
The Potential of Tree and Shrub Legumes in Agroforestry Systems

Ana I. Ribeiro-Barros, Maria J. Silva, Isabel Moura,
José C. Ramalho, Cristina Máguas-Hanson and
Natasha S. Ribeiro

Additional information is available at the end of the chapter

<http://dx.doi.org/10.5772/intechopen.69995>

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 CO₂ [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 N₂, 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. <i>Bauhinia</i> spp., <i>Cercis</i> spp.
Detarioideae	84	ca. 760	Mainly tropical, e.g. <i>Amherstia</i> spp., <i>Detarium</i> spp., <i>Tamarindus</i> spp.
Duparquetioideae	1	1	West and Central Africa, <i>Duparquetia orchidaceae</i>
Dialioideae	17	ca. 85	Widespread throughout the tropics, e.g. <i>Dialium</i> spp.
Caesalpinioideae*	148	ca. 4400	Pantropical, e.g. <i>Caesalpinia</i> spp., <i>Senna</i> spp., <i>Mimosa</i> spp., <i>Acacia</i> spp.
Faboideae (Papilionoideae)	503	ca. 14,000	Cosmopolitan, e.g. <i>Astragalus</i> spp., <i>Lupinus</i> spp., <i>Pisum</i> 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
<i>Acacia senegal</i> (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]
<i>Brachystegia boehmii</i> 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
<i>Brachystegia spiciformis</i> 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
<i>Cajanus cajan</i> (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]
<i>Gliricidia sepium</i> (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]
<i>Leucaena collinsii</i> 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
<i>Pterocarpus angolensis</i> 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
<i>Sesbania sesban</i> (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]
<i>Tephrosia candida</i> (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
<i>Tephrosia vogelii</i> 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 $1 \text{ kg.N.ha}^{-1}\text{.yr}^{-1}$, 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 $700 \text{ kg.N.ha}^{-1}\text{.yr}^{-1}$ (Table 2) [33, 39, 40]. Despite the fact that many genera from the sub-families 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 angustissima*, *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 $60 \text{ kg.N.ha}^{-1}\text{.yr}^{-1}$ 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



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

coffee plantations were above $40 \text{ kg.N.ha}^{-1}.\text{yr}^{-1}$, 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 ($^{13}\text{C}/^{12}\text{C}$), oxygen ($^{18}\text{O}/^{16}\text{O}$), nitrogen ($^{15}\text{N}/^{14}\text{N}$) 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 ($^{15}\text{N}/^{14}\text{N}$) 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 $\delta^{15}\text{N}$ of a particular compound may change and, together with the complexity of the N geochemical cycle, the use of $\delta^{15}\text{N}$ should be carefully evaluated when applied to natural ecosystems.

However, there are substantial evidence that the natural abundance ratios for $^{15}\text{N}/^{14}\text{N}$ 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 $\delta^{15}\text{N}$ 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 $\delta^{15}\text{N}$ 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 $\delta^{15}\text{N}$ signatures close to the atmospheric value (0%), which strongly differ from the $\delta^{15}\text{N}$ signature of non-fixing species, $\delta^{15}\text{N}$ 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 $\delta^{15}\text{N}$ 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 $\delta^{15}\text{N}$ 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

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.

Acknowledgements

The authors like to acknowledge Fundação para a Ciência e a Tecnologia through the research units UID/AGR/04129/2013 (LEAF), UID/GEO/04035/2013 (GeoBioTec), CE3C, Fundo para a Investigação Aplicada e Multisectorial. The authors thank Luís Catarino (CE3C), and Mark Stalmans (E.O. Wilson Biodiversity, Lab. Gorongosa National Park) for kindly providing the photographs.

