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REVIEW

Nitrogen-fixing trees increase organic carbon sequestration in forest and agroforestry ecosystems in the Congo basin

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Abstract

Experimental evidence on the effects of introducing nitrogen-fixing trees (NFTs) in forests and agroforestry systems on soil properties, crop yields, carbon (C) sequestration, and other ecosystem services in the Congo basin is scarce. A systematic literature review was conducted to study the effects of integrating NFTs in forests and agroforestry systems on tree biomass carbon stocks, soil properties (i.e., soil organic C (SOC), N, P, CEC, C:N ratio), crop yields and other ecosystem services; and examine their contribution to the objectives of 4 per 1000 Initiative. Electronic search engines (Google, Google Scholar) were searched focusing on *Acacia auriculiformis*–based agroforestry in the Democratic Republic of Congo (DRC) and *Acacia mangium*–based forestry in Republic of the Congo (RoC). This study suggests that integrating NFTs in both agricultural and forest landscapes in the Congo basin (DRC and RoC) improves the soil health through C sequestration and nutrient restoration relative to tropical savannas. This practice also generates other ecosystem services (i.e., pulp and fuelwood energy supply, poles for electricity network, food availability, land restoration). Integrating NFTs in forest and agroforestry ecosystems could therefore improve soil health and food security, mitigate climate change, and hence promote the objectives of 4 per 1000 Initiative.

Keywords Nitrogen-fixing trees · 4 per 1000 Initiative · Agroforestry · Forestry · Central Africa

Introduction

In December 2015, France launched the 4 per 1000 Initiative "Soils for Food Security and Climate Change" at the COP 21 (www.4p1000.org). This Initiative promotes organic C sequestration to simultaneously improve or sustain soil health and enhance food security and climate change adaptation and resilience not only in agricultural, but also in forest ecosystems (Rumpel et al. 2018). The initiative encourages implementation of soil management practices that take into account the soil, climatic, biophysical, and socioeconomic characteristics of the targeted region (Rumpel et al. 2019). Two-thirds of world's forests are found in ten countries, with Democratic Republic of Congo (DRC) ranked in the 7th position (FAO, UNEP 2020). The Congo basin is the second largest rainforest ecosystem after Amazon, extending from DRC (with 60% of overall area) to eight other countries, including the Republic of the Congo (RoC) (FAO, ITTO 2011; http://www.rainforests.mongabay.com/congo/). Net deforestation rate has increased in Africa since 1990 (FAO, UNEP 2020) with an average annual deforestation rate of 3.94 million ha from 2010 to 2020. This pressure on forest

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ecosystems is also reported in the Congo basin; both in DRC and in RoC, around 94% of population rely on fuelwood for energy (Shure et al. 2012). Land management practices with trees, especially nitrogen-fixing tree (NFT)–based forest and agroforestry systems, are widely promoted to meet the 4 per 1000 objectives in the Congo basin (Rumpel et al. 2019), preserve natural forests and biodiversity, and provide fuelwood energy and other ecosystem services (Bisiaux et al. 2009; Lescuyer et al. 2009; Shure et al. 2012).

Trees are an integral part of planted forests and agroforestry systems in many landscapes, where they provide several ecosystem services that support livelihoods and enhance ecological stability (Sinclair 1999). They are introduced or selectively retained in agricultural and forest ecosystems to enhance ecological processes and functions that undergird ecosystem productivity and resilience. Introducing NFTs in both forest and agricultural ecosystems improves soil fertility, which in turn increases crop yields and tree productivity, reduces atmospheric CO_2 by sequestering carbon (C) in the soil and aboveground biomass (Bernhard-Reversat 1993; Binkley 2005; Kimaro et al. 2007; Kasongo et al. 2009; Tassin et al. 2012; Epron et al. 2013; Nsombo 2016) with the potential for climate change mitigation and adaptation, and increases ecosystem resilience to climate change (www.4per1000.org; Rumpel et al. 2018, 2019). These practices also provide other ecosystem services such as land restoration, pulp and fuelwood supply, preservation of natural forests and ecosystem biodiversity, and non-timber forest products, such as honey, insects, and wild fruits (Bisiaux et al. 2009; Shure et al. 2012; Sebukyu and Mosango 2012). Benefits from these practices, especially in tropical and subtropical areas (Sanginga et al. 1986; Binkley 1992; Resh et al. 2002; Chen et al. 2011; Tassin et al. 2012; Bouillet et al. 2013; Forrester et al. 2013; Bauters et al. 2015; Pereira et al. 2018), have been well-documented.

Besides C sequestration, one major benefit of introducing NFTs in agricultural and planted forest ecosystems is their ability to improve soil nitrogen (N) status and availability to crops or trees growing in close proximity. Non-NFTs benefit from the biological N fixation by NFTs in mixed-species forest plantations (Epron et al. 2013; Paula et al. 2015). This ecosystem service meets the requirements for crop production and tree productivity on degraded and N-deficient soils (Kasongo et al. 2009; Kuyah et al. 2016; Nsombo 2016; Tchichelle et al. 2017). Through a symbiotic relationship between arbuscular mycorrhizal fungi (AMF) and N-fixing bacteria (NFB), NFTs enhance biological N_2 fixation thereby improving soil fertility (C storage, nutrient cycling, etc.), land restoration, crop yields, and tree productivity (Franco and Faria 1997; Chaer et al. 2011; Bini et al. 2013, 2018).

Effective nutrient cycling and C storage in NFT monocultures or in its mixed stands with non-NFTs lead to availability of soil N and P (Bini et al. 2013; Santos et al. 2017a) and greatly stimulate both microbial activities and nutrient dynamics in the litter (Bini et al. 2012; Pereira et al. 2018). Intercropping NFTs and non-NFTs also supports distinct microbial communities with specific roles for each species; it increases nitrate amounts in the pure NFT stands (Rachid et al. 2013). Microbiological and chemical changes also occur through maximized AMF root colonization of non-NFT species and phosphatase activity leading to enhanced P cycling in soil and litter, favoring plant growth too (Bini et al. 2013; Koutika et al. 2020a; Pereira et al. 2020). Improved tree and crop growth (i.e., increased below- and aboveground biomass) was reported following the introduction of NFTs in agricultural and forest ecosystems (Kimaro et al. 2007; Epron et al. 2013; Nsombo et al. 2016). This is a response to higher N availability due to the symbiotic fixation of atmospheric N_2, which in turn enhances C accretion and reduces C loss, contributing to climate change mitigation, and land restoration and conservation (Binkley 1992; Lal 2012, 2015; Fornara et al. 2013; Tchichelle et al. 2017; Voigtlaender et al. 2019; Mayer et al. 2020). Enhanced microbial activity in litter and soil in agricultural and forest ecosystems containing NFTs favors SOC mineralization (Bini et al. 2012; Santos et al. 2017a, b) and improves carbon cycling and storage efficiency (Bini et al. 2012, 2013; Pereira et al. 2017, 2018). Paustian et al. (1990) also highlights the beneficial effects of NFTs in strengthening the link between the sequestered SOC and other nutrients, such as N and P, and simultaneously improving both the quality of sequestered C and the efficiency of its storage in a longer term.

