Chapter 12

The Potential of Tree and Shrub Legumes in Agroforestry Systems

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Abstract

Climate variability and changes are utmost important primary drivers of biological processes. They are intimately associated with a wide array of abiotic stresses, highlighting the vulnerability of ecosystems and endangering biodiversity. Nitrogen-fixing trees and shrubs (NFTSs) constitute a unique group of plants for their wide range of applications at the environmental, social and economic levels. In this chapter, we review and analyse the potential of this group of legumes in agroforestry towards sustainable agriculture in Africa. In the first part, the intertwined pillar of sustainable agriculture is brought forward under the context of growing population and climate changes. The second part addresses general aspects of legumes, including botany and the symbiosis with rhizobia. The third part includes the application of NFTS as N-fertilizers in agroforestry, highlighting the importance of an accurate choice of the crop(s)/NFTS combination(s) and cropping type (intercropping, multistrata or fallows). The implementation of agroforestry systems with NFTS should be supported by fundamental research strategies such as stable isotopes and systems biology and preceded by experimental assays, in order to identify the factors promoting N-losses and to design appropriate management strategies that synchronize legume-N availability with the crop demand.

Keywords: Africa, agroforestry, climate changes, sustainable agriculture, tree, shrub legumes

1. Introduction

Global agriculture is facing a series of challenges mainly related to growing population, climate changes and loss of biodiversity. Firstly, it is estimated that crop production must increase more than 60% by the year 2050 to fulfil the needs of the world's population [1]. Secondly, drought and soil salinization are expected to result in losses of up to 50% of arable lands by the middle of this century [1, 2]. Thirdly, the spreading of agriculture to arid and semi-arid regions under intensive irrigation management will promote secondary soil salinization [3]. Thus, the future of agriculture must rely on the sustainable intensification of crop production to feed the increasingly growing population, as well as on the use of tolerant cultivars that are able to cope with extreme environmental conditions, i.e. low fertility and saline soils, increasing water shortage periods as well as raising air temperatures and CO_2 [4, 5].

These challenges will be particularly critical in the developing countries, which have the highest rates of population growth and where most of the farmland is managed by smallholders [6]. It is estimated that in these countries one of five persons still live on less than $1.25 a day [7]. In this context, intensive agriculture based on agro-chemicals and mechanization is not sustainable and the systems must rely on appropriate cropping and post-harvest practices, preferably based on local ecosystem-based resources. Such practices include, for example, the implementation of integrated agroforestry systems, crop-livestock integration and crop-aquaculture production, that concomitantly have the potential to promote the conservation and the rational use of biodiversity and other ecosystem services.

According to the Food and Agriculture Organization of the United Nations (FAO), sustainable agriculture lies at the core of the 2030 Agenda [7]. Indeed, 6 of the 17 sustainable development goals (SDGs) concentrate on this issue. These are as follows: (i) SDG 2—*End hunger, achieve food security and improved nutrition and promote sustainable agriculture*; (ii) SDG 6—*Ensure sustainable consumption and production patterns*; (iii) SDG 12—*Ensure sustainable consumption and production patterns*; (iv) SDG 13—*Take urgent action to combat climate change and its impacts*; (v) SDG 14—*Take urgent action to combat climate change and its impacts*; (vi) SDG 15—*Sustainably manage forests, combat desertification, halt and reverse land degradation, halt biodiversity loss*. Besides that, all the other 11 SDGs cross cut issues towards the end of hunger and poverty.

Since 2014, FAO has supported over 80 initiatives in Africa to promote sustainable agricultural production practices [8]. To achieve that, three intertwined pillars are considered essential: (i) *efficient use of resources*, i.e. agriculture intensification to produce more with less impact on natural resources; (ii) *environment protection and conservation*, i.e. better management of natural resources in order to protect biodiversity (and ecosystem's stability), water, soil fertility and reduce pollution and (iii) *resilient agriculture*, i.e. adopting approaches to adapt and mitigate the impact of climate change.

Legume fixing trees and shrubs play a crucial role in biodiversity dynamics. From the ecological point of view, their introduction in cropping systems may contribute to reduce the use of chemical fertilizers and to ecosystems stability.