Author details

Ana I. Ribeiro-Barros^{1,2*}, Maria J. Silva^{1,2}, Isabel Moura¹, José C. Ramalho^{1,2}, Cristina Máguas-Hanson³ and Natasha S. Ribeiro⁴

*Address all correspondence to: aribeiro@itqb.unl.pt

1 Plant Stress & Biodiversity Lab, Linking Landscape, Environment, Agriculture and Food (LEAF), School of Agriculture (ISA), University of Lisbon (ULisboa), Portugal

2 GeoBioTec, Faculdade de Ciências e Tecnologia (FCT), Universidade NOVA de Lisboa (UNL), Portugal

3 Center for Ecology, Evolution and Environmental Changes (cE3c), Faculdade de Ciências, Universidade de Lisboa, Portugal

4 Faculty of Agronomy and Forest Engineering, Eduardo Mondlane University, Maputo, Mozambique

References

- [1] FAO. World agriculture towards 2030/2050: The 2012 revision [Internet]. ESA E Working Paper No. 12-03. FAO. 2012. Available from: http://www.fao.org/fileadmin/userupload/esag/docs/AT2050_revision_summary.pdf
- [2] Mahajan S, Tuteja N. Cold, salinity and drought stresses: An overview. *Archives of Biochemistry and Biophysics*. 2005;**444**:139-158. DOI: 10.1016/j.abb.2005.10.018
- [3] Chaves MM, Flexas J, Pinheiro C. Photosynthesis under drought and salt stress: Regulation mechanisms from whole plant to cell. *Annals of Botany*. 2009;**103**:551-560. DOI: 10.1093/aob/mcn125
- [4] CSSA. Position Statement on Crop Adaptation to Climate Change. [Internet]. Crop Science Society of America;. 2011. Available from: <https://www.crops.org/files/science-policy/cssa-crop-adaptation-position-statement.pdf>
- [5] FAO. Save and Grow. A Policymaker's Guide to the Sustainable Intensification of Smallholder Crop Production [Internet]. 2011. Available from: <http://www.fao.org/ag/save-and-grow/en/index.html>
- [6] FAO. Strategic Work of FAO to Increase the Resilience of Livelihoods [Internet]. 2017. Available from: <http://www.fao.org/3/a-i6463e.pdf>
- [7] FAO. FAO and the 17 Sustainable Development Goals. [Internet]. 2015. Available from: <http://www.fao.org/3/a-i4997e.pdf>
- [8] IFAD. Smallholders, Food Security, and the Environment. [Internet]. 2013. Available from: <https://www.ifad.org/documents/10180/666cac24-14b6-43c2-876d-9c2d1f01d5dd>
- [9] Wojciechowski MF, Mahn J, Fabaceae JB. Legumes. The Tree of Life Web Project [Internet]. Available from: <http://tolweb.org/>
- [10] Lewis G, Schrire B, MacKinder B, Lock M. *Legumes of the World*. Kew: Royal Botanical Garden; 2005. 577 p. ISSN: 0967-8018
- [11] LPWG. A new subfamily classification of the Leguminosae based on a taxonomically comprehensive phylogeny. *Taxon*. 2017;**66**:44-77. Available from: <http://www.ingenta-connect.com/contentone/iapt/tax/2017/00000066/00000001/art00004>
- [12] Rundel PW. Ecological success in relation to plant form and function in the woody legumes. In: Stirton CH, Zarucchi JL, editors. *Advances in Legume Biology*. Vol. 29. Monographs in Systematic Botany from the Missouri Botanical Garden. ST. Louis ; 1989. pp. 377-398
- [13] ILDIS. International Legume Database & Information Service. [Internet]. 2015 Available from: <http://www.ildis.org/leguminosae/>
- [14] De Faria SM, Lewis GP, Sprent JI, Sutherland JM. Occurrence of nodulation in the Leguminosae. *New Phytologist*. 1989;**111**:607-619. DOI: 10.1111/j.1469-8137.1989.tb02354.x