The effects of integrating NFTs in forest and agroforestry ecosystems on soil fertility (increase in C, N stocks, microbial activity, nutrient cycling, etc..), plant growth and productivity, and environment have been reported worldwide (Forrester et al. 2013; Kaonga et al. 2005, 2008; Kimaro et al. 2007; Pereira et al. 2018; Mayer et al. 2020). While introducing NFTs, such as *Acacia mangium* and *Acacia auriculiformis*, in agricultural and forest ecosystems has improved soil fertility through C sequestration and enhanced other ecosystem services, data on their performance in Central African countries (i.e., DRC and RoC) are scarce.

Tropical native savannas on inherently poor and coarse-textured soils cover approximately 6 million hectares in Central African countries, including DRC, Gabon, and RoC (Schwartz and Namri 2002). In DRC, savannas in the Batéké Plateau have been used mainly for development of agroforestry. The majority (60%) of the country's population, estimated at nearly 80 million, lives in rural areas where unsustainable and low productivity slash-and-burn agriculture is practiced, leading to land degradation including deforestation, forest degradation, and desertification. To address this problem, agroforestry practices using the leguminous trees were adopted to improve soil health, increase crop yields, provide wood energy, and mitigate climate change through sequestration of carbon, leading to a sedentary sustainable agricultural practice which could alleviate poverty (Bisiaux et al. 2009; Kasongo et al. 2009; Tassin et al. 2012; Dubiez et al. 2019). To promote sustainable agricultural systems and provide wood energy and other ecosystem services, the Congolese government introduced *Acacia auriculiformis*–based agroforestry on low fertile Arenosols of Batéké plateau near Kinshasa (Kasongo et al. 2009; Proces et al. 2017).

In RoC, savannas of the Congolese coastal plains were afforested using eucalypt in the 1950s (Makany 1964 (cited in Koutika et al. 2020a); Delwaulle et al. 1981) to preserve natural forests and halt the deforestation, use unsuitable soils for agriculture, and provide both pulp wood for the industry and fuel energy for the local population (Shure et al. 2012). These plantations are contributing greatly to climate change mitigation by fixing C in the soil and plants, and providing other ecosystem services. Eucalypt productivity often declines after successive rotations and harvests (Corbeels et al. 2005; Laclau et al. 2005). In addition, *Acacia mangium* was introduced in the 1990s to restore soil fertility and improve and sustain forest productivity (Bernhard-Reversat 1993; Bouillet et al. 2013; Epron et al. 2013).

Kuyah et al. (2016) assert that the recent surge of interest in ecosystem services within agricultural landscapes requires formal assessment of the roles that trees play across the spectrum of ecosystem services provision, now considered important in Sub-Saharan Africa (SSA). They argue that the importance of trees in provision of individual ecosystem services is widely studied, but studies of ecosystem services that increase or decrease when trees are incorporated in SSA agricultural landscapes are scarce. The services which trees provide may show both trade-offs (where some ecosystem services increase while others decrease) and synergies (when the services are enhanced simultaneously) (Rodriguez et al. 2006; Raudsepp-Hearne et al. 2010). The lack of data on certain ecosystem services provided by trees in agroecosystems makes it difficult to establish all the synergies and trade-offs associated with trees in the landscape (Kuyah et. al. 2016). This review addresses three questions: what is the scientific evidence base that integration of NFTs in agricultural and forest landscapes improves soil health and enhances other ecosystem services in DRC and RoC? Are there quantitative studies that demonstrate the effects of introducing NTFs in forest and agroforest ecosystems? How do these tree-based land-use systems contribute to the objectives of the 4 per 1000 initiatives?

This review was conducted to (i) study the effects of integrating *A. mangium* in forests (RoC) and *A. Auriculiformis* in agroforestry ecosystems (DRC) on soil properties, aboveground tree biomass C, crop productivity, and other ecosystems services; and (ii) assess how these tree-based ecosystems are related to the 4 per 1000 objective in this specific region of the Congo basin. This review will enhance our understanding of the role of NFT-based agricultural and forest ecosystems: (i) on soil properties (C, N, and P dynamics), crop and tree productivity, food availability and other ecosystem services, and climate change mitigation and adaptation; and (ii) in addressing the objectives of the 4 per 1000 Initiatives of improving soil health, enhancing food security, and increasing the resilience of ecosystems and livelihoods against climate change.

Methods

Systematic literature review

A systematic literature review was undertaken to study the effects of introducing NFTs on soil properties (C sequestration, N and P availability), plant/tree, and other ecosystem services in agroforestry ecosystems (DRC) and forest plantations (RoC); and examine how these tree-based production systems contribute to the promotion of the objectives of 4 per 1000.

This review process adopted the principles of systematic review described by Jesson et al. (2011): (1) mapping the field through a scoping review; (2) comprehensive search; (3) quality assessment; (4) data extraction; (5) synthesis; and (6) write up. The methodology accumulates evidence through secondary studies, providing deep insights into identified knowledge domains and/or bridging knowledge gaps by reviewing primary studies.

A number of search terms were created by breaking down the research questions into individual concepts to ensure the search was exhaustive and representative of relevant studies that have been conducted on integration of NFTs in agricultural and forest landscapes and their effect on carbon sequestration, soil fertility, and crop yields. The search strategy considered synonyms, singular and plural forms, different spellings, broader terms, and classification terms used by databases to sort contents into categories.

Inclusion and exclusion criteria

All retrieved publications and papers were pre-screened for inclusion in the review using predetermined criteria for inclusion and exclusion of primary studies comprising the following:

- Research questions (scope, topic): what is the effect of integrating NFTs in planted forests and agroforestry/agricultural systems on soil and plant carbon stocks, soil nutrients (N and P status), and other ecosystem services? How does the introduction of *A. mangium* in forest in RoC and *A. Auriculiformis* in agroforestry ecosystems in DRC contribute to achievement of the objectives of

4 per 1000 initiatives (soils, climate change, and food security)?

