half of SDGs of the United Nations.

**Keywords:** fast growing tree plantations; inherently nutrient-poor soil; improved germplasms; increased stand wood biomass; healthier soils; sustainable development goals



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## 1. Introduction

Afforestation and/or reforestation involve carbon (C) sequestration in both above and below ground [1,2], fostering soil health improvement and wood pulp and fuel energy production for industry and population [3,4]. This also enhances ecosystem biodiversity, furnishes other products (non-timber forest, food such as honey, insects, and game) and enables payment of other environmental services [5,6] provided by forest ecosystems. In addition to the above-mentioned ecosystem services, practices using trees in nature-based approaches, such as agroecology including agroforestry, also contribute to food security, climate warming mitigation and restoration of degraded lands, as well as sustainable production and human well-being, especially in southern regions [7,8]. These aforementioned principles, concepts, and practices address important societal challenges at the beginning of the 21st century.

This contributes directly and/or indirectly to more than half of the sustainable development goals (SDG) of the Agenda 2030 of the United Nations specifically, SDG 1 "No

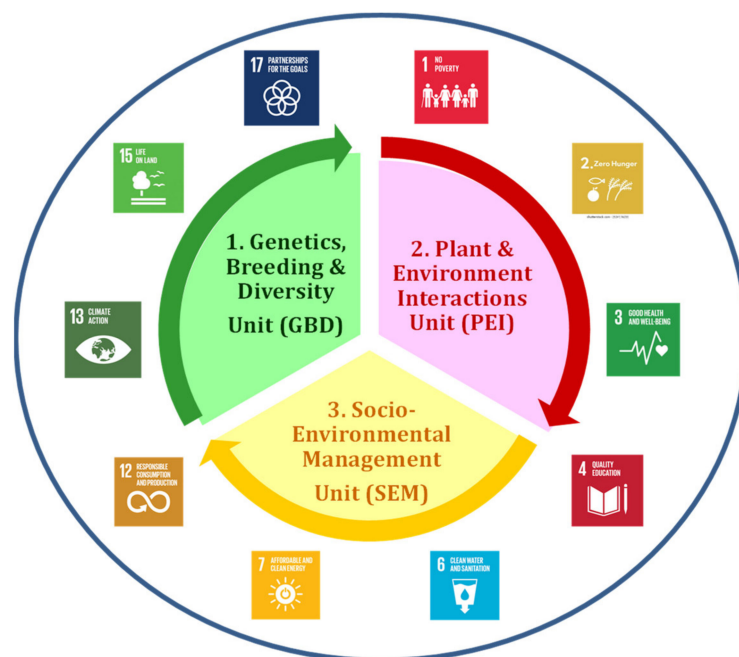
Poverty”, SDG 2 “Zero Hunger”, SDG 3 “Good Health and Well-Being”, SDG 4 “Quality Education”, SDG 6 “Clean Water and Sanitation”, SDG 7 “Affordable and Clean Energy”, SDG 12 “Sustainable Production and Consumption”, SDG 13 “Climate Action”, SDG 15 “Life on Land” and SDG 17 “Partnership for the Goals”. Nature-based approaches and practices enabling sustainable management of forest ecosystems, e.g., boosting C sequestration in both soil and biomass, are crucial to tackle food insecurity, climate warming, degraded lands and to enhance other ecosystem services they provide [5,9–11]. Healthier soils rich in carbon (C) harbor improved physical, chemical and biological properties and have the ability to boost the resilience of human societies to pandemics and other crises [12]. The carbon cycle in tropical forest ecosystems, both natural and planted, includes aboveground C, plant respiration, photosynthesis, atmospheric deposition, C mineralisation/decomposition, litterfall, root exudation, soil C stock and drainage [10], stores about  $471 \pm 93$  Gt C of living, soil and necromass [1].

Sustainability of forest ecosystems therefore relies on C sequestration (soil, biomass) which improves soil fertility, mitigates climate change, restores land and ecosystem biodiversity, and fosters the well-being of surrounding population [1,2,6,10]. Native tropical savannas on sandy soils improper to agriculture in the Congolese coastal plains started to be afforested using fast growing trees (eucalyptus (*Eucalyptus* spp.) and tropical pines) in the beginning of the 1950s [13]. Production of wood pulp and fuel energy for industry and rural population was the primary goal. Nowadays, this nature-based solution greatly contributes to SDG 7 (Affordable Clean Energy for all) [14,15]. In fact, forest ecosystems help around 94% of Congolese households to fulfil their needs in fuel wood energy, e.g., wood and charcoal [6]. In addition, these forest plantations also currently contribute to climate change mitigation through C storage in both soil and woody biomass meeting SDG 12 (Sustainable Production and Consumption), SDG 13 (Climate Action) [16–20], as well as conserving natural forests for SDG 15 (Life on Land) [21].

Research conducted in the Congolese coastal plains on forest planted on previous native tropical savannas has regional importance. This savanna ecosystem extends to around 6 million hectares from the Democratic Republic of the Congo, Gabon and the Republic of the Congo [22]. Research priorities for the sandy soils beneath both ecosystems’ savanna and forest have been set up for their sustainable use [11]. The authors set as primary priority building and maintaining health of these sandy soils, strongly related to two other priorities [11], namely improving crop and/or forest production (SDGs 2, 12 and 15), and fulfilling the need for fuelwood (SDG 7). Our research area is located in the world’s second largest rainforest ecosystem, the Congo basin. Most countries in the Congo basin rely on trees for more than 90% of their fuel energy [6].

The forest plantations established in the Congolese coastal plains have been largely studied at Centre de Recherche sur la Durabilité et la Productivité des plantations Industrielles (CRDPI). The Centre has the primary mission of managing research projects devoted to planted forest productivity and sustainability. It was created in 1994 as an Association of CIRAD (France), Industrial and Congolese Research Department. CRDPI is a national institution since 2017 after the dissolution of this Association. It is composed of three units: (1) Genetics, Breeding and Diversity (GBD); (2) Plant and Environment Interactions (PEI) and (3) Socio-Environmental Management (SEM) units (Figure 1).

The Centre is one of the most important forest research institutions in Central Africa. It has a considerable genetic material heritage (20 certified clones, more than 1300 clones to be certified), impressive results on biogeochemical processes (soils, trees and water), and socio-economic and environmental contexts of forests with local population and environment. Since 1994, more than 120 peer-reviewed papers have been published, while over 15 PhD and 50 Masters I and II have been supervised in genetics, plants and environment relationship, and environmental and social management research units. Overall performed research greatly contributes to meet 10 SDGs (1, 2, 3, 4, 6, 7, 12, 13, 15 and 17) out of the 17 SDGs of the United Nations of Agenda 2030.