- [15] Sprent J. Legume Nodulation: A Global Perspective. Wiley-Blackwell, Oxford; 2009. p. 200
- [16] Young ND, Debelle F, Oldroyd GED, et al. The Medicago genome provides insight into the evolution of rhizobial symbioses. *Nature*. 2011;**480**:420-424. DOI: 10.1038/nature10625
- [17] Carelli ML, Fahl JJ, Ramalho JC. Aspects of nitrogen metabolism in coffee plants. *Theoretical and Experimental Plant Physiology*. 2006;**18**:9-21. DOI: 10.1590/S1677-04202006000100002
- [18] Smil V. Nitrogen in crop production: an account of global flows. *Global Biogeochemical Cycles*. 1999;**13**:647-662. DOI: 10.1029/1999GB900015
- [19] Vance CP. Symbiotic nitrogen fixation and phosphorous acquisition. *Plant nutrition in a world of declining renewable resources*. *Plant Physiology*. 2001;**127**:390-397. DOI: <http://dx.doi.org/10.1104/pp.010331>
- [20] Burris RH, Roberts GP. Biological nitrogen fixation. *Annual Review of Nutrition*. 1993; **3**:317-335
- [21] Galloway JN, Dentener FJ, Capone DG, et al. Nitrogen cycles: Past, present, and future generations. *Biogeochemistry*. 2004;**70**:153-226. DOI: 10.1007/s10533-004-0370-0
- [22] Wagner SC. Biological nitrogen fixation. *Nature Education Knowledge*. 2011;**3**:15. Available from: <http://www.nature.com/scitable/knowledge/library/biological-nitrogen-fixation-23570419>
- [23] Paul EA. Towards the year 2000: Directions for future nitrogen research. In: Wilson JR, editor. *Advances in Nitrogen Cycling in Agricultural Ecosystems*. CAB International, Wallingford; 1988. pp. 417-425. DOI: 10.1007/BF00032239
- [24] Pawlowski K, Ribeiro A, Bisseling T. Nitrogen fixing root nodule symbioses: legume nodules and actinorhizal nodules. In: El-Gewely MR, editor. *Biotechnology Annual Review*. Vol. II. Elsevier Science, Rijeka; 1996. pp. 151-184. DOI: [https://doi.org/10.1016/S1387-2656\(08\)70009-7](https://doi.org/10.1016/S1387-2656(08)70009-7)
- [25] Palmer E, Pitman N. *Trees of Southern Africa*. Balkema, Cape Town; 1972. 312 p.
- [26] Campbell B, Frost P, Byron N. Miombo woodlands and their use: Overview and key issues. In: Campbell B editor. *The Miombo in Transition: Woodlands and Welfare in Africa*. Bogor: CIFOR; 1996. pp. 1-5. ISBN: 979-8764-07-2
- [27] Ribeiro NS, Syampungani S, Nangoma D, Ribeiro-Barros A. Miombo woodlands research towards the sustainable use of ecosystem services in Southern Africa. In: Lo Y-H, Blanco JA, Roy S, editors. *Biodiversity in Ecosystems – Linking Structure and Function*. InTech, Rijeka; 2015. pp. 493-409. DOI: 10.5772/58494
- [28] Moura I, Maquia I, Rija AA, et al. Biodiversity studies in key species from the African mopane and miombo woodlands. In: Bitz L, editor. *Genetic Diversity*. InTech, Rijeka; 2017. DOI: 10.5772/66845