- Definitions and conceptualisation (terms and concepts): Agroforestry, in this study, is a collective name for land-use systems and technologies where woody perennials (trees, shrubs, palms, bamboos, etc.) are deliberately used on the same land management units as agricultural crops and/or animals, in some form of spatial arrangement or temporal sequence. In agroforestry systems, there are both ecological and economical interactions between the different components (FAO 2015). According to FRA (2000), ""forest plantations" are defined as those forest stands established by planting or/and seeding in the process of afforestation or reforestation." These forests consist of either introduced or indigenous species which meet a minimum area requirement of 0.5 ha; tree crown cover of at least 10% of the land cover; and total height of adult trees above 5 m.
- Qualitative and quantitative measurements and key variables: Primary studies that measured soil and tree biomass carbon stocks, soil nutrients (N and P), crop productivity, and other ecosystem services in agroforestry, agricultural and planted forest ecosystems in the Congo basin, and geographically matched ecosystems. The study also included qualitative and quantitative review of secondary data on the ecosystems.
- Study design: Primary studies included randomized experimental designs and generating data that are analyzed using the standard statistical software.
- Time frame: Literature published in the last 30 years (1990–2020).
- Data sources: the study reviewed articles, books and book chapters, theses and dissertations and bibliographies, and data available in English and French.

Based on these guidelines, data and studies were identified using the formal electronic database search; cross-referencing to bibliographies of key papers; and expert peer reviews. Electronic databases (Web of Science, Google Scholar, Google) and completed thematic and matrix analyses of quantitative and qualitative literature published to date were searched. A manual search of key journals and of the reference list by initial searchers was conducted to minimize the risk of missing the relevant reviews.

Search for primary studies and reviews

After a general literature search and careful consideration, the search focused on key phrases "nitrogen-fixing trees/NFTs," "agriculture/agricultural production systems," "forests," "*Acacia mangium*/*A. mangium*," "*Acacia auriculiformis*/*A. auriculiformis*," "carbon stocks/concentration," and "nitrogen/N/stocks/concentration," as these terms are interdisciplinary and can be used in a very broad sense. Several alternative phrases (i.e., "tree-based system" instead of "agroforestry systems," "carbon stocks," or "carbon content," or "food security," or "food security and nutrition") were checked by conducting a text search. Key search strings included author(s), year of publication, place of research, research aim/objective, research method, and main findings. After reading the titles, abstracts, and conclusions, articles were included in the review if they met the search criteria.

Extraction of information and quality assessment

Although no specific tool for quality assessment was used, the study ensured that information extracted from the full texts or articles that met the inclusion criteria and were valid (closeness to truth) and applicable (useful) by assessing the research protocol, research questions, sources of data, and scope of the review for coherence. Assessment of the quality of studies included several variables: appropriateness of study design for addressing the research objectives; conditions of the study; measurement of study variables; appropriate use of statistics; quality of reporting; quality of intervention; generalizations; and author conflict of interest. However, there was a need to balance the comprehensiveness of the search against the value of identifying all available studies and the time available.

Results and discussion

A systematic review of electronic databases resulted in the identification of 11,681 unique citations (Supplementary information). Several of the papers captured by the initial search included documentaries, summaries, opinions, and general comments on land-use systems. They were also unrelated to the topic, the working definition, and this type of study. After refining the search, 168 entries were identified. The studies were further screened based on the relevance of their abstracts, full-text review, and hand search process. After this review, 77 articles were included in the review. Reasons for the full-text review exclusions include failure to address the research questions, poorly structured articles, and availability of more recent data. Large proportions (circa 55%) of primary studies were from Africa, especially Central Africa. The second largest category (30%) comprised articles which covered the science and principles of ecosystem carbon and nutrient dynamics. The remaining proportion consisted of entries from non-African continents. There was a great diversity in methodologies used in measuring ecosystem carbon and nutrients, which makes direct comparison of values complex.

Effects of nitrogen-fixing trees in agroforestry and forest ecosystems on C and other ecosystem services

C sequestration in both biomass and soil

Carbon was sequestered in tree biomass and the soil in *Acacia auriculiformis*–based agroforestry systems in Batéké Plateau (DRC) (Kasongo et al. 2009; Peltier et al. 2017; Tassin et al. 2012; Proces et al. 2017; Dubiez et al. 2019). Lejolly (2018) reported that a 7-year rotation sequestered 50.3 t C ha^{-1} in aboveground biomass on the plateau. This quantity of aboveground biomass C sequestered in *A. auriculiformis*–based agroforestry systems was significantly greater than that (6.05 t C ha^{-1}) reported for *Pentaclethra eetveldeana* (Lubini et al. Personal com.), but similar to that (50.11 ± 7.14 t C ha^{-1}) found in Ouèdo (southern Benin) after 30 years (Kooke et al. 2019). Apart from climate and species, C sequestration in both soil and biomass depends, to a larger extent, on the age of plantation, quality, and quantity of organic residues added to, or removed from, the soil and soil type (Mayer et al. 2020).

Spatial and vertical distribution of SOC stocks depends on composition and density of tree species. Significant differences in SOC stocks have been observed across several savanna ecosystems, including the Lésio-Louna and Léfini reserves and Téké plateau in RoC (Kooke et al. 2019), and across different densities of vegetation cover (including *A. auriculiformis* and *A. mangium*) and depths in the Batéké Plateau in DRC (Nsombo 2016). Nsombo (2016) also reported a decrease in SOC concentration with increasing depth, although a slight accumulation was noticed between 30 and 60 cm resulting probably from the impact of the root systems and leaching dissolved organic C (DOC). Stocks down to 120 cm ranged from 124.7 and 268.1 t C ha^{-1} (Nsombo 2016). In other studies, soil C concentration under *A. auriculiformis* fallow in Batéké plateau (DRC) increased in the 0–25 cm layer from 0.86 to 1.87% in 8 years and to 2.92% (17 years) (Kasongo et al. 2009), while SOC concentrations increased from 1.2 to 1.4% of C in the 23 years of acacia-based agroforestry (Peltier et al. 2017). Apart from increasing forest growth, copious N-rich organic inputs to the soil improve microbial populations and increase decomposition rate and carbon accretion in the A soil horizon.

Soil and aboveground biomass C stocks in *A. auriculiformis*–based agroforestry ecosystems in DRC were significantly higher than those of agricultural ecosystems (Nsombo 2016). Kooke et al. (2019) showed that the agroforestry ecosystems in south Benin had significantly greater C stocks than agricultural ecosystems. Similarly, SOC stocks in *A. auriculiformis*–based agroforestry in DRC were greater than those found in mixed-species forest plantations of eucalypt and acacia in Congolese coastal plains (RoC), although only the 0–25-cm layer was considered in the latter (Koutika et al. 2014; Tchichelle 2016; Tchichelle et al. 2017). Significantly higher SOC stocks in forest and agroforest systems with NFTs could be attributed to increased tree growth due to biological nitrogen fixation, which in turn increases organic C inputs to the soil through litter, and root shedding and exudates.