**Figure 1.** The 3 units of CRDPI related to ten out of the seventeen sustainable development goals (SDG) of the United Nations, Agenda 2030 i.e., SDG 1 “No Poverty”, SDG 2 “Zero Hunger”, SDG 3 “Good Health and Well-Being”, SDG 4 “Quality Education”, SDG 6 “Clean Water and Sanitation”, SDG 7 “Affordable and Clean Energy”, SDG 12 “Sustainable Production and Consumption”, SDG 13 “Climate Action”, SDG 15 “Life on Land” and SDG 17 “Partnerships for the goals”.

From a natural hybrid derived from an unknown antecedent, the productivity of the clonal forest has increased from 7–10 metric tons/hectare (t/ha) to more than 30 t/ha nowadays [14,23–30]. Studies on plants and environment including soils have been also carried out [30–32]. For instance, optimal density of planting (800 stems/ha), the effects of density on the mortality and growth of plants to evaluate the maximum productivity of clones [33,34], and appropriate fertilization (starter dose and no additional fertilization beyond 2 years) [35] have been established.

The richness variability in mineral elements of soils and trees along with the variability of tree growth [36], the use of coppice (no more than two stems), planting spacing (2.65 m × 4.70 m) and other silvicultural studies [37] have been also determined. Soil organic matter, water-balance and nutrient (C, N, P) dynamics have been also studied [19,38–46]. Soils beneath these forest plantations previously under savannas are mainly Arenosols, the most represented soil type in Africa [8]. These soils are inherently nutrient-poor, especially in nitrogen (N) (less than 0.08% in the top 0.5 cm) [22,47]. To both sustain the productivity of eucalyptus plantations and improve soil attributes, two main practices have been experimented with: the management of organic residues [18,38,43,44] and the introduction of nitrogen-fixing trees (NFTs) such as acacia (*Acacia mangium* Willd) in eucalyptus plantation [8,45,48,49].

The management of organic residues evidenced the best tree growth in stands containing the higher quantity of residues [38]. The introduction of acacias in eucalyptus plantations showed higher stand wood biomass in mixed-species (half eucalyptus and half acacia) relative to monocultures of acacia and eucalyptus [18]. Mixed-species plantations of acacias and eucalyptus enhance forest productivity through the transfer of N fixed by acacia to non-NFTs, such as eucalyptus [18,20], improve soil fertility mainly nitrogen status at the end of the 7-year rotation [19,45,46]. Higher N concentration was found in forest floor litter of acacia at 1.66% ± 0.16% compared to eucalyptus stands (0.44% ± 0.06%), with N stocks of 254 ± 36 kilograms (kg)/hectare (ha) (acacia) and 72 ± 6 kg/ha (eucalyptus) [45].

Carbon is sequestered in both soil and biomass [18–20,45,50]. For instance, C stocks increased in the mixed-species (half acacia and half eucalyptus) stands ( $17.8 \pm 0.7$  t/ha) relative to pure acacia ( $16.7 \pm 0.4$  t/ha) and eucalyptus stands ( $15.9 \pm 0.4$  t/ha) in the first 25 cm of the soil profile at the end of the first 7-year rotation [19]. Available phosphorus (P) was higher in coarse particulate organic matter (cPOM, 4000–250  $\mu$ m) of the afforested stands (mixed-species and monoculture of acacia and eucalyptus) (>60 milligrams/kilograms (mg/kg)) relative to savanna (11 mg/kg) [51]. Higher immobilized P in organic forms was reported in stands containing acacias [52] and higher P concentration in acacia wood (0.61 g of P/kg of dry mass) relative to eucalyptus (0.57 g of P/kg of dry mass) in mixed-species stands sampled 2 years into the second rotation [52,53].

Partial comparative analyses can be made comparing eucalyptus plantation ecosystems in the Congolese plains to those in Brazil, the world's largest eucalyptus agro-forestry producer [18,35,54]. Acacias have been introduced in the *Eucalyptus urophilla* x *E. grandis* plantations at Tchissoko (Congo), and *Eucalyptus grandis* at Itatinga (State of Sao Paulo, Brazil) [18,35] to sustain forest productivity and improve soil fertility. Main characteristics of the two experimental sites such as climate, altitude, and relief are available in [18]. There is a positive effect of growing eucalyptus with acacias on stand wood production in Congo (Tchissoko) but not in Brazil (Itatinga). Soil type is Ferralic Arenosol (with a ratio of clay: silk: sand of 3:6:91) in Congo, and Ferralsol (with a ratio of clay: silk: sand of 13:3:84) in Brazil. The mean temperature is of 25.7 °C in Congo compared to 19 °C in Brazil.

Studies showed no changes in soil C and N stocks in the upper 0–15 cm layer in the mixed-species (half acacia and half eucalyptus) stands, acacia and eucalyptus monocultures after 6 years of plantation in Brazil [55]. However, soil C and N stocks increased in the 0–25 cm in the mixed-species stands relative to eucalyptus monoculture after 7 years of plantation in the Congo [19]. Higher C stocks in mixed-species plantations have been reported in other studies showing higher decomposition rates in mixed eucalyptus–acacia litter in Australia [56,57]. This is due to the accelerated decomposition of litter and enhanced soil microbial activities enabling more effective nutrient cycling [58]. An increase in microbial activity has been also reported in acacia and eucalyptus stands relative to monoculture or fertilized stands at 27 months after planting in Brazil [54,58–61]. Nevertheless, a similarity has been reported between the Congolese and Brazilian sites regarding the type of soil phosphorus (P) form, specifically 70% of soil P in both locations is in the inorganic form [52,62].

Up to now, an overview of most important findings to sustain forest plantations established in the Congolese coastal plains has never been made. The aim of this paper is to highlight the importance of research conducted for almost three decades for sustainable development. This research has been made to elaborate improved germplasms (resistant to diseases, climate warming, e.g., drought), build healthy soils (rich in C, N and available P), and manage the impact of forest plantations on the environment and the welfare of rural populations. Sustainable management of forest plantations will be presented in three main steps or hypotheses in this paper: (i) Improved germplasms will perform better on nutrient-poor soils in the Congolese coastal plains than the natural hybrids; (ii) Appropriate practices (management of organic residues and introduction of nitrogen fixing species) will enable the creation of healthier soils and environment to foster climate change mitigation, land restoration and conservation of ecosystem biodiversity; (iii) Sustainable management of these forest plantation ecosystems facilitated by efficient social and environment management will contribute directly and/or indirectly to ten out of seventeen SDGs of the Agenda 2030 of the United Nations. Our research aims to boost sustainable development through nature-based solutions and appropriate practices in the Republic of the Congo as well as neighboring countries.