2. Description and functioning

The Fabaceae or Leguminosae family is the third largest group of flowering plants and the second most important in agriculture [9]. According to recent molecular and morphological studies, Fabaceae is a single monophyletic family [9, 10], comprising more than 18,000 species distributed over ca. 800 genera and six sub-families (**Table 1**) [11]: (i) Cercidoideae and (ii) Detarioideae, both comprising mainly tropical species; (iii) Duparquetioideae, a sub-family from western and central Africa, with only one species identified; (iv) Dialioideae, widespread throughout the tropics; (v) the pantropical Caesalpinioideae, with more than 4000 species (including the former sub-family Mimosoideae) and (vi) the cosmopolitan and largest legume sub-family, Faboideae (Papilionoideae), with ca. 14,000 species, mainly herbs and small shrubs.

Varying in habit from annual herbs to large trees, legumes are conspicuous and well represented throughout temperate and tropical regions [9, 12, 13]. The family is particularly diverse in tropical forests and temperate shrub lands with a seasonally dry or arid climate. Such preference for semi-arid to arid habitats seems to be related to a nitrogen-demanding metabolism [9]. The vast majority of legume species (ca. 90%) is able to establish symbiosis with nitrogen-fixing diazotrophic bacteria of the genera *Rhizobium* or *Bradirhizobium* (collectively called rhizobia) at the root and, in some cases, at the shoot level [14]. The symbiosis results in the formation of a new plant organ, i.e. the root- or stem-nodule, where bacteria are hosted and fix atmospheric N_2, receiving in exchange energy and carbon to sustain their own metabolism as well as the symbiotic process [15]. This type of symbiosis has around 58 million years and arose from the genome duplication of the sub-family Papilionoideae [16].

Nitrogen is among the key elements for plant growth and production, being decisive to the adequate plant response to environmental stresses [17]. It is a major component of chlorophyll (photosynthesis), purines and pyrimidines (nucleic acids), amino acids (proteins) and ATP

Subfamily	Genera (number)	Species (number)	Distribution
Cercidoideae	12	ca. 335	Mainly tropical, e.g. *Bauhinia* spp., *Cercis* spp.
Detarioideae	84	ca. 760	Mainly tropical, e.g. *Amherstia* spp., *Detarium* spp., *Tamarindus* spp.
Duparquetioideae	1	1	West and Central Africa, *Duparquetia orchidaceae*
Dialioideae	17	ca. 85	Widespread throughout the tropics, e.g. *Dialium* spp.
Caesalpinioideae*	148	ca. 4400	Pantropical, e.g. *Caesalpinia* spp., *Senna* spp., *Mimosa* spp., *Acacia* spp.
Faboideae (Papilionoideae)	503	ca. 14,000	Cosmopolitan, e.g. *Astragalus* spp., *Lupinus* spp., *Pisum* spp.

*Includes the former sub-family Mimosoideae.

Table 1. Sub-families, number of genera and species, distribution and examples of tree and shrub legumes (adapted from LPWG [11]).

(energy). Although it is one of the most abundant elements in the Earth, its predominant form, i.e. N_2 (g), cannot be directly assimilated by the plants, which need reduced forms of this element (NH_4^+, NO_2^- and NO_3^-) [18, 19]. This conversion can be achieved chemically through the Harber-Bosch process, or biologically through bacterial nitrogen fixation [20]. While chemical nitrogen fixation is cost intensive and 40–50% of the nitrogen applied as fertilizer is lost via denitrification, runoff or leaching, only 10–20% of the biologically fixed nitrogen is lost that way [21]. Besides that, the use of chemical fertilizers has a series of ecological impacts, such as air, soil and water pollution [22]. Thus, there is a strong interest in symbiotic N_2 fixation between legumes and rhizobia towards the improvement of agricultural systems, i.e. better productivity with the least ecological impact [23, 24].

In Africa, tree and shrub legumes provide a wealth of goods and services (e.g. wood, food, medicines, energy and housing) to millions of rural and urban dwellers (**Table 2** and **Figure 1**) [25, 26]. The interest on this group of legumes has increased tremendously in the last decades, particularly regarding soil erosion control [27, 28] and farming systems (e.g. windbreaks, shade trees, nitrogen fertilizers, forage, fruits and vegetables) [29–32].