Eucalypt plantations are established on sandy soils (> 90% of sand) (Mareschal et al. 2011) with low soil organic matter (SOM) content (< 1%) and CEC (< 0.5 cmolc kg^{-1}) (Nzila et al. 2002) in the Congolese coastal plains (RoC). Introducing acacia species in these plantations increased SOC stocks (Koutika et al. 2014; Tchichelle et al. 2017) and stand wood biomass (Epron et al. 2013; Tchichelle 2016). At the end of a 7-year rotation in RoC, increments in SOC stocks to 25-cm depth in mixed-species (50% acacia and 50% eucalypt) stands (17.8 ± 0.7 t. ha^{-1}) were significantly higher than those observed in pure acacia (16.7 ± 0.4 t. ha^{-1}) and eucalypt stands (15.9 ± 0.4 t. ha^{-1}) (Koutika et al. 2014). Estimated stock increments in pure acacia and mixed-species stands were 0.8 t. ha^{-1} and 1.9 t. ha^{-1}, respectively, greater than baseline stocks in eucalypt stands (15.9 t. ha^{-1} (Koutika 2021)). SOC storage in acacia stands is probably attributable to the lower turnover of old C and a higher accretion of new C (Resh et al. 2002; Mayer et al. 2020) because the leguminous acacia tree has high aboveground biomass production (Kimaro et al. 2007; Epron et al. 2013; Sang et al. 2013). In addition, mixed-species forests may deliver forest functions and services more effectively than monocultures and may show less temporal variation in growth and more stable productivity in comparison with pure stands, due to reduced tree species competition for resources (Russo et al. 2019). Thus, integration of NFTs in forest and agroforestry systems may increase resource use efficiency.

The great potential of NFTs for enhancing soil and biomass C accretion leading to higher stocks when intercropped with non-NFTs or crops in agroforestry and forest systems is very well-documented worldwide (Binkley 1992; Resh et al. 2002; Albrecht and Kandji 2003; Kaonga 2005; Nair et al. 2009; Chen et al. 2011; Forrester et al. 2013; Pereira et al. 2018; Voigtlaender et al. 2019; Koutika and Richardson 2019; Mayer et al. 2020; Table 1). This trend is more pronounced in subtropical and tropical climates where the number of N-fixing species is greater than in other geographies (Menge et al. 2017; Steidinger et al. 2019, cited in Mayer et al. 2020). Such trends include increased C contents and/or SOC stocks in mixed stands of acacia and eucalypt in Brazil (Pereira et al. 2018; Voigtlaender et al. 2019), South China (Chen et al. 2011), Vietnam (Sang et al. 2013), Malaysia (Lee et al. 2015), and Australia (Forrester et al. 2013). Organic C stocks in improved fallows in Sub-Saharan countries are positively correlated with the quantity and quality biomass produced (Albrecht and Kandji 2003; Kaonga 2005; Kimaro

Table 1 Benefits of introducing nitrogen-fixing trees (NFTs) in forest and agroforestry ecosystems linked to 4 per 1000 objectives

Practices	Localization	Soil attributes				Climate change			Food security	Other ecosystem services			References
		C storage	N	P	Others	Mitigation	Adaptation	Resilience		Land restoration	Fuelwood energy supply	Forest products	
Agroforestry													
	Tropical systems	+	+		+	+	+	+	+	+	+	+	Albrecht and Kandji 2003
	DR Congo	+	+			+	+	+	+	+	+	+	Bisiaux et al. 2009
	DR Congo	+							+	+	+		Dubiez et al. 2019
	Zambia	+				+	+	+	+		+		Kaonga 2005
	DR Congo	+	+			+	+	+	+	+	+		Kasongo et al. 2009
	Tanzania	+							+		+	+	Kimaro et al. 2007
	DR Congo	+	+		+	+	+	+	+	+	+	+	Nsombo 2016
	DR Congo	+	+			+	+	+	+	+	+	+	Peltier et al. 2017
	Uganda	+	+	+	+				+	+	+	+	Sebukyu and Mosango 2012
Agroforestry & forestry	DR Congo, RoC								+	+	+	+	Shure et al. 2012
Forestry	RoC	+	+		+	+	+	+		+			*Bernhard Reversat,* 1993
	Brazil		+	+	+	+	+	+		+			Bini et al. 2013
	Brazil		+	+	+	+	+	+		+			Bini et al. 2018
	Brazil	+	+		+	+	+	+		+			Chaer et al. 2011
	Brazil & RoC	+	+		+	+	+	+					Bouillet et al. 2013
	South China	+				+	+	+		+			Chen et al. 2011
	Brazil & RoC	+	+			+	+	+			+		Epron et al. 2013
	Australia	+	+			+	+	+					Forrester et al. 2013
	Brazil	+	+		+	+	+	+		+			Franco and Faria 1997
	RoC	+	+			+	+	+			+		Koutika et al. 2014
	RoC	+	+	+		+	+	+			+		Koutika et al. 2016
	RoC	+	+			+	+	+			+		Koutika et al. 2017
	DR Congo								+	+	+	+	Lescuyer et al. 2009
	Malaysia	+				+	+	+				+	Lee et al. 2015
	Brazil		+		+	+	+	+					Paula et al. 2015
	Brazil	+	+		+	+	+	+				+	Pereira et al. 2018
	Vietnam	+				+	+	+	+				Sang et al. 2013
	RoC	+	+			+	+	+				+	Tchichelle et al. 2017
	Brazil	+	+			+	+	+				+	Voigtlaender et al. 2019

NFTs, nitrogen-fixing trees; *c*, carbon; *N*, nitrogen; *P*, phosphorus; *DR*, Congo Democratic Republic of the Congo; *RoC*, Republic of the Congo

et al. 2007). In eastern Zambia, SOC stocks in NFT-based agricultural systems (32.2–37.8 t C ha^{-1}) were significantly higher than those (22.2 and 26.2 t C ha^{-1}) measured in maize monocultures (maize – fertilizer, maize + fertilizer (compound D and urea), respectively), presumably because treatments with trees produced more total organic C inputs than those without trees (Kaonga and Coleman 2008).

Increased C stocks in both soil and biomass in *A. auriculiformis*–based agroforestry ecosystems (DRC) (Kasongo et al. 2009; Nsombo 2016; Peltier et al. 2017) and forest plantation of acacia-eucalypt in RoC (Epron et al. 2013; Koutika et al. 2014; Tchichelle 2016; Tchichelle et al. 2017) demonstrate that integration of NFTs in forest plantations and agroforestry ecosystems in the Congo basin can achieve higher soil and tree C sequestration rates than savanna ecosystems and could hence sustain these fragile ecosystems.