## 2. Research Conducted at CRDPI and the Agenda 2030 of the United Nations

The studied area is the previous savanna ecosystems on Arenosols common in other surrounding countries such as Gabon and Democratic Republic of Congo [11,22]. To sustain

forest plantations established on Arenosols and improve livelihood in the Congolese coastal plains, several studies have been conducted in the Genetics, Breeding and Diversity (GBD), Plant and Environment Interactions (PEI) and Socio-Environmental Management (SEM) units of CRDPI. These studies may be applicable to other regions with similar pedoclimatic conditions in the Central African region [11], or to the entire continent as Arenosols are the most common soil type in Africa [8].

Sustaining forest plantations and improving human well-being, research conducted in the Congolese coastal plains contributes directly and/or indirectly to ten SDGs of United Nations (Figure 1). In the following sections, we will show how conducted research in the Congolese coastal plains may be linked to Agenda 2030. This can enhance sustainable development in other areas and countries.

### 2.1. Sustainable Development Goal 1 of 'No Poverty'

Since its creation in 1994, Centre de Recherche sur la Durabilité et la Productivité des plantations Industrielles (CRDPI) has been contributing to Sustainable Development Goal (SDG) 1 'No Poverty' through research conducted on fast growing tree plantations installed on soils commonly identified as unsuitable for agriculture in the Congolese coastal plains. These forest plantations were mostly eucalyptus and tropical pines [14] at the beginning. From 1953 to 1981, seeds of 62 eucalyptus species that originated from Brazil, South Africa, and Australia have been introduced in Republic of the Congo ([63], Table 1).

Eucalyptus species names and characteristic features for these introduced species are indicated as well as their potential value for commercialization (suitable vs. unsuitable based on height). However, nowadays, only hybrids are mostly used in forest plantations in the Republic of the Congo (Table 1). In fact, most species introduced had very low growth and productivity (less than 7 cubic meters (m<sup>3</sup>)/hectare (ha)/year) and were unsuitable for the environment [15], (Table 2), while some specific diseases were reported [64]. Productivity of forest plantations slightly increased to 10 m<sup>3</sup>/ha/year in 1960s [14], (Table 2). However, through extensive research conducted on genetics, the productivity of hybrid clones could reach 40 m<sup>3</sup>/ha/year in the 1990s [24,27–29,65–68], (Table 2). Nowadays, *E. urophilla x grandis* is the mostly used hybrid clone in plantations on the Congolese coastal plains.

Studies have also been conducted to investigate the relation between improved germplasm and the environment [30,31,37,39–41]. Other research has focused on socio-economic aspects, namely the relation between forest plantations and local population [5,6,21,69]. It has been reported that more than 90% of households used fuel-wood in most countries of Central Africa [6] and rural population relies strongly on non-timber forest products and payment for other environment services [5].

Overall, studies aim to contribute to SDG 1 through two main pathways: (i) increase in incomes (creation of healthier soils to boost crop production and supply of forest products such as wood, non-timber forest products etc.) [5,8] and (ii) secure fuel-wood energy supply and biodiversity conservation [6,69]. This shows how directly or indirectly sustainable management of forest ecosystems alleviates poverty (increased incomes, improved access to forest products and education) of rural population and meets the SDG 1 of the United Nations.

**Table 1.** List of the sixty-two eucalyptus species introduced in the Congo from 1953 to 1981 [63]<sup>1</sup> (Species were mostly unsuitable and research has been performed on hybrid clones. Currently mostly clones of *E. urophylla x grandis* are used in forest plantations in the Republic of the Congo).

Eucalyptus Species Name	Characteristic Features	Height (m)	Suitable/Unsuitable
<i>Acmenioïdes</i>	Clear branch stem, two-tone leaves	30–40	Suitable
<i>Alba</i>	Forked and flexuous tree, broad, deltoid to broadly lanceolate leaves	<15	Unsuitable
<i>Andrewsii</i>	Persistent sub fibrous bark on large branches	up to 40	Suitable
<i>Apodophylla</i>	Forked and flexuous tree	<15	Unsuitable
<i>Argophloia</i>	Grows on slopes and creeds	<15	Unsuitable
<i>Bigalerita</i>	Similar to <i>E. alba</i>	<15	Unsuitable
<i>Botryoïdes</i>	Evergreen bark, thick and bicolored leaves	30–40	Suitable
<i>Brassiana</i>	Rough trunk, pedunculate and lanceolate leaves	30	Suitable
<i>Brassii</i>	Light cutlery and defective shape	15	Unsuitable
<i>Camaldulensis</i>	Smooth bark of light color with buff and bluish hues, elongated leaves	40	Suitable
<i>Citriodora</i>	Smooth, white or bluish bark, lemon-smelling leaves	20–40	Suitable
<i>Cloeziana</i>	Poor shape, leaves and pruning	>20	Unsuitable
<i>Contracta</i>	Vigor and average shape (only 7.1 m at 52 months)	<15	Unsuitable
<i>Crebra</i>	Fairly narrow crown, quite narrow, green or grey-green leaves	20–30	Suitable
<i>Cullenii</i>	Similar to <i>E. crebra</i> (but only 13 m height at 55 months)	<15	Unsuitable
<i>Deanei</i>	Gum-like bark, broad leaves and also lanceolate leaves (adults)	45–55	Suitable
<i>Deglupta</i>	Thin, variegated bark, conical crown with horizontal branches	30–60	Suitable
<i>Drepanophylla</i>	Very dark ironbark bark type, lanceolate leaves	25–30	Suitable
<i>Exserta</i>	Sub fibrous bark, very narrow linear, lanceolate leaves	up to 25	Unsuitable
<i>Ferruginea</i>	No information available	-	-
<i>Grandis</i>	Strip bark at base, pedunculate, lanceolate and wavy leaves	40–60	Suitable
<i>Hendersonii</i>	Vigor and average shape (8.2 m at 52 months)	<15	Unsuitable
<i>Houseana</i>	Similar to <i>E. alba</i> (13.1 m at 70 months)	<15	Unsuitable
<i>Huberiana</i>	No information available	-	-
<i>Kirtoniana</i>	Stable hybrid <i>tereticornis</i> X <i>robusta</i>	-	-
<i>Leptophleba</i>	Unsuitable species with a height of 11.5 m at 55 months	-	-
<i>Maculata</i>	Wide crown, thick and smooth bark, pedunculate and lanceolate leaves	35–45	Suitable
<i>Mãidenii</i>	Barrel without branches on more than half the height	60–75	Suitable
<i>Melanophloia</i>	Stem often flexuous, glaucous, amplexicaule and lanceolate leaves	5–30	Unsuitable
<i>Microcorys</i>	Persistent sub fibrous bark, bicolored and acuminate leaves	30–55 m	Suitable
<i>Microtheca</i>	Short-trunked and often multiple-trunked tree	15–20	Unsuitable
<i>Miniata</i>	Straight barrel, grey or rusty bark, oblong or lanceolate leaves	15–30	Suitable

Table 1. Cont.