Species	**Applications**	**Origin**	**kg.N.ha^{-1}.yr^{-1}**
Acacia senegal (L.) Willd.	Poles, household, agriculture crafts, firewood, charcoal (stem and branches); tannin, ropes (bark); food (pods and seeds); forage (foliage and pods); honey (flowers); gum Arabic (Gum), medicine (various); erosion control; nitrogen fixation; fertilizer; fencing; intercropping [90, 91]	Drier tropical Africa, from Senegal and Mauritania (west) to Eritrea and Ethiopia (north-east) and South Africa (south); Oman, Pakistan and India [92]	28.7–46.7 [33] 7–12 [93] less than 20 [94]
Brachystegia boehmii Taub. (**Figure 1A**)	Small articles, firewood (stem and branches); ropes, twine, cloth and fishing nets, tanning, beehives (bark); food for edible larvae (leaves); medicinal (various) [25, 95–97]	Angola, Botswana, Malawi, Mozambique, Tanzania, Zaire, Zambia, Zimbabwe [13]	Not available
Brachystegia spiciformis Benth. (**Figure 1B**)	Construction, furniture, household items, firewood, charcoal (stem and branches); tannin, beehives, ropes, sacks (bark); forage (foliage and pods); honey (flowers); medicinal (various); nitrogen fixation, shading [91, 98, 99]	Angola, Kenya, Malawi, Mozambique, Tanzania, Zaire, Zambia, Zimbabwe [13]	Not available
Cajanus cajan (L.) Millsp. (**Figure 1C**)	Light construction, baskets, fuel (stems and branches); forage (vegetative parts); honey (flowers); food (seeds and pods); medicinal (various); erosion control; shading, sheltering, nitrogen fixation; fertilizer; intercropping [91, 100]	Unknown origin, probably Indian and African [13, 101]; India [100]	260 [91] 86 [94] 96 [102] 142 [103]
Gliricidia sepium (Jacq.) Walp.	Farm implements, furniture, posts, firewood, charcoal (stem and branches); forage (foliage and pods); honey and food (flowers); medicine and rodenticide (various); erosion control; shading; nitrogen fixation; fertilizer; fencing [91]	Central America, Caribbean, South America, Asia (Java and Peninsular Malaysia) [13]	210 [104] 35–38 [105] 108 [106]
Leucaena collinsii Britton & Rose1	Timber, firewood (stems and branches); forage (leaves); food (seeds); similar to gum Arabic (Gum); shading; nitrogen fixation; fertilizer; fencing; intercropping [91]	Mexico and Guatemala [13, 91]	Not available

Species	**Applications**	**Origin**	**kg.N.ha^{-1}.yr^{-1}**
Pterocarpus angolensis DC. (**Figure 1D**)	Building, furniture and handicrafts (stem); fish poison (bark); body anointment (root bark); tannin, dyestuff (Sap); forage (foliage); honey (flowers); medicine (various); erosion control; nitrogen fixation [91]	Angola, Mozambique, Namibia, South Africa, Swaziland, Tanzania, Zaire, Zambia [13]	Not available
Sesbania sesban (L.) Merr.	Firewood, charcoal (Stem and branches); tannin, ropes (Bark); forage (leaves and young branches); food (flowers), ropes, fishnets (fiber); gum (seeds and bark); medicine (various); shading; fencing; fertilizer; nitrogen fixation; intercropping [91]	Africa, Asia, Australia [13]	84 [102] 100 [103]
Tephrosia candida (Roxb.) DC.	Firewood (stem and branches); forage and insecticide (leaves); erosion control, shading; land reclamation; nitrogen fixation; fertilizer; fencing; intercropping [91]	India, SE Asia [13]	Not available
Tephrosia vogelii Hook.f	Fish poison, insecticide and molluscicide (leaves); medicine (various); shading; fencing; nitrogen fixation; fertilizer [91]	Tropical Africa, SE Asia [13, 91]	150 [103]

Table 2. Examples of tree and shrub legumes and their applications in formal and informal economies.