Correlation between soil organic carbon and soil N status and availability

As SOC concentration in Arenosols increased in an *A. auriculiformis* fallow in Batéké plateau (DRC), soil N concentration also increased from 0.045% (beginning) to 0.28% (17 years) in one (Kasongo et al. 2009), and from 0.05% (beginning) to 0.08% (23 years) in another *A. auriculiformis* agroforestry systems on Batéké plateau (Peltier et al. 2017). Introducing *A. mangium* in the eucalypt plantations significantly improved N status of Arenosols in the Congolese coastal plains (RoC) (Tchichelle 2016; Koutika et al. 2017; Tchichelle et al. (2017) observed similar SOC trends in Batéké plateau (DRC) though with a different tree species (*A. auriculiformis*) (Kasongo et al. 2009; Peltier et al. 2017). N stocks to 25 cm depth were estimated at 1.25 ± 0.02 t. ha^{-1} in pure *A. mangium* plots compared with 1.19 ± 0.02 t. ha^{-1} in the pure eucalypt stands, while the highest value (1.28 ± 0.03t. ha^{-1}) was reported for the acacia-eucalyptus stands in RoC (Koutika et al. 2014). The cumulative net N stocks in soils under acacia (343 ± 21 kg ha^{-1}) and acacia-eucalyptus stands (287 ± 17 kg ha^{-1}) were significantly higher than those under eucalyptus (189 ± 12 kg ha^{-1}) within the first 2 years of the second 7-year rotation (Tchichelle et al. 2017). Koutika et al. (2017) also reported that soil N concentration at 0–5 cm depth was 30% higher in coarse particulate organic matter (POM, 4000–250 μm) in *A. mangium* monoculture than in pure eucalypt stands in year 2 of the second 7-year rotation. An increase in the N:P ratio of eucalypt leaves from 9.4 ± 0.5 at end of the first 7-year rotation to 13.1 ± 0.6 in year 2 of the second rotation (Koutika et al. 2016) showed that soil N status of the mixed-species plantations established in the Congolese coastal plains increased, suggesting a reduction in the growth-limiting effect of N. As in other parts of world (Forrester et al. 2013; Pereira et al. 2018; Voigtlaender et al. 2019) and SSA (Sanginga et al. 1986; Kaonga 2005; Kimaro et al. 2007), studies involving NFTs, *A. auriculiformis*, *or A. mangium* in agroforestry (Kasongo et al. 2009; Nsombo 2016) and forestry (Tchichelle 2016; Koutika et al. 2017) reported an improved N status of inherently nutrient-poor Arenosols that are common in the targeted areas of both countries.

C sequestration is strongly linked to N (van Groningen et al. 2017). Besides increased C storage, integrating NFTs in agroforestry and forest ecosystems leads to improved soil N availability and status which benefit the growth of non-NFTs or crops (Sanginga et al. 1986; Kimaro et al. 2007; Kasongo et al. 2009; Epron et al. 2013; Forrester et al. 2013; Tchichelle et al. 2017; Pereira et al. 2018; Voigtlaender et al. 2019; Mayer et al. 2020). Inoculated *Leucaena leucocephala* (Lam) de Wit provided more than 500 kg of N ha^{-1} year^{-1} for the subsequent maize crop (Sanginga et al. 1986), whereas the eucalypt, a non-NFT, benefitted from the atmospheric N_2 fixed by a NFTs in mixed-species forest plantations (Paula et al. 2015) resulting in higher stand wood biomass (Epron et al. 2013). Paula et al. (2015) demonstrated the transfer of a significant amount of N from NFTs in mixed plantations to trees or crops close to them using ^{15}N pulse-labelling in evaluating belowground transfer of N from *A. mangium* to *Eucalyptus grandis* trees in a Brazilian planted forest during the first few days after labelling. The NFTs that mostly create symbioses with arbuscular mycorrhizal fungi (AMF) and nitrogen-fixing bacteria (NFB) accelerate soil fertility improvement and/or land restoration with further increase in crop yields and tree productivity because AMF can enhance biological N_2 fixation, while NFB improves mycorrhizal colonization (Bini et al. 2013, 2018). Integration of NFTs in forest plantations and agroforestry systems in the Congo basin can therefore sustain these fragile ecosystems.

Sequestered C is linked to microbial communities and nutrient cycling

Increased SOC stocks are probably due to the enhanced decomposition of the litter accelerated by dynamics of the soil microbial environment, i.e., microbial activity (Bini et al. 2012, 2013; Pereira et al. 2018). This is strongly correlated to N, C, and P contents, revealing a more effective nutrient cycling and greater stimulation of microbial activity in both litter and soil (Bini et al. 2012, 2013; Pereira et al. 2017). These changes are further observed at the arbuscular mycorrhizal fungi level where fungi root colonization and the activities of acid and alkaline phosphatase improve P cycling and nutrition (Bini et al. 2018). Apart from the N-rich materials directly returned by coppicing, trees also return sizeable quantities of organic C and other nutrients through root detritus, root exudates, and mycorrhizal hyphae (Kaonga et al. 2008). Integrating NFTs in agroforestry and forest systems enhanced soil C sequestration, microbial activity, and nutrient cycling evidenced by an increase and change in microbial and bacterial activity and communities (Bini et al. 2012, 2013, 2018; Pereira et al. 2017, 2018, 2020; Koutika et al. 2020b).

NFTs require P to sustain symbiotic N_2 fixation (Binkley 1992; Binkley et al. 2005), which is linked to microbial communities (Bini et al. 2012, 2013, 2018). This was demonstrated by a decrease in available P in the topsoil of the mixed-species forest (50% acacia and 50% eucalypt) relative to the pure eucalypt stands at the end of the first 7-year rotation (6.94 ± 045 mg kg^{-1} versus 8.46 ± 0.79 mg kg^{-1}) in RoC (Koutika et al. 2014). Furthermore, readily available soil inorganic P (Pi HCO_3) also decreased in pure acacia relative to quantities in pure eucalypt stands in the 0–5 cm (i.e., 1.7 vs 2.17 mg kg^{-1} at year 2 of the second rotation) (Koutika et al. 2016). P availability and cycling were positively linked to bacterial and fungal communities in the mixed-species plantations of acacia and eucalypt in RoC (Koutika et al. 2020b) in Brazil (Pereira et al. 2020), respectively. However, its concentration increased in afforested stands of both acacia and eucalypt compared to those found in the savanna the third year of the second rotation (Koutika and Mareschal 2017), probably due to the ability of non-NFTs, and acacias in particular, to access P from deeper soil layers (Sitters et al. 2013). These findings show the effects of introducing NFTs on nutrient cycling and fertility status of nutrient-poor Arenosols like those found in the Congolese coastal plains (RoC) and Batéké plateau (DRC). Integrating NFTs with non-leguminous tree species (i.e., eucalypt) or crops (such as cassava or maize) can contribute to achieving the objective of the Initiative 4 per 1000 by enhancing C and nutrient (N and P) stocks, improving overall soil health, sustaining ecosystems, and improving food security (Fig. 1).