Eucalyptus Species Name	Characteristic Features	Height (m)	Suitable/Unsuitable
<i>Moluccana</i>	Straight barrel, evergreen bark grey, glossy green and lanceolate leaves	20–30	Suitable
<i>Nesophila</i>	Balanced barrel and crown, bark in small scales, pedunculate leaves,	25–30	Suitable
<i>Normantonensis</i>	No information available	-	-
<i>Oligantha</i>	Unsuitable species (6.0 m at 62 months)	<15	Unsuitable
<i>Pachycalyx</i>	Unsuitable species (7.9 m at 55 months)	<15	Unsuitable
<i>Papuana</i>	Good shaped barrel, coarse bark, lanceolate and bicolored leaves	25–30	Suitable
<i>Phaeotricha</i>	Fibrous bark, pedunculate, lanceolate and somewhat falsified leaves	24–30	Suitable
<i>Paniculata</i>	Pedunculate, lanceolate, bicolored with a green top leaf	25–30	Suitable
<i>Pellita</i>	Strongly framed crown, thick, pedunculate, and a little falsified leaf	25–45	Suitable
<i>Peltata</i>	Peeled leaves (11.8 m tall at 52 months)	<15	Unsuitable
<i>Pilularis</i>	Rough bark, pedunculate, dark green, lanceolate, varnished leaves	35–60	Suitable
<i>Polycarpa</i>	Bark in strip or rough scales, bicolored and lanceolate leaves	20	Unsuitable
<i>Propinqua</i>	Plate bark and rough surface, thick, pedunculate and bicolored leaves	35–40	Suitable
<i>Punctata</i>	Bark in irregular plates, pedunculate, lanceolate and bicolored leaves	35	Suitable
<i>Raveretiana</i>	Scaled bark, pedunculate, lanceolate, bicolored, firm leaves	15–25	Suitable
<i>Regnans</i>	Shaft straight and net of branches	90	Suitable
<i>Resinifera</i>	Red-brown fibrous bark, pedunculate, lanceolate, glossy green leaves	30–40	Suitable
<i>Robusta</i>	Subfibrous bark, glossy green bicolored on top, thick, lanceolate leaves	25–30	Suitable
<i>Rudis</i>	Bad shape and unsuitable species for the region	10–20	Unsuitable
<i>Saligna</i>	Persistent bark at base, pedunculate, lanceolate and bicolored leaves	40–55	Suitable
<i>Scabra</i>	No information available	-	-
<i>Sideroxylon</i>	Dark brown coarse bark, concolored, pedunculate and lanceolate leaves	20–30	Suitable
<i>Tereticornis</i>	Gum-like bark, whitish gray surface, pedunculate and lanceolate leaves	>45	Suitable
<i>Tesselaris</i>	Short trunk, bark in scales, pedunculate and lanceolate leaves	>30	Suitable
<i>Tetrodonta</i>	Bark in long compact fibres, lanceolate, curved and concoloured leaves	25–30	Suitable
<i>Thozetiana</i>	Bark leaving in plates, alternate and lanceolate leaves	20–25	Suitable
<i>Torelliana</i>	Subfibrous then scaly bark, lanceolate and two-colored leaves	25_30	Suitable
<i>Umbr</i>	Dense crown and fairly straight trunk (height < 10 m to 60 months)	<10 m	-
<i>Urophylla</i>	Fibrous bark and smooth (top), pedunculate, lanceolate, pointed leaves	up to 50	Suitable
<i>Viminaliso</i>	Rough bark, alternate pedunculate and lanceolate leaves	30–55	Suitable

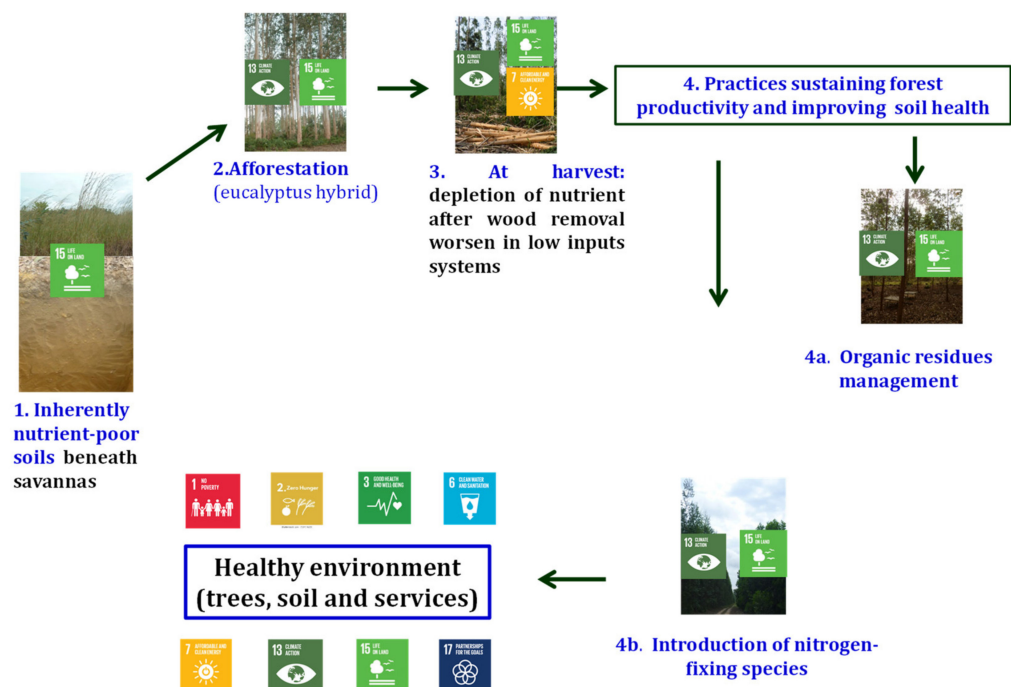
<sup>1</sup> Seeds originated from Brazil, South Africa, and Australia.

## 2.2. Sustainable Development Goal 2 of ‘Zero Hunger’

On a regular basis and according to the United Nations World Food Programme, there are around 957 million people worldwide who do not have enough food. There are several ways to address the SDG 2 of the United Nations, either directly (increase crop production and food supply through agroforestry and forestry systems) or indirectly (sustain food production systems by creating healthy soils, plants and environment).

The population of the most populous country in the Congo basin, the Democratic Republic of the Congo (DRC), is estimated at nearly 80 million, while that of the Republic of the Congo (RoC) is around 16 times lower [50]. However, the Republic of the Congo is still struggling to feed its population due to the poorly developed agriculture. Several studies conducted in the Congolese coastal plains lead to reduce hunger directly and/or indirectly, especially through agroforestry systems but also via forestry systems (non-timber forest products, game, insects, etc.) [8], (Table 3). Table 3 highlights some important findings of sustainable management of forest plantations. These findings took into account the specificity of the region, e.g., hybrids instead of introduced species, planting characteristics (density, spacing, length of rotation etc.) and practices adapted to environment and needs of local population.