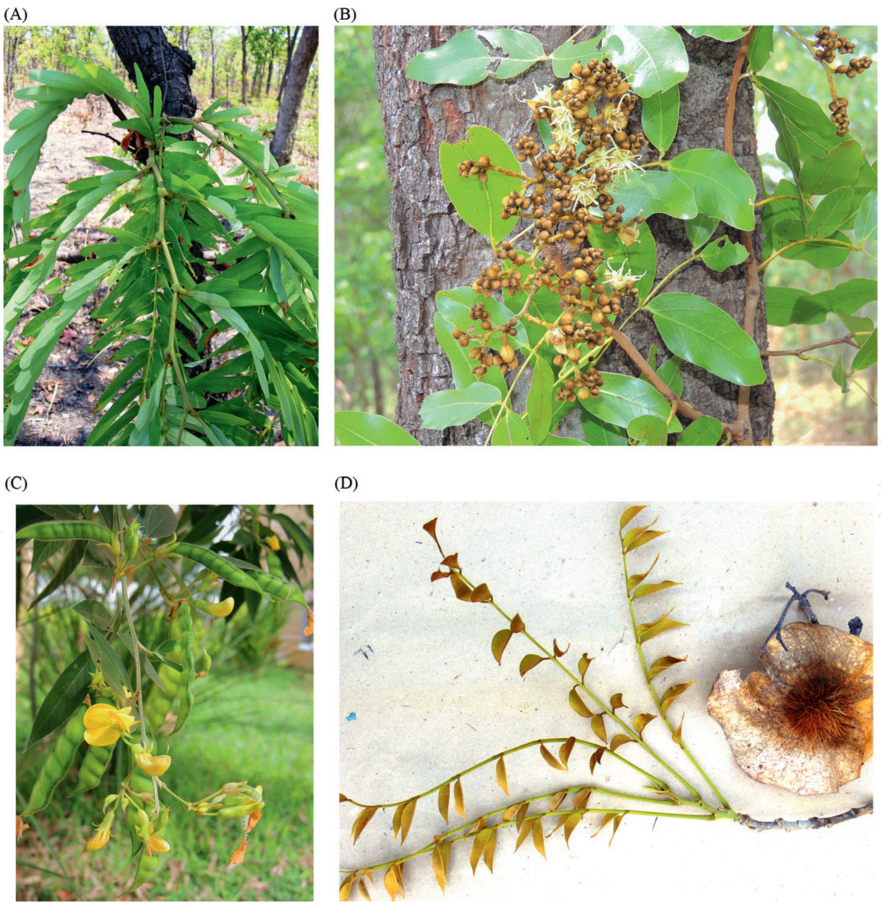

Figure 1. Details from *Brachystegia boehmii* leaves (A); *Brachystegia spiciformis* leaves and flowers (B); *Cajanus cajan* leaves, flowers and pods (C); *Pterocarpus angolensis* young leaves and mature fruit (D). Credits to Moura (A, D) and Catarino (B, C).

3. Importance and role in agroforestry tropical systems

Most tree and shrub legumes are resilient to extreme environments, e.g. erosion, low fertility, salinity, drought, fire and other adverse conditions [33–36]. Such abilities seem to be innate and enhanced by the symbiosis with N_2-fixing rhizobia [30, 37]. According to Diabate et al. [30] and Sprent [38], the use of nitrogen-fixing tree and shrubs (NFTSs) constitute a promising strategy to recover soil fertility, representing a sustainable agricultural approach to smallholder farmers. This is particularly important in sub-Saharan Africa where 80% of the farmland is managed by smallholders whose livelihoods depend strongly on the agricultural sector [6]. Most of these households live below the poverty line and therefore cannot afford the use of fertilizers. For example, smallholders from Niger, Namibia and Mozambique use less than 1 $kg.N.ha^{-1}.yr^{-1}$, i.e., 100 times less than the average fertilizer needs for most crops [1, 34].

The rates of N_2 fixation by NFTS depend on the species, climate and soil type, ranging from 0.1 to 700 $kg.N.ha^{-1}.yr^{-1}$ (**Table 2**) [33, 39, 40]. Despite the fact that many genera from the subfamilies Mimosoideae and Caesalpinioideae do not always establish root-nodule symbiosis, under proper environmental conditions, many species nodulate and fix atmospheric N at rates closer to those obtained with the traditional legumes belonging to the Papilionoideae [33]. Additionally there is also evidence that NTFS are also able to increase P availability in the soil, mostly due to mycorrhizal associations [41].