- [29] Smith OW. Fodder trees and shrubs in range and farming systems in tropical humid Africa. In: Speedy A, Pugliese PL, editors. Legume Trees and other Fodder Trees as Protein Sources for Livestock. FAO Animal Production and Health Paper 102; 1991. Available from: <http://www.fao.org/docrep/003/T0632E/T0632E04.htm#ch4>
- [30] Diabate M, Munive A, De Faria SM, et al. Occurrence of nodulation in unexplored leguminous trees native to the West African tropical rainforest and inoculation response of native species useful in reforestation. *New Phytologist*. 2005;**166**:231-239. DOI: 10.1111/j.1469-8137.2005.01318.x
- [31] Ribeiro A, Romeiras MM, Tavares J, et al. Ethnobotanical survey in Canhane village, district of Massingir, Mozambique: Medicinal plants and traditional knowledge. *Journal of Ethnobiology and Ethnomedicine*. 2010;**6**:33. DOI: 10.1186/1746-4269-6-33
- [32] Dewees P, Campbell B, Katerere Y, et al. Managing the Miombo Woodlands of Southern Africa: Policies, incentives, and options for the rural poor. *Journal of Natural Resources Policy Research*. 2011;**2**(1): 57-73. DOI: 10.1080/19390450903350846
- [33] Adams M, Simon J, Fautsch P. Woody legumes: A (re)view from the South. *Tree Physiology*. 2010;**30**:1072-1082. DOI: 10.1093/treephys/tpq061
- [34] Bruning B, Rozema J. Symbiotic nitrogen fixation in legumes: Perspectives for saline agriculture. *Environmental and Experimental Botany*. 2013;**92**:134-143. DOI: <http://dx.doi.org/10.1016/j.envexpbot.2012.09.001>
- [35] Maquia I, Ribeiro NS, Silva V, et al. Genetic diversity of *Brachystegia boehmii* Taub. and *Burkea africana* Hook.f. across a fire gradient in Niassa National Reserve, northern Mozambique. *Biochemical Systematics and Ecology*. 2013;**48**:238-247. DOI: <https://doi.org/10.1016/j.bse.2012.12.020>
- [36] Ribeiro NS, Matos CN, Moura IR, et al. Monitoring vegetation dynamics and carbon stock density in miombo woodlands. *Carbon Balance and Management*. 2013;**8**:11. DOI: 10.1186/1750-0680-8-11
- [37] Gutteridge RC, Shelton HM. Forage tree legumes in tropical agriculture. In: Gutteridge RC, Shelton HM, editors. Tropical Grassland Society of Australia, CSIRO Australia; 1998. Available from: <http://www.fao.org/ag/agp/agpc/doc/publicat/gutt-shel/x5556e05.htm#1.1> the role of forage tree legumes in cropping and grazing systems
- [38] Sprent J. West African legumes: The role of nodulation and nitrogen fixation. *New Phytologist*. 2005;**166**:326-330. DOI: 10.1111/j.1469-8137.2005.01499.x
- [39] Vanlauwe B, Giller KE. Popular myths around soil fertility management in sub-Saharan Africa. *Agricultural Ecosystems and Environment*. 2006;**116**:34-46. DOI: <https://doi.org/10.1016/j.agee.2006.03.016>
- [40] Ajayi OC, Place F, Akinnifesi FK, et al. Agricultural success from Africa: The case of fertilizer tree systems in southern Africa (Malawi, Tanzania, Mozambique, Zambia and Zimbabwe). *International Journal of Agriculture Sustainability*. 2011;**9**:129-136. DOI: 10/3763/ijas.2010.0554