Nature-based solutions (afforestation, agroforestry) and practices (organic residues management, introduction nitrogen-fixing species) lead to improve soil health and nutrient availability or dynamics (C, N, P and S). They have beneficial impact on crop production and food production systems. Research conducted in the Congolese coastal plains (Republic of the Congo, RoC) and surrounding countries is therefore indirectly linked to SDG 2 ‘Zero Hunger’ (Figure 2). For instance, a four-fold and two-fold increase in yields of two major crops, cassava and maize, respectively, were reported after eight years, as result of the improved soil N status in agroforestry relative to savanna ecosystems in the Democratic Republic of the Congo (DRC) [50,70].



**Figure 2.** An example of nature-based solutions to improve environment (sustain forest productivity and improved soil health and services) and contribute to eight out of the seventeen Sustainable Development Goals of the United Nations Agenda 2030.

In the same country (Mampu, Batéké plateau), agroforestry using *Acacia auriculiformis* (1987–1993) produced 10,000 metric tons (t)/hectare (ha)/year of cassava, 1200 ha/year of maize, and 6 t/year of honey [9]. An increased yields of both cassava and maize by 6 t/ha



(9 to 15 t/ha) and 1 t/ha (0.5 to 1.5 t/ha) were also noticed [71]. This has been presented in a review paper on C sequestration in mixed-species plantations using nitrogen-fixing species and their benefits in forestry (Republic of the Congo) and agroforestry systems (Democratic Republic of the Congo) [8,9,50,72]. Another study [73] reported that sustainable management of trees in agroforestry and multifunctional agriculture systems greatly benefit to local population with regards to aspects including food security in Cameroon.

Both forest and agroforestry systems can alleviate hunger. This can happen through investigations into soil and plant functions and processes, C sequestration, nutrient dynamics and environment interaction in forestry systems (RoC), and how it may be tested in agroforestry (DRC). Sequestering C in agroforestry or forestry systems creates healthy soils and co-benefits such as securing crop production, food availability and wood energy supply [8–10,72]. Therefore, through sustainable management of forest and agroforestry systems, an inherently nutrient-poor soil may become healthier with enhanced physical, chemical and biological properties [72]. Healthy soil has a great potential to increase crop production (secure food quantity and quality, halt hunger) and meet the SDG 2 of Agenda 2030 for sustainable development.

### 2.3. Good Health and Well-Being

Some practices linked to nature-based solutions have been adopted to sustain the forest plantations on inherently nutrient-poor soil previously beneath savannas and foster healthy environment and healthy people [27,28,35,48]. Organic residues management in forest plantations induce a decrease in wood productivity in the stands where organic residues were removed twelve months after planting [38]. However, no difference was found in soil C concentration and forest productivity after 21 years (3 rotations of 7 years each) [44]. Introduction of nitrogen-fixing trees (NFT) such as acacia and eucalyptus increased stand wood biomass, soil C and N stocks, and led to build healthier soils with the potential to enable a healthy environment and improve human welfare and health [44,72].

To be healthy, one must eat healthy food and live in a healthy environment [12]. Studies of major processes occurring between plant [38,65,66,74,75], soil and root systems [30,38–41,76,77] have been investigated to ensure healthy soils and environment. The two previous sections supported the positive effects of forest plantations on SDG 1 and 2 which further foster SDG3. Increased incomes will enable access to education, health and food. Improved soil health, has the potential to boost food production and security, improve social, environmental and economic situations, foster healthy populations [6,21,69,71,72] and therefore contribute to SDG3. Sustainable management of forest plantations established in the Congolese coastal plains meets all of the first three Sustainable Development Goals (Figure 1, Table 3).

**Table 2.** History of elaboration of improved germplasm through genetic performance since the introduction of the species in the Congolese coastal plains.

Period	Activities	Forest Productivity ( $\text{m}^{-3} \text{ha}^{-1} \text{y}^{-1}$ )	Remarks	References
The 1950s	Introduction of 62 species <sup>1</sup>	7	Most species unsuitable for the agro ecological area	[14]
The 1960s	Species sorting	10	Best species ( <i>E. torelliana</i> , <i>saligna</i> , <i>tereticornis</i> , <i>urophylla</i> , <i>alba</i> )	[14]
The 1960s	Appearance of natural hybrids (unknown fathers)	<12	<i>E.</i> PF1 <i>E.</i> 12ABL x <i>E. saligna</i>	[14]

Table 2. Cont.

Period	Activities	Forest Productivity ( $m^{-3} ha^{-1} y^{-1}$ )	Remarks	References
The 1980s	Herbaceous cuttings Implementation of clonal tests	Production cap: 18 Mean production: 12	Possibility of multiplication of clones	[15]
The 1980s	First controlled crossings	Production cap: 20 Best clones: 30	without precise scheme (SP)	[24,65,66]
The 1990s	Reciprocal recurrent production scheme (SRR)	Production cap: 25 Best clones: 40	<i>E. urophylla</i> x <i>E. grandis</i> and <i>E. urophylla</i> x <i>E. pellita</i>	[27–29,67,68,75]
The 1990s	Reciprocal recurrent production scheme (SRR)	Production cap: 25 Best clones: 40	<i>E. urophylla</i> x <i>E. grandis</i> and <i>E. urophylla</i> x <i>E. pellita</i>	[27–29,67,68,75]

<sup>1</sup> Seeds originated from Brazil, South Africa, and Australia.

**Table 3.** Forest research conducted in the three units of Centre de Recherche sur la Durabilité et la Productivité des plantations Industrielles (CRDPI) contribute directly and/or indirectly to ten Sustainable Development Goals (SDG) of Agenda 2030 of the United Nations.