Nitrogen-fixing trees, climate change adaptation and resilience, and 4 per 1000 Initiative objectives

Contribution of biomass and soil C stocks to climate change mitigation

For decades, SSA has been identified as the most vulnerable geographic region to climate change (Kotir 2011; Mbow et al. 2014), while agroforestry has been recommended as a suitable ecosystem-based climate change adaptation practice, mainly for smallholders in the tropics (Albrecht and Kandji 2003; Verchot et al. 2007; Mbow et al. 2014; Table 1). This is strengthened by IPCC's recognition of

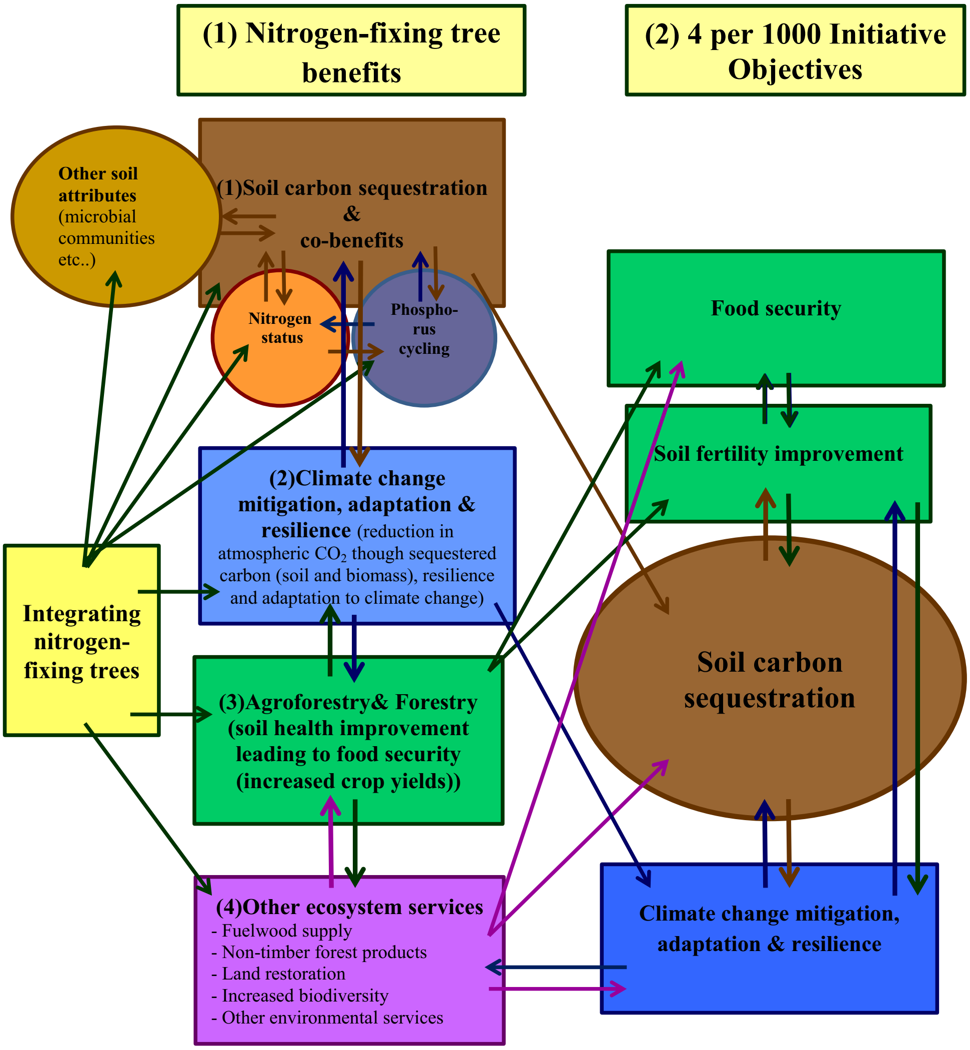

Fig. 1 Conceptual scheme of nitrogen-fixing tree benefits (1) linked to 4 per 1000 Initiative objectives (2): (1) Soil carbon sequestration and co-benefits (nitrogen status, phosphorus cycling, microbial communities and other soil attributes); (2) climate change mitigation (reduction in atmospheric CO_2 through carbon sequestration, resilience and adaptation to climate change); (3) agroforestry and forestry (soil health improvement leading to food security (increased crop yields)); and (4) other ecosystem services (fuelwood, non-timber forest products, land restoration, increased biodiversity and other environmental services): how introducing nitrogen-fixing trees in agroforestry and forestry lead to carbon sequestration and co-benefits and other ecosystem services and promote the Initiative 4 per 1000 in the Congo basin (DR Congo and Republic of the Congo) (Soil carbon sequestration and co-benefits (brown); climate change (blue); soil improvement and food security (green); other ecosystem services (violet); shapes used do not mean anything)

agroforestry as the land-use system with greatest potential to sequester ca. 600 Mt C year^{-1} by 2040 compared to 200 Mt C year^{-1} for forest management (IPCC 2000). It offers several pathways to assure food security and welfare for small-scale farmers in Africa and contribute at the same time to climate change mitigation and adaptation strategies (Mbow et al. 2014). Although no direct studies have been conducted in the two targeted countries, different agroforestry projects implemented in DRC and forest plantations in RoC may contribute to climate change adaptation and resilience of ecosystems and human livelihoods.

Increased aboveground biomass and soil C stocks have the potential to mitigate climate change (Mbow et al. 2014). A comparison of *A. mangium* and eucalypt plantations at Itatinga in Brazil with those at Tchissoko in RoC showed that eucalypt growth rate in mixed-species plantations was significantly higher than that of pure stands in the latter (Bouillet et al. 2013; Epron et al 2013). This suggests that mixed non-N fixers in stands benefitted from the N_2 fixed by *A. mangium* at the Congolese site, but no significant differences were found within Brazilian plots. This may be attributed to differences in soil types and forest management practices. Even though soils in both locations contained more than 80% of sand, soils in Brazil (Itatinga, Sao Paulo state) are Ferralsols with 13% of clay and 3% of silt, while those in the Republic of the Congo (Tchissoko) are Ferralic Arenosols with only 3% of clay and 6% of silt. This shows the potential for these plantations to mitigate climate change; increasing C fixation in aboveground biomass and the soil may contribute to reduction of atmospheric CO_2 concentrations and mitigation of climate change, especially because these plantations span over 35,000 ha in the Congolese coastal plains.