- [41] Houlton BZ, Wang YP, Vitousek PM, Field CB. A unifying framework for dinitrogen fixation in the terrestrial biosphere. *Nature*. 2008;**454**:327-330. DOI: 10.1038/nature07028
- [42] Akinnifesi KK, Sileshi AG, Chirwa PW, et al. Fertilizer trees for sustainable food security in the maize-based production systems of East and Southern Africa. A review. *Agronomy for Sustainable Development*. 2010;**30**:615-629. DOI: 10.1016/B978-0-444-52512-3.00022-X
- [43] Mafongoya PL, Jiri O. Nutrient dynamics in wetland organic vegetable production systems in eastern Zambia. *Sustainable Agriculture Research*. 2016;**5**:78-85. DOI: 10.5539/sar.v5n1p78
- [44] Hartemink A, Buresh R, Van Bodegom P, et al. Inorganic nitrogen dynamics in fallows and maize on an Oxisol and Alfisol in the highlands of Kenya. *Geoderma*. 2000;**98**:11-33. DOI: [https://doi.org/10.1016/S0016-7061\(00\)00072-0](https://doi.org/10.1016/S0016-7061(00)00072-0)
- [45] Rosenstock TS, Tully KL, Arias-Navarro C, et al. Agroforestry with N₂-fixing trees: sustainable development's friend or foe? *Current Opinion in Environmental Sustainability*. 2014;**6**:15-21. DOI: <http://doi.org/10.1016/j.cosust.2013.09.001>
- [46] Chikowo R, Mapfumo P, Leffelaar PA, et al. Integrating legumes to improve N cycling on smallholder farms in subhumid Zimbabwe: Resource quality, biophysical and environmental limitations. *Nutrient Cycling in Agroecosystems*. 2006;**76**:219-231. DOI: 10.1007/s10705-005-2651-y
- [47] Mafongoya PL, Bationo A, Kihara J, et al. Appropriate technologies to replenish soil fertility in southern Africa. *Nutrient Cycling in Agroecosystems*. 2006;**76**:137-151. DOI 10.1007/s10705-006-9049-3
- [48] Roskoski JP. Nitrogen fixation in a Mexican coffee plantation. *Plant and Soil*. 1982;**67**:283-291. DOI: 10.1007/BF02182775
- [49] Soto-Pinto L, Perfecto Y, Castillo-Hernandez J, et al. Shade effect on coffee production at the northern Tzeltal zone of the state of Chiapas, Mexico. *Agriculture, Ecosystems and Environment*. 2000;**80**:61-69
- [50] Galloway G, Beer J. Oportunidades para fomentar la silvicultura en cafetales de América Central. Serie Técnica 285: CATIE, Turrialba; 1997. 166 p.
- [51] Bellefontaine R, Petit S, Pain-Ordet M, et al. Trees outside forests. Towards a better awareness. *FAO Conservation Guide* 35; 2002. ISBN 92-5-104656-5 Available from: <http://www.fao.org/docrep/005/Y2328E/y2328e00.htm#toc>
- [52] Gupta S, Nadarajan N, Gupta DS. *Legumes in the Omic Era*. Springer, New York; 2014. 360 p. ISBN 978-1-4614-8370-0
- [53] Lonati M, Probo M, Gorlier A, et al. Nitrogen fixation assessment in a legume-dominant alpine community: comparison of different reference species using the N-15 isotope dilution technique. *Alpine Botany*. 2015;**125**:51-58. DOI: 10.1007/s00035-014-0143-x
- [54] Wahbi S, Maghraoui T, Hafidi M, et al. Enhanced transfer of biologically fixed N from faba bean to intercropped wheat through mycorrhizal symbiosis. *Applied Soil Ecology*. 2016;**107**:91-98. DOI: 10.1016/j.apsoil.2016.05.008