SDG and CRDPI's Units	Some Important Research Findings	Direct SDGs	Indirect SDGs
Genetics, Breeding and Diversity (GBD)	- Improved germplasms [24,65,67,68,75]		SDG 1
	- Increased productivity (from 7 to 40 $m^3$ /ha/year) [14,24,67,68,75].	SDG 15 SDG 13 SDG 17	SDG 2 SDG 3 SDG 7 SDG 12
Plant and Environment Interactions (PEI)	- Planting spacing, density, use of starter dose, optimal growth), [30,34].		SDG 1
	- Nitrogen transfer from NFTs to non-NFTs [18,35]. - Increased stand wood biomass in mixtures (NFTs and non-NFTs) [18,20]. - Improved soil health in mixed-species plantations [19,45,46]	SDG 12 SDG 13 SDG 15 SDG 17	SDG 2 SDG 3 SDG 6 SDG 7
Socio-environmental management (SEM)	- High reliance and consumption of fuel wood energy in most countries located in the Congo basin [5,6]	SDG 1 SDG 2 SDG 3 SDG 4 SDG 7	SDG 6
	- Benefits of mixed-species plantations (incomes, crop and fuel wood supply and other forest products) [5,6,8] - Transfer of knowledge and technologies	SDG 13 SDG 12 SDG 15 SDG 17	

#### 2.4. Sustainable Development Goal 4 of 'Quality Education'

As for the challenge of elaborating the first eucalyptus clone [78], studies conducted in the Congolese coastal plains contribute directly and indirectly to quality education through training, namely PhD and Master Programs (Figure 1, Table 3). In fact, since its creation, more than fifteen PhD programs have been fully or partially supervised and conducted at

CRDPI. These studies were related to forest plantation sustainability with regard to genetic studies in improving germplasms [1,27–29,65–68,75].

Applied research has also improved field issues such as density (800 stems/ha), spacing of plantation (2.65 m × 4.70 m), fertilization planning (starter dose and no fertilization beyond 2 years) and rotations length (e.g., 7 years). These studies also help to figure out if genetics and/or environmental factors impact tree growth [34]. Other research has investigated management and improvement of nutrients [30,37], soil attributes through rooting [76,77], organic residues management [43,44,79] or intensive silviculture (introduction of nitrogen-fixing trees) to sustain forest productivity and improve soil health [8,19,20,45,46,50].

This shows how sustainable forest management (improved germplasms, soil health and socio-economic and environmental contexts) allow the forest productivity to reach 40 metric tons (t)/hectare (ha)/year on inherently nutrient-poor soils and sandy soils of the Congolese coastal plains. Sustainable management of the forest plantations established in the Congolese coastal plains reported increased C stocks (an additional 0.8 t/ha/year for acacia monoculture) and 1.9 t/ha/year (half acacia and half eucalyptus relative to eucalyptus) in an FAO manual on re-carbonizing global soils [80]. Finally, research conducted at CRDPI through PhD and Master I and II programs, contributes to the SDG 4 ‘Quality Education’ of the Agenda 2030 of the United Nations. This currently enables education of several people with extensive responsibilities for the Republic of the Congo as well as other countries.

### 2.5. Sustainable Development Goal 6 of ‘Clean Water and Sanitation’

This is one of the more indirectly linked SDGs to support research on forestry in the Congolese coastal plains (Table 3). For instance, findings highlighted an improvement in soil health, especially regarding its physical, chemical and biological soil fertility [18–20,45,46]. Improved soil health may be positively linked to clean water. In fact, it well knows that enhanced soil health led to clean water. A healthy soil rich in C (organic residues) harbors higher ability not only to retain water in aggregates favoring plant growth, but also to enable the availability of clean ground water [41,45,46].

As result of organic residue management to sustain productivity of monoculture plantations and improve soil fertility, nutrient cycling did improve soil services especially the potential to create clean ground water [38,43,44]. At the same time, healthier soil rich not only in C and N stocks but also in available P reported in acacia and eucalyptus plantations established in the Congolese coastal plains [10,11,45,46,72], increased their potential to enhance water holding capacity and cycling. In fact, regarding water quality, Laclau et al. [41] reported extremely low nutrient concentrations in solutions collected by tension lysimeters at all depths measured. This is probably due to high nutrient requirement of low-input forest plantations and low nutrient availability of weather soils commonly found in the Congolese coastal plains.

With regard to water use, the productivity of eucalyptus plantations established nearby Tchissoko village located in the Congolese coastal plains was not limited by water demand [81]. With annual rainfall of 1125 mm, evapotranspiration of forest plantations was only 747 mm (66%) at Tchissoko (Congo), while it reached 1288 mm which was 95% of the annual rainfall of 1360 mm in Itatinga in Sao Paulo state, Brazil [81]. Therefore, studies conducted in the Congolese plains indirectly contribute to the SDG 6 of Agenda 2030 for sustainable development (Figure 1, Table 3).

### 2.6. Sustainable Development Goal 7 of ‘Affordable and Clean Energy’

Forest plantations established on the Congolese coastal plains enable (i) pulp wood for industry, fuel-wood energy and other forest products (non-timber forest products, etc.) for local populations [5,8]. The region as the entire country harbors high consumption of forest products. The primary goals of forest plantation establishment in the Congolese coastal plains are to insure adequate supply of industrial pulp wood as well as local wood

energy [6]. Over 96% of households depended on wood fuel (charcoal and fuelwood) as their energy source in the Republic of the Congo [6].

In 2009, fuelwood consumption was evaluated at 35%, with 75% and 25% of fuelwood from planted and natural forests, respectively [6]. Forest plantations therefore have a major role in reducing pressure of the local population on natural forests which may have diminished by over 1000 hectares/year otherwise [6]. Forest plantations help to preserve natural forests and biodiversity and contribute to supply fuel wood energy for local populations. Research conducted to sustain forest plantations at the Centre de Recherche sur la Durabilité et la Productivité des Plantations Industrielles improves population livelihoods by providing access to fuel energy to satisfy SDG 7.

### 2.7. Sustainable Development Goal 12 of 'Sustainable Production and Consumption'

Studies conducted to sustain forest plantations of the Congolese coastal plains are directly and/or indirectly linked to SDG 12 (Figure 1, Table 3). Production and consumption of wood have been estimated in most countries of the Congo Basin including the Republic of the Congo in 2010 [6]. The authors estimated that more than 90% of households rely on fuel wood, charcoal and wood waste for their fuel energy with around 213,880 metric tons (t) (fuel wood) 25,461 t (charcoal). Overall consumption was estimated at 1,029,856 t equivalent of wood with the higher consumption noticed in the four more populated towns of the country [6]. Therefore, producing sustainable fuel wood in the Republic of the Congo is paramount.

Past research contrasted wood production and water use for forest plantations in Tchissoko, Republic of the Congo versus Itatinga, Sao Paulo state, Brazil [81]. The authors [81] estimated rainfall and evaporation were 1360 mm and 1288 mm, respectively, at these forest plantations in Brazil which produced 18 metric tons (t) of wood/hectare (ha)/year. Wood production was only 16.6 t/ha/year in the Republic of the Congo with rainfall and evapotranspiration of 1125 mm and 747 mm, respectively. It was concluded that wood production in the Congolese coastal plains mostly depends on soil fertility and not on water needs [81].

