Chapter

Agroforestry: An Approach for Sustainability and Climate Mitigation

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Abstract

Agroforestry Systems (AFS), or the association of trees with crops (or animals), is a strategy for land management and use that allows production within the sustainable development: (a) environmentally (production environmentally harmonic); (b) technically (integrating existing resources on the farm); (c) economically (increase in production), and (d) socially (equality of duties and opportunities, quality of life of the family group). As an intentional integration of trees or shrubs with crop and animal production, this practice makes environmental, economic, and social benefits to farmers. Given that there is a set of definitions, rather than a single definition of Agroforestry (AF) and AFS, it is justified to explore the historical evolution and the minimum coincidences of criteria to define them and apply them in the recovery of degraded areas. Knowing how to classify AFS allows us to indicate which type or group of AFS is suitable for a particular area with its characteristics. The greatest benefit that AFS can bring to degraded or sloping areas lies in their ability to combine soil conservation with productive functions. In other words, AF is arborizing agriculture and animal production to obtain more benefits including climate change adaptation and mitigation by ecosystem services.

Keywords: agroforestry, agroforestry systems, silvopastoral systems, land use, tree biomass, climate change mitigation, carbon sequestration, live fences, shade trees

1. Introduction

Agroforestry systems (AFS) date back to the Mayan civilization, from 600 to 300 BC, with an apogee estimated to have lasted until 300 or 900 AC. this culture developed in the region of humid forests, but it is claimed that its agrarian system would have developed in the highlands of Guatemala until reaching the Yucatan jungle, where they practiced a pre-Hispanic style of agriculture adapted to forest management, which may well be called agroforestry [1–3]. The Mayan were poly-farmers; so that, they can be considered a culture with knowledge of land use and forest management; they used to practice a