- [55] Kohl DH, Shearer GB, Commoner B. Fertilizer nitrogen: Contribution to nitrate in surface water in a corn belt watershed. *Science*. 1971;**174**:1331-1334
- [56] Amarger N, Mariotti A, Mariotti F. Essai d'estimation du taux d'azote fixé symbiotiquement chez le lupin par le traçage isotopique naturel (^{15}N). *Comptes Rendus de l'Academie des Sciences*. 1977;**284**:2179-2182
- [57] Shearer G, Kohl DH. N_2 -Fixation in field settings: estimations based on natural ^{15}N abundance. *Australian Journal of Plant Physiology*. 1986;**13**:699-756. DOI: 10.1071/PP9860699
- [58] Evans RD. Physiological mechanisms influencing plant nitrogen isotope composition. *Trends in Plant Science*. 2001;**6**:121-126. Available from: <http://plants.trends.com>
- [59] Robinson D. $\delta^{15}\text{N}$ as an integrator of the nitrogen cycle. *Trends in Ecology and Evolution*. 2001;**16**:153-162. DOI: [https://doi.org/10.1016/S0169-5347\(00\)02098-X](https://doi.org/10.1016/S0169-5347(00)02098-X)
- [60] Högborg P. ^{15}N natural abundance in soil-plant systems. *New Phytologist*. 1997;**137**:179-203. DOI: 10.1046/j.1469-8137.1997.00808.x
- [61] Hopkins DW, Dowd RW, Shiel RS. Comparison of L- and D-amino acid metabolism in soils with differing microbial biomass and activity. *Soil Biology and Biochemistry*. 1997;**29**:23-29. DOI: [https://doi.org/10.1016/S0038-0717\(96\)00266-0](https://doi.org/10.1016/S0038-0717(96)00266-0)
- [62] Nadelhoffer KJ, Fry B. Nitrogen isotopic studies in forest ecosystems. In: Lajtha K, Michener R, editors. *Stable Isotopes in Ecology and Environmental Sciences*. Blackwell Scientific Publications, Oxford; 1994. pp. 22-44. DOI: 10.1002/9780470691854
- [63] Lorens P, Oliveras I, Poyatos R. Temporal variability of water fluxes in a *Pinus silvestris* forest patch in Mediterranean mountain conditions. *Hydrology of Mediterranean and Semiarid Regions*. 2003;**278**:101-105
- [64] Fry B. *Stable Isotope Ecology*. Springer, New York; 2006. p. 300p.
- [65] Cernusak LA, Pate JS, Farquhar GD. Diurnal variation in the stable composition of water and dry matter in fruiting *Lupinus angustifolius* under field conditions. *Plant Cell and Environment*. 2002;**25**:893-907. DOI: 10.1046/j.1365-3040.2002.00875.x
- [66] Pate JS, Unkovich MJ, Erskine PD, et al. Australian mulga ecosystem $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ abundance of biota components and their ecophysiological significance. *Plant Cell and Environment*. 1998;**21**:1231-1242. DOI: 10.1046/j.1365-3040.1998.00359.x
- [67] Pardo LH, Templer TH, Goodale CL, et al. Regional assessment of N saturation using foliar and root N-15. *Biogeochemistry*. 2006;**80**:143-171. DOI: 10.1007/s10533-006-9015-9
- [68] Boddey RM, Silva LG, Reis V, et al. Assessment of bacterial nitrogen fixation in grass species. In: Triplett ED, editor. *Prokaryotic Nitrogen Fixation: A Model System for Analysis of a Biological Process*. Horizon Scientific Press, Wisconsin; 2000. ISBN: 978-1898486190
- [69] Unkovich M, Blott K, Knight A, et al. Water use, competition and crop production in low rainfall, alley farming systems of south-eastern Australia. *Crop Pasture Science*. 2013;**54**:751-762. DOI: <https://doi.org/10.1071/AR03049>