Practices leading to improved soil health such organic residues management and introduction of nitrogen-fixing species have been thereafter adopted to intensify forest production and improve soil fertility and health [18,20,35,38,43,48]. In addition, studies on biogeochemical processes in forest ecosystems conducted in the Congolese coastal plains may improve agriculture which is poorly developed in the Republic of the Congo. This can foster sustainable food production and consumption for both agriculture and forest products, as it has been carried out in the neighboring country of the Democratic Republic of the Congo [8,9,70,74,82]. Research conducted in the Congolese coastal plains to sustain forest plantations may fully contribute to the SDG 12 through enhanced socio-economic and environmental management (participatory research) (Table 3).

### 2.8. Sustainable Development Goal 13 of 'Climate Action'

Mitigating anthropogenic global warming was not the primary goal of establishing forest plantations in the Congolese coastal plains at the very beginning [14]. Nevertheless, it has become a crucial goal currently, along with the fulfilment of needs for wood (pulp and fuel energy) [6,69], other forest products, and the conservation of natural forests [32,72,83]. Nature-based solutions aiming to manage organic residues and introduce nitrogen-fixing trees can increase forest productivity (stand wood biomass) and mitigate climate change (C sequestration in biomass and soil) [18,44,84]. C sequestration and reduction of greenhouse gas emissions have become crucial [32,83,84] due to their impact not only in addressing climate change but also regarding other co-benefits such as soil and environment health and services, which can increase adaptation and resilience to climate change and pandemics [8,11,12,50,72].

Soil organic matter status or characterization is vital to evaluate soil and/or ecosystem health [72,85,86]. Ecosystem health depends on both soil attributes and biomass character-

istics. Transferred nitrogen (N) from acacia to eucalyptus boosts forest productivity (stand wood biomass) [18,35] and improves soil attributes through litterfall and roots [76,77,87]. This further enables C sequestration (soil and biomass) [18–20,80], and enhanced availability of nutrients such as P in forest litter of mixed-species stands [52]. Increased carbon stocks in the first 25 centimeters (cm) of the soil profile contributed to higher biomass yields for mixed-species (half acacia and half eucalyptus) stands of 1.9 metric tons (t)/hectare (ha) compared to acacia monoculture stands (0.8 t/ha) [80].

Due the strong correlation between C and N but also with P [88,89], higher values of the cumulative net N stocks were reported in acacia ( $343 \pm 21$  kilograms (kg)/hectare (ha) and acacia–eucalyptus mixed-species ( $287 \pm 17$  kg/ha) stands relative to eucalyptus ( $189 \pm 12$  kg/ha) [45]. Sustainable management of forest plantations through practices, such as managing organic residues or introducing nitrogen-fixing species, fostered healthier soils and agro-forestry species with the potential to both mitigate and adapt to climate change. Carbon storage occurring in both trees with greater woody biomass and in soil with higher carbon stocks, along with other soil attributes have the potential to mitigate climate change and contribute to Sustainable Development Goal 13.

### 2.9. Sustainable Development Goal 15 of 'Life on Land'

Overall studies conducted in the Congolese coastal plains are strongly linked to SDG 15. Soil and especially soil carbon (C) sequestration has been at the center of several studies and concepts over the last decades [90]. It has been reported how sustainable soil C management may prevent future pandemics [12]. In fact, soil C plays a vital role in enhancing environmental and human health through its positive impact on soil health on which rely food quantity and quality (nutritious value) [12]. Similar to previous SDG 3 related to human health and well-being, carbon sequestration and co-benefits such as healthy soils can also address Life on Land (SDG 15) (Figure 2).

To foster C sequestration and enable healthy soils and other services terrestrial ecosystems provide including life on land, one must consider soil biota at the very beginning. Soil biota drive interaction between soil function, environment, and human activities to further boost C sequestration and build healthy soils and environment [50,85]. Sustaining forest ecosystems through introduction nitrogen-fixing species such as acacias [20,35,48] or managing organic residues [43,44] had a tremendously positive impact on both forest productivity and soil attributes [18,19,42,44,91].

Using  $^{15}\text{N}$  dilution method to estimate symbiotic nitrogen fixation and its accumulation in acacia monoculture and mixture, a prior study reported beneficial effects on physiological trends. Here, eucalyptus trees were taller when acacias were in greater proportion in mixed-species stands relative to eucalyptus monocultures and nitrogen (N) mineral mass was greater for mixed-species stands compared to monocultures [46]. In addition, N derived from the atmosphere in the mixture was 60% higher than that expected based on the amount found in acacia monoculture. It was also found that 16% of N accumulated in eucalyptus trees and aboveground eucalyptus litterfall derived from the atmosphere. Reduced competition for light and soil water also contributed to the increased growth of acacias in the mixture, showing that both species benefit from growing in a mixed stand [46].

Establishment of forest ecosystems on former savannas can positively impact the livelihoods of local people. Storage of C in woody biomass is critical to meeting local needs for fuel wood. Soil C in soils can benefit other agro-forestry components such as non-timber forest products, food crops, and ecosystem services [5,6,18,71,73], meeting the Sustainable Development Goals (SDGs) we have reviewed. Management of forest ecosystems through C sequestration in both soil and biomass [18,19] also has great potential to mitigate climate change and increase crop production by improving soil fertility and soil health. This also further restores land and ecosystem biodiversity (enhanced soil fauna, animals, insects) [9,50,71,73], consistent with SDGs 2 and 13. Overall benefits of forest ecosystems enable life on land including humanity.

Forest and agro-forestry nature-based solutions that introduce nitrogen-fixing trees (NFTs) such as acacias may be beneficial in areas where soils are nutrient-poor (especially N), unsuitable for agriculture, and where fuel wood consumption is high. However, given the fact that phosphorus (P) is needed for symbiotic N fixation, one must be aware of the potential risk of depletion in soil available P [89]. In addition, a preliminary study on invasiveness risk of *Acacia mangium* must be conducted prior to any establishment, since this species is invasive in some countries [92]. Preference must be given to local NFTs species if available to fully meet the United Nations' SDG 15.

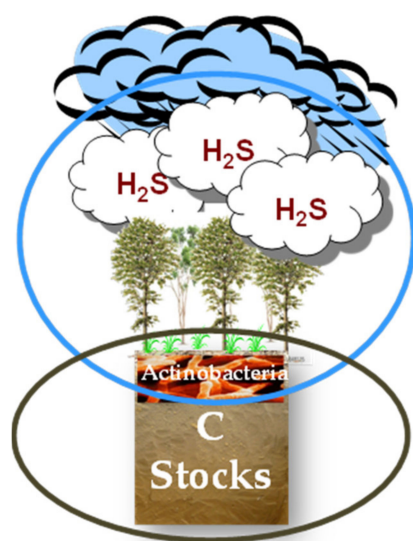
#### 2.10. Sustainable Development Goal 17 of 'Partnership for the Goals'

Research conducted on forest plantations established in the Congolese coastal plains have been always strongly linked to several partners at national, regional and global levels. Overall research such as published papers and theses (PhDs and Masters) are mostly the results of different projects involving European, Asian and South American countries. In the last two decades, there have been at least six showcase projects.