Studies of non-CO_2 greenhouse gas emissions such as N_2O in the area in the Congo basin are scarce. However, *A. mangium* efficiently reduces N_2O emissions when its bark tannins are applied to water-saturated soils, contributing to mitigating climate change (Matsubara and Ohta 2015). In coffee and peach palm agroforestry systems with a leguminous cover crops in Peru, Palm et al. (2002) showed a reduction in N_2O emissions compared with a neighboring second forest, and emissions were much lower than in intensive and low-input agriculture. Albrecht and Kandji (2003) and Verchot et al. (2007) argue that agroforestry systems have great potential for reduction of greenhouse gas emissions. However, the cooling effect of CO_2 sequestration is partially offset by the warming effect of soil N_2O emissions, resulting in net cooling of the CO_2–N_2O effect (Kou-Giesbrecht and Menge 2019). The effects of NFTs in forests and agroforests depend on NFT species, temperature, precipitation, N deposition, and CO_2 fertilization. NFTs can either mitigate or exacerbate climate change relative to non-fixing trees, contingent on their fixation strategy and N deposition (Kou-Giesbrecht and Menge 2019). Biological N fixation has the capacity to self-regulate, feeding back to ecosystem-level N levels (Kou-Giesbrecht and Menge 2019). A deficiency in N levels can stimulate N fixation, which can promote plant growth and CO_2 fixation. But, the strength of feedback varies across N-fixing species: obligate N fixers fix N at the same rate per unit of biomass regardless of environmental conditions, while facultative N fixers adjust N fixation to meet their needs (ibid). But Kou-Giesbrecht and Menge (2019) assert that rhizobial N-fixing trees in tropical forests downgrade N fixation either through facultative or through incomplete regulator N fixation strategy. Considering the current low levels of N deposits (Kou-Giesbrecht and Menge 2019), observed soil and vegetal carbon sequestration in NFT-based forests and agroforest systems in the DRC and RoC demonstrates their net CO_2-N_2O cooling effect relative to non-NFT-based land-use systems.

Several studies (Baah-Acheamfour et al. 2016; Ni and Goffman 2018; Yu, 2017) Gutlein et al. 2018) show that methanotrophs (methane-eating bacteria) absorb atmospheric methane that diffuses into forest and agroforestry soils. Baah-Acheamfour et al. (2016) showed that forest soils had 36% higher CH_4 uptake than herblands without trees. Gutlein et al. (2018) also found that protection of aboveground and belowground C and N stocks of agroforestry and arable systems increases CH_4 uptake; CH_4 uptake is positively correlated with SOC; and forest soils with well-aerated litter layers were a significant sink for atmospheric CH_4 (uptake to 4 kg C ha^{-1} year^{-1}) regardless of low annual temperatures at higher elevation. These findings suggest that integration of NFTs in forest and agroforestry systems, which increased N-rich litter and SOC stocks, supported a biologically active top soil for a thriving population of methanotrophs, thus increasing soil uptake of CH4. Thus, NFT-based systems present opportunities for reducing GHG emissions.

Effects of nitrogen-fixing tree-based agroforestry on crop yields and food security

Nitrogen-fixing tree-based agroforestry and soil fertility

Mean CEC values (2.8 to 3.8 cmol + /kg) of soils under 23-year-old agroforestry systems with NFT species were significantly higher than those of savanna ecosystem soils in DRC (Peltier et al. 2017). *Acacia auriculiformis* fallows (> 10 years) increased soil nutrient content and nutrient-holding capacity of Arenosols in the Batéké Plateau (DRC) despite a significant drop in pH probably due to humification and nitrification processes (Nsombo 2016). In addition, harvesting both cassava and maize crops led to removal of minerals from the soil–plant system, and a decline in exchangeable bases in the soil, resulting in low soil pH (Peltier et al. 2017). Although there may be a risk of soil acidification evidenced by a drop in pH (5.5 to 4.6) and depletion of exchangeable bases, the overall change in soil characteristics in agroforestry after NFT integration improved both soil fertility and crop yields. Previous studies in RoC have shown that Arenosols of the Congolese coastal plains have low iron oxide contents despite their acidity (Mareschal et al. 2011) and low ability to fix P (Laclau et al. 2010; Koutika 2019). In agroforestry ecosystems, enhanced C and N dynamics improved nutrient-holding capacity and cycling which increased in the long term (Kasongo et al. 2009; Nsombo 2016). However, absolute amounts of soil nutrients at the beginning of a new 8-year cropping period of the *A. auriculiformis* fallow were still low, and a quick nutrient release from litter (leaves and twig biomass after logging through slash-and-burn practices) was required to sustain the ecosystem (Nsombo 2016). These studies suggest that tree-mediated nutrient cycling through uptake of inorganic nutrients (N, P, K) and their cycling contributed to improved soil fertility, increased crop productivity, restoration of degraded land, and replenishment of SOM. Agroforestry systems have great potential to sequester C and improve soil fertility, especially when NFTs are integrated (Nair et al. 2009; Kimaro et al. 2007; Kaonga et al. 2008; Biseaux et al. 2009; Kasongo et al. 2009; Sebukyu and Mosango 2012; Peltier et al. 2017).

Soil fertility improvement in NFT-based agroforestry may be attributed to decomposition of large quantities of organic materials from trees, and increasing SOC content and CEC, which are strongly linked to organic inputs to tropical soils. Furthermore, decomposition of large quantities of litter correspondingly increased quantities of organic acids produced, which partly explains the drop in pH (Binkley 1992, 2005; Kasongo et al. 2009; Nsombo 2016; Peltier et al. 2017). But *A. auriculiformis* increased N content while simultaneously decreasing C/N ratio (ibid). All these processes occurring in soil after introduction of NFTs in agroforestry systems in the Batéké plateau (DRC) may result from enhanced microbial activity and nutrient cycling (Bini et al. 2012, 2013; Pereira et al. 2017, 2018, 2020). Changes in bacterial communities were found in acacia-eucalypt plantations in RoC. Stands containing acacia showed differences in community composition (beta diversity) and *Firmicutes* phylum prevalence compared to *Proteobacteria* in the pure eucalypt (Koutika et al. 2020b). These changes may also result from creation of more labile organic substances and conditions favoring their decomposition, such as an enhanced SOM mineralization due to the limited C saturation potentiality of Arenosols, the effects of new organic residues rich in N, edaphic/climate conditions, and the age of the plantation (Marin-Spiotta et al. 2009; Derrien et al. 2014).

Healthy soils lead to increased crop yields

In 8 years, improved soil N status further resulted in fourfold and twofold increase in yields of two major crops, cassava and maize, respectively, compared to those in the savanna ecosystem (Lejolly 2018). The forestry (industrial plantations) and agroforestry areas comprised 8000 ha of *A. auriculiformis* established from 1987 to 1993 in Mampu (Batéké plateau, DRC) (Bisiaux et al. 2009). Apart from improving soil fertility and other ecosystem services, the project produced 10,000 t ha^{-1} year^{-1} of cassava, 1200 ha^{-1} year^{-1} of maize, and 6 t year^{-1} of honey. In the same line, yields of both cassava and maize increased by 6 t ha^{-1} (9–15 t ha^{-1}) and 1 t ha^{-1} (0.5–1.5 t ha^{-1}), respectively, in DRC (Nsombo 2016). Several studies of NFT-based agroforestry and forestry systems reported an enhanced N availability (Albrecht and Kandji 2003; Kimaro et al. 2007; Kasongo et al. 2009; Forrester et al. 2013; Peltier et al. 2017; Tchichelle et al. 2017; Koutika and Richardson 2019).