- [70] Hellmann C, Sutter R, Rascher KG, et al. Impact of an exotic N₂-fixing *Acacia* on composition and N status of a native Mediterranean community. *Acta Oecologica*. 2011;**37**:43-50. DOI: 10.1016/j.actao.2010.11.005
- [71] Rascher K, Hellmann C, Werner C, et al. Community scale ¹⁵N isoscapes: tracing the spatial impact of an exotic N₂-fixing invader. *Ecology Letters*. 2012;**15**:484-491 DOI: 10.1111/j.1461-0248.2012.01761.x
- [72] Ulm F, Hellmann C, Cruz C, et al. N/P imbalance as a key driver for the invasion of oligotrophic dune systems by a woody legume. *Oikos*. 2016;**2**:231-240. DOI: 10.1111/oik.03810
- [73] Craine J, Elmore A, Aidar M, et al. Global patterns of foliar nitrogen isotopes and their relationships with climate, mycorrhizal fungi, foliar nutrient concentrations, and nitrogen availability. *The New Phytologist*. 2009;**183**:980-992. DOI: 10.1111/j.1469-8137.2009.02917.x
- [74] Snoep JL, Westerhoff HV. From isolation to integration, a systems biology approach for building the silicon cell. In: Alberghina L, Westerhoff V, editors. *Systems Biology: Definitions and Perspectives*. Topics in Current Genetics. Springer-Verlag, Berlin Heidelberg; 2005. pp. 13-30. ISBN: 978-3540229681
- [75] Sauer U, Heinemann M, Zamboni N. Genetics: Getting closer to the whole picture. *Science*. 2007;**316**:550-551. DOI: 10.1126/science.1142502
- [76] Kitano H. Computational systems biology. *Nature*. 2002;**420**:206-210. DOI: 10.1038/nature01254
- [77] Kitano H. Systems biology: A brief overview. *Science*. 2002;**295**:1662-1664. DOI: 10.1126/science.1069492
- [78] Nützman HW, Huang A, Osbourn A. Plant metabolic clusters – from genetics to genomics. *New Phytologist*. 2016;**211**:771-789. DOI: 10.1111/nph.13981
- [79] Bode R, Ivanov AG, Hu NPA. Global transcriptome analyses provide evidence that chloroplast redox state contributes to intracellular as well as long-distance signaling in response to stress and acclimation in *Arabidopsis*. *Photosynthetic Research*. 2016;**128**:287-312. DOI: 10.1007/s11120-016-0245-y
- [80] He B, Tao X, Gu Y, et al. Transcriptomic analysis and the expression of disease-resistant genes in *Oryza meyerian* under native conditions. *PLoS One*. 2015;**7**:e0144518. DOI: 10.1371/journal.pone.0144518.
- [81] Pechanova O, Takáč T, Samaj J, et al. Maize proteomics: An insight into the biology of an important cereal crop. *Proteomics*. 2013;**13**:637-662. DOI: 10.1002/pmic.201200275
- [82] Lee DG, Ahsan N, Lee SH, et al. Chilling stress-induced proteomic changes in rice roots. *Journal of Plant Physiology*. 2009;**166**:1-11. DOI: 10.1016/j.jplph.2008.02.001
- [83] Peng Z, Wang M, Li F, et al. A proteomic study of the response to salinity and drought stress in an introgression strain of bread wheat. *Molecular and Cellular Proteomics*. 2009;**8**:2676-2686. DOI: 10.1074/mcp.M900052-MCP200

- [84] Cheng L, Gao X, Li S, et al. Proteomic analysis of soybean [*Glycine max* (L.) Meer.] seeds during imbibition at chilling temperature. *Molecular Breeding*. 2010;**26**:1-17. DOI: 10.1007/978-3-319-41448-5
- [85] Varshney RV, Kudapa H, Roorkiwal M, et al. Advances in genetics and molecular breeding of three legume crops of semi-arid tropics using next-generation sequencing and high-throughput genotyping technologies. *Journal of Biosciences*. 2012;**37**:811-820. DOI: 10.1007/s12038-012-9228-0
- [86] Kole C, Muthamilarasan M, Henry R, et al. Application of genomics-assisted breeding for generation of climate resilient crops: progress and prospects. *Frontiers in Plant Science*. 2015;**6**:563. DOI: 10.3389/fpls.2015.00563
- [87] Sundell D, Mannapperuma C, Netotea S, et al. The plant genome integrative explorer resource: PlantGenIE.org. *New Phytologist*. 2015;**208**:1149-1156. DOI: 10.1111/nph.13557
- [88] Gaiser T, de Barros I, Lange FM, et al. Water use efficiency of a maize/cowpea intercrop on a highly acidic tropical soil as affected by liming and fertilizer application. *Plant and Soil*. 2004;**263**:165-171. DOI: 10.1023/B:PLSO.0000047733.98854.9f
- [89] Antoniou C, Chatzimichail G, Xenofontos R, et al. Melatonin systemically ameliorates drought stress-induced damage in *Medicago sativa* plants by modulating nitro-oxidative homeostasis and proline metabolism. *Nutrient Cycling in Agroecosystems*. 2015;**101**:107-121. DOI: 10.1007/s 10705-014-9647-4
- [90] Fagg CW, Allison GE. *Acacia senegal* and the gum arabic trade: monograph and annotated bibliography. Tropical Forestry Papers. Series 42: Oxford Forestry Institute; 2004. 260 p. 4 ISBN 10: 0850741572
- [91] Orwa C, Mutua A, Kindt R, et al. Agroforestry Database: A Tree Reference and Selection Guide. World Agroforestry Centre, Kenya; 2009. Available from: <http://www.worldagroforestry.org/output/agroforestry-database>
- [92] Boer E. *Acacia senegal* (L.) Willd. Record from PROTA4u. In: Oyen, LPA, Lemmens RHMJ, editors. Wageningen: PROTA; 2002. Available from: <http://www.prota4u.org/search.asp>
- [93] Raddad AY, Salih AA, El Fadl MA, et al. Symbiotic nitrogen fixation in eight *Acacia senegal* provenances in dryland clays of the Blue Nile Sudan estimated by the ¹⁵N natural abundance method. *Plant and Soil*. 2005;**275**:261-269. DOI: 10.1007/s11104-005-2152-4
- [94] Sanginga N. Role of biological nitrogen fixation in legume based cropping systems; a case study of West Africa farming systems. *Plant and Soil*. 2003;**252**:25-39. DOI: 10.1023/A:1024192604607
- [95] Augustino S, Hall JB, Makonda FBS, et al. Medicinal resources of the Miombo woodlands of Urumwa, Tanzania: Plants and its uses. *Journal of Medicinal Plants Research*. 2011;**5**:6352-6372. DOI: 10.5897/JMPR10.517