First, the 'ABIOGEN' project aimed to describe the mechanisms for adaptation to drought for two tree species used on plantations, namely pine and eucalyptus. Second, the 'SEPANG' project defined the conditions for applying the genomic selection in the context of plant breeding in the tropics. The third project called 'ClimaAfrica' evaluated the impact of climatic changes on water availability in agriculture and forestry. The fourth 'WUETREE' project sought to understand the genetic and environmental determinants of water use efficiency to improve sustainability on tree plantations. The fifth project titled 'Site Management and productivity in Tropical Plantation forests' estimated the effects of litter management practices on soil fertility and forest productivity. This was set up similar to the structure of CIFOR. Finally, the sixth project called 'Intens&Fix' promoted ecological intensification of planted forest ecosystems through biophysical modelling and socioeconomically assessment of associated nitrogen fixing species.

The last two projects involved several countries. The project run by CIFOR involved Australia, Brazil, Congo, China, India, Indonesia, South Africa and Vietnam. The last project called 'Intens&Fix' included Brazil, Congo and France. This project shed light on the positive impact of sustainable forest management, including organic residue management and introduction of nitrogen-fixing trees (NFTs), on forest productivity and soil attributes [38–41,43,44]. They also help to understand how N may be transferred from NFTs to non-N-fixing species enabling an increase in stand wood biomass [18,20,35] and healthier soils [19,20,45,46,52,88,93,94]. A project funded by UNESCO (International Geoscience Programme) aiming to evaluate the capacity networks mapping and monitoring C stocks involving Mexico, Chile, United States of America and Republic of the Congo (CRDPI), is currently in progress and will contribute to the United Nations' SDGs 13, 15, and 17.

Recent studies were conducted in frame of a program involving The World Academy of Science (TWAS) and Agenzia Nazionale per le Nuove tecnologie, l'Energia e lo Sviluppo economico sostenibile and (ENEA, Italy). They highlighted the potential impact of human activities (afforestation and oil exploitation) on bacterial community composition [93]. Oil exploitation occurring in the Congolese coastal plains since the end of the 1960s may have boosted the prevalence of *Actinobacteria* in the bacterial community composition of forest soil [93]. This phylum is dominant in the areas with high concentrations of H<sub>2</sub>S [95]. *Actinobacteria* biomass growth is enhanced by sulfur (S) amendments [96], and the phylum has the ability to decompose organic residues [97]. This may explain the increased C stocks reported in the mixed-species plantations at the end of 7-year rotation [19,72,80] (Figure 3). Overall research conducted through different projects in strong partnership contributes to the SDG 17 'Partnerships for All Goals' as it also meets previously mentioned SDGs (Figures 1 and 3; Table 3).



**Figure 3.** Link between human activities (afforestation and oil exploitation) and soil attributes driven by soil microorganisms (e.g., *Actinobacteria*) contributing to Sustainable Development Goals from Agenda 2030 by the United Nations.

Our research summarizes a large set of findings in genetics, plant and environment interactions and socio-economic and environmental management during almost three decades of forest plantation research on nutrient-poor soils in the Congolese coastal plains. However, there are some limitations. More details on other methods are not provided in this review because of the large set of results investigated. This may make reproduction of our results more challenging. Nevertheless, all cited materials are available for further investigation. The aim of this review is to link conducted research to Sustainable Development Goals (SDGs) of Agenda 2030 of the United Nations. This will benefit targeted countries in the Congo basin as well as other countries with similar conditions for sustainable development.

### 3. Recommendations

To sustain forest plantations especially when they are established on inherently nutrient-poor soils such as those of the Congolese coastal plains, not only improved germplasms must be elaborated but also sustainable management of both soils and environment through appropriate practices in close link with rural population. Improved germplasms through genetics must be adapted to the specificity of the area of the implementation. Preference must be given to improved germplasms which are more adapted to local conditions than those that are introduced (e.g., the 62 species introduced from Brazil, South Africa and Australia in this case).

This is supported by the increase in productivity from 7 to 40 metric tons (t)/hectare (ha)/year. Technical parameters of plantation and appropriate practices such as organic residues management and introduction of nitrogen-fixing trees, must also be adopted according the specificity of area of establishment taking into account planting materials, soils, and socio-economic and environmental contexts. For instance, the optimal length of rotation is 7 years with a density of 800 planted tree stems/ha. No fertilization is carried out beyond 2 years in the low-input forest plantations established on Arenosols in the Congolese coastal plains. At Itatinga in Sao Paulo state in Brazil, the length of rotation is 6 years, the density of plantation is 1111 planted tree stems/ha, and unlike Congolese forest plantations, fertilization is carried out beyond 2 years in the better managed forest plantations installed on Ferralsols, richer in soil nutrients.

Finally, adoption of nature-based solutions and practices for sustainable development may be successful when they are easily endorsed by the local population. People living

around these forest plantations need to obtain financial/economic and environmental benefits. Financial/economic benefits include income which enables access purchasing food, education, health benefits, welfare, fuel wood as an energy source, non-timber forest products and food (e.g., wild game, insects). An example of a potential, long-term, spillover environmental benefit for those living around more sustainable forest plantations is increase in biodiversity.

#### 4. Conclusions

For the first eucalyptus clones planted on the Congolese coastal plains [78], overall research conducted in the Congolese coastal plains from the creation of CRDPI (1994) to date (2022) evidences a challenge: sustaining forest plantations on inherently nutrient-poor and sandy soils strengthened by socio-environmental management. Important findings such as improved germplasms leading to increased forest productivity, optimal technical planting criteria (spacing, density, fertilization, etc.) associated with the adoption of sustainable practices such as increasing organic residues and integrating nitrogen-fixing trees and plants. Additionally, there are also socio-economic benefits such as increasing family incomes, supply of wood-based fuel, and education, as well as environmental benefits.

Sustainable forest management in the Congolese coastal plains is crucial for the Republic of the Congo, which is strongly committed to sustainable development by promoting afforestation, reforestation and conservation of the natural forests. The country is located in the world's second largest rainforest ecosystem. However, high consumption of wood fuel energy, where more than 90% of households consume this type of energy, may threaten natural forests but also forest plantations, and thus compromise the potential to contribute to the United Nations' Agenda 2030 for sustainable development.

Nevertheless, the Republic of the Congo has a good afforestation program through national institutions or services such as PRONAR (Programme National d'Afforestation et de Reboisement) and SNR (Service National de Reboisement) using national and/or private funds. Other regions of the Republic of the Congo such as Pool, Plateaux, Niari, Lékoumou, Cuvette, are being afforested. These regions may therefore benefit from the studies conducted in the Congolese coastal plains over the last three decades.

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