Integration of *A. auriculiformis* in agroforestry in the Batéké Plateau (DRC) improved soil fertility and ensured the availability of the two staple crops in the area. This system contributes to mitigation of climate change through C sequestration in the soil and plant biomass leading to improved soil health with enhanced nutrient cycling. The practice therefore contributes to the realization of the objectives of the 4 per 1000 Initiative (Fig. 1), i.e., C sequestration and co-benefits to sustain agriculture systems and secure food availability in the largest and more populated country of the Congo basin.

Other ecosystem services

Besides C and nutrient cycling, trees provide several other strongly interconnected ecosystem services (Rodriguez et al. 2006; Raudsepp-Hearne et al. 2010). In the two study countries, other ecosystem services may be directly linked to both rural and urban populations (i.e., pulp, fuelwood, and non-timber products supply) (Lescuyer et al. 2009; Bisiaux et al. 2009; Asaah et al. 2011; Shure et al. 2012; Table 1; Fig. 1). They may also be indirectly linked to environmental services, land restoration, reforestation, and/or afforestation for industrial goods and services, preservation of natural forests, preference of native NFT species to exotic species to reduce the risk of introducing invasive species, and loss of biodiversity and tourism (Lescuyer et al. 2009; Lal 2012, 2015; Koutika and Richardson 2019).

Fuelwood supply and non-timber forest products

With a population of about 80 million and 60% of it living in the rural areas, DRC has the higher production and consumption of fuelwood energy in the Congo basin (Shure et al. 2012). In 2009, fuelwood consumption was estimated at 94% against 79% in Cameroon, 35% in RoC, and only 24% in Gabon (Shure et al. 2012). An *A. auriculiformis* plantation, which was part of the agroforestry/forestry project (1987–1993) on 8000 ha in Mampu (DRC), produced 8000–12,000 t ha^{-1} $year^{-1}$ of charcoal (Bisiaux et al. 2009). Charcoal production is lower in the less populated RoC (around 5 millions), and the pressure on natural forests is lower than in DRC. Ten years ago, charcoal derived from forest plantations and natural forests represented 45% and 55% of total consumption, respectively, compared with 75% of fuelwood from plantations and 25% from natural forests in RoC (Nkoua et al. 2010; cited on Shure et al. 2012). At that time, over 96% of households depended on wood fuel (charcoal and fuelwood) as their energy source (Marien 2006 cited in Shure et al. 2012). Therefore, forest plantations, including those integrating NFTs, play a crucial role in reducing the pressure from the local (rural and urban) population on natural forests which may have declined by over 1000 ha $year^{-1}$ (Nkoua 2010; cited in Shure et al. 2012). The forest plantations established in the Congolese coastal area (RoC) greatly contribute to the fuel energy supply (Nkoua 2010 cited in Shure et al. 2012), preserving natural forests and biodiversity, and hence promote the objective of the Initiative 4 per 1000.

Land restoration

Lal (2015) distinguished between two main categories of soil degradation, anthropogenic and natural degradation, which are further categorized into four main types: physical, chemical, biological, and ecological. Soil and biomass C pools in degraded soils may be restored through sustainable forest management, i.e., integration of trees in degraded ecosystems (Lal 2012). Land restoration may be accelerated using NFTs (Franco and Faria 1997; Chaer et al. 2011). NFTs such as *Acacia mangium* were used to restore lands severely degraded by soil erosion, construction, and mining activities (Chaer et al. 2011); soil fertility by adding around 12 t of dry litter and 190 kg of N ha^{-1} $year^{-1}$ to the soil (Franco and Faria 1997) in Brazil, and soil C and N cycling processes in southern China (Wang et al. 2010). NFTs such as *A. mangium* are also often used to rehabilitate degraded forest ecosystems (Machado et al. 2018). The species was prioritized because of its important role in cycling of N and P, the most limiting soil nutrients in the Amazonian tropical forest ecosystems (Machado et al. 2018). It also creates conditions that foster a positive correlation between C sequestration, N and P stocks, and the high aboveground biomass production in Vietnam (Sang et al. 2013). In South China, increments in soil N concentration ($0.103 \pm 0.02\%$) under *A. mangium* were significantly higher than those ($0.092 \pm 0.01\%$) found in soils under *A. auriculiformis*–based systems (Yang et al. 2009). No reported studies on rehabilitated land were found in the two countries, although both *A. mangium* and *auriculiformis* have been widely used to improve soil fertility of nutrient-poor Arenosols.

Contributions of nitrogen-fixing tree-based forest plantation and agroforestry to food security

Integration of NFTs in forest plantations and agroforestry systems improve soil biological, chemical, and physical properties enhancing biogeochemical cycles (C and N cycles), biodiversity, and ecosystem productivity. These ecosystems increase household food security by improving availability, accessibility, utilization, and stability of food supply, and increasing dietary variety. Apart from timber, NTFPs (including medicines, fruits, mushrooms, insects, and honey) are harvested for household consumption and commercial purposes. Forest and agroforestry systems in the Congo basin contribute to reduced deforestation and forest degradation (REDD), forest carbon enhancement, improved forest management, restoration of degraded soils, and sustainable development. NFT-based forest and agroforestry systems therefore contribute significantly to household food security.

Conclusions

Integration of NFTs in planted forests and agroforestry systems enhances biogeochemical processes resulting in substantial fixation of C in the soil and tree biomass, an increase in quantities of major nutrients (i.e., N and P), and their availability for tree and crop growth and production; improves cation exchange capacity and C: N ratio enhancing the availability and use of nutrients by plants; and increases biological activities that favor plant growth and productivity through increased microbial and bacterial communities and activities, which result in substantial biomass increments and high crop yields — narrowing crop yield gaps increases food supply and reduces hunger.

Introduction of NFTs in planted forests and agroforestry systems leads also to improved soil health enhancing soil biological, chemical, and physical properties and alleviating soil degradation. Agricultural and forest ecosystems that include leguminous tree species show enhanced biological N_2 fixation, which increases available N for ecosystem primary production. Increased available N enhances carbon fixation in plant biomass and the soil. This translates into higher crop yields and tree biomass production. Increased net primary production, especially in trees, increases the size of the carbon sink and reservoir. Increased crop production decouples the commodity value chain from deforestation and forest degradation as it reduces pressure on the forest while increasing food production and preserving ecosystem biodiversity. Increased system productivity could enhance timber and NTFPs, which could enhance food security by increasing its availability, accessibility, stability, and utilization. The combined climate change mitigation and adaptation, improved soil health, and food security recommend these ecosystems for the promotion of the objectives of 4 per 1000 Initiative.

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