The use of fertilizer tree legumes (*Acacia anguistissima, Cajanus cajan, Gliricidia sepium, Leucaena collinsii, Sesbania sesban, Tephrosia candida* and *Tephrosia vogelii*) for sustainable maize (*Zea mays*) production has been analysed by Akinnifesi and collaborators [42] in East and Southern Africa (Zambia, Zimbabwe, Malawi and Tanzania). The authors reported a contribution of more than 60 $kg.N.ha^{-1}.yr^{-1}$ through biological nitrogen fixation (BNF), reducing the need of chemical N fertilizers in 75%. Besides that, N-fertilizer trees substantially increased crop yield, providing evidence that together with good management practices, maize yields can double as compared with traditional practices (without mineral fertilization). In Zambia, Mafongoya and Jiri [43] have analysed the use of *G. sepium* as green manure for cabbage (*Brassica oleracea*) and onion (*Allium cepa*) production. This practice produced higher crop yields than the unfertilized and full rate fertilized controls: ca. 16 (unfertilized), 43 (full rate fertilized), 48 (gliricidia) and 65 $ton.ha^{-1}$ (half rate fertilizer and gliricidia) for cabbage and 22 (unfertilized), 43 (full rate fertilized), 65 (gliricidia) and 85 $ton.ha^{-1}$ (half rate fertilizer and gliricidia) for onion. In addition, gliricidia biomass replenished the soil with residual N, which was used by a subsequent crop, maize. In this case, the yields obtained (ca. 3–5 $ton.ha^{-1}$) were similar or slightly higher than those obtained with full rate fertilizer (ca. 2.5 to 4 $ton.ha^{-1}$) and unfertilized crop (ca. 1.5–3 $ton.ha^{-1}$). Nevertheless, caution should be paid to the potential environmental hazard of NO_3 leaching and resultant eutrophication [43–45], as well as to the choice of the best crop(s)/NFTS combination(s) and cropping type (intercropping, multistrata or fallows) [46–47].

Another interesting NFTS-based agroforestry system is the tree cropping system, like those used for coffee production (**Figure 2**). Such system is very popular in Latin America [48–51] and less exploited in Africa. In Mexico, the rates of N_2 fixation obtained by *Inga jinicuil* in

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Figure 2. Agroforestry system with *Albizia* sp., coffee and maize in Gorongoza, Mozambique. Credits to Stalmans.

coffee plantations were above 40 kg.N.ha^{-1}.yr^{-1}, corresponding to 53% of the average amount of fertilizer applied annually. This observation reinforces the importance of the use of non-crop legumes in coffee agro-ecosystems [48–50]. According to the literature [49, 50], *Inga* spp. is the most popular choice from Mexico to Nicaragua. *G. sepium* and *Erythrina poeppigiana* are often the common choice in the low-lying areas of Honduras and Nicaragua and Costa Rica, respectively [51]. In Africa, similar systems may constitute a promising and sustainable solution to improve coffee (or fruits) productivity in the region.

4. Towards scientific knowledge

Legume research has been mainly focused on annual grain crops [34, 52–54]. Instead, a limited amount of knowledge has been produced in perennials. In this section, we will discuss the potential of the two promising strategies to analyse nitrogen mineralization and metabolism in tree legumes, i.e. stable isotopes and, briefly, systems biology.

4.1. Stable isotopes

The use of stable isotopes at natural abundance levels has brought a new dimension to our understanding of plant physiology and ecology. Analyses of the relative natural abundances of stable isotopes of carbon ($^{13}C/^{12}C$), oxygen ($^{18}O/^{16}O$), nitrogen ($^{15}N/^{14}N$) and deuterium (D/H) have been used across a wide range of scales, from cell to community and ecosystem level, contributing much to our understanding of the interactions between biosphere, pedosphere and atmosphere.

In general terms, processes such as diffusion and enzymatic incorporation favour the lighter isotope and lead to depletion of the heavier isotope as compared to source material. Natural abundance of ^{15}N can provide valuable information about N sources used by plants and fluxes of N in the ecosystems [e.g. 55–57]. There has been some debate on the interrelationship between nitrogen natural abundance ($^{15}N/^{14}N$) in soils and plants, and the use of a tracer or indicator of fractionation during N-uptake, assimilation and transport [58, 59]. Indeed, a variety of fractionations may occur during processes related to nitrogen transformation in soils

[60, 61] and plants [59], which may complicate source-sink relationships. For example, nitrification discriminates against ^{15}N more than N mineralization, which makes NH_4^+ isotopically heavier than the organic N from which it is derived [60]. Additionally, the $\delta^{15}N$ of a particular compound may change and, together with the complexity of the N geochemical cycle, the use of $\delta^{15}N$ should be carefully evaluated when applied to natural ecosystems.