- [96] Maroyi A. An ethnobotanical survey of medicinal plants used by the people in Nhema communal area, Zimbabwe. *Journal of Ethnopharmacology* 2011;**136**:347-354. DOI: 10.1016/j.jep.2011.05.003
- [97] Bruschi P, Mancini M, Mattioli M, et al. Traditional uses of plants in a rural community of Mozambique and possible links with Miombo degradation and harvesting sustainability. *Journal of Ethnobiology and Ethnomedicine*. 2014;**10**:59. DOI: 10.1186/1746-4269-10-59
- [98] Hines AD, Eckman K. Indigenous multipurpose trees of Tanzania. Uses and economic benefits for people. Working Paper. FAO, Rome; 1993. p. 276
- [99] PROTA4U Web database. Available from: <https://prota4u.org/database/>
- [100] van der Maesen, L.J.G., 2006. *Cajanus cajan* (L.) Millsp. Record from PROTA4U. In: Brink M, Belay G, editors. Wageningen: PROTA. Available from: <http://www.prota4u.org/search.asp>
- [101] Le Houérou HN. *Cajanus cajan* (L.) Millsp. FAO. 2006. Available from: <http://www.fao.org/ag/agp/agpc/doc/gbase/data/pf000150.htm>
- [102] Chikowo R, Mapfumo P, Nyamugafata P, et al. Woody legume fallow productivity, biological N₂-fixation and residual benefits to two successive maize crops in Zimbabwe. *Plant and Soil*. 2004;**262**:303-315. DOI: 10.1023/B:PLSO.0000037053.05902.60
- [103] Gathumbi SM, Ndufa JK, Giller KE, et al. Do species mixtures increase above- and belowground resource capture in woody and herbaceous tropical legumes? *Agronomy Journal*. 2002;**94**:518-526. DOI: 10.2134/agronj2002.5180
- [104] Liyanage MS, Danso SKA, Jayasundara HPS. Biological nitrogen fixation in four *Gliricidia sepium* genotypes. *Plant and Soil*. 1994;**161**:267-274. DOI: 10.1007/BF00046398
- [105] Hairiah K, Van Noordwijk M, Cadisch G. Quantification of biological N₂ fixation of hedgerow trees in Northern Lampung. *Netherlands Journal of Agricultural Science*. 2000;**48**:47-59. DOI: 10.1016/S1573-5214(00)80004-4
- [106] Danso SKA, Bowen GD, Sanginga N. Biological nitrogen fixation in agro-ecosystems. *Plant Soil*. 1992;**141**:177-196. DOI: 10.1007/BF00011316