However, there are substantial evidence that the natural abundance ratios for $^{15}N/^{14}N$ in soil and plants are useful integrators of the types and turnover rates of N cycling [62–64]. These ratios can indicate whether a range of plants have access to the same N source [59]. For instance, differences in leaf $\delta^{15}N$ can indicate differences in rooting depth or root characteristics, such as mycorrhizal or N-fixing root associations [59, 65]. Also, nitrification and plant uptake properties (such as timing and type of uptake) can be determined by the leaf $\delta^{15}N$ signatures [66, 67]. Robinson [59] developed a mixing model to account for contrasting N sources which provided useful insights on the quantification of biological N fixation in tree legumes [68, 69]. Since N_2-fixing species typically have $\delta^{15}N$ signatures close to the atmospheric value (0%), which strongly differ from the $\delta^{15}N$ signature of non-fixing species, $\delta^{15}N$ can be used as a sensitive tracer of N flow within an ecosystem. This approach was successfully used in the oligotrophic Portuguese primary dunes utilizing foliar $\delta^{15}N$ of the non-leguminous native shrub *Corema album* [70–72]. As the invasive *Acacia longifolia* and the native *Stauracanthus spectabilis* were the only legumes co-occurring with *C. album*, with no further sources of organic matter, this system represents an ideal model to quantify the impact of *A. longifolia* invasion. Similar to other ericoid $\delta^{15}N$ mycorrhizal plants [73], *C. album* exhibited depleted foliar values without legume influence which, together with its high abundance in this system, may function as a good monitoring plant for legume influence [71].

4.2. Systems biology

Systems biology is an emerging approach applied to biological scientific research that focuses on the complex interactions within biological systems, frequently associated with the environmental conditions. The best known example is the *Human Genome Project* which allowed major advances in human genetics and in the development of new medical therapies [74, 75]. Systems biology, commonly called '*Omics*' is associated with high-throughput analysis of e.g. genomes (DNA, *genomics*), transcriptomes (RNA, *transcriptomics*), proteomes (proteins, *proteomics*), metabolomes (metabolites, *metabolomics*), lipidomes (lipids, *lipidomics*) and interactomes (interactions between molecules, *interactomics*) coupled with bioinformatics, which integrates computational, statistical and mathematical modelling [76, 77]. In plants, systems biology has been essentially focused on models, such as arabidopsis and annual crops (e.g. rice, wheat, tomato, soybean, maize, sorghum, chickpea or groundnut) [78–85]. Systems biology research in perennial plants is still restricted to a small group of trees, namely eucalyptus, poplar, abies and pine (reviewed in Refs. [86, 87]). Among others, such studies led to significant advances on the global knowledge of plant biology (development and functioning), genomics-assisted breeding towards the production of crops tolerant to extreme temperatures, salinity, drought, pests and diseases, or the discovery of new bio-compounds with application in agriculture, medicine and in a wide range of industries [78, 79, 86, 87].

In our laboratory, we have recently initiated an integrated approach, combining eco-physiology and system's biology to understand the responses of two tree legumes (*Brachystegia boehmii* and

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Colophospermum mopane) to abiotic stresses, namely high temperatures, drought and low soil fertility. Preliminary results indicate that these plants have an innate ability to cope with extreme environments and that such capacity is linked to an enhanced water and mineral use efficiency [88], reinforcement of the photosynthetic machinery and the antioxidant system as well as an elevated osmoprotection state [unpublished data; 89].

5. Concluding remarks

Agriculture has a primordial role to fight poverty and hunger and increase crop resilience to climate changes. The introduction of tree and shrub nitrogen-fixing trees into cropping systems is the most straightforward approach to reduce the use of chemical fertilizers, improving the soil ecosystem and the livelihoods of smallholder farmers in southern Africa. Additionally, agroforestry may improve ecosystem services such as, soil organic matter, biodiversity and N-retention. However, it is not devoid of environmental consequences, specifically N-leaching. Therefore, the implementation of agroforestry systems with NFTS should be preceded by experimental assays, in order to identify the factors promoting N-losses and design appropriate management strategies that synchronize legume-N availability with the crop demand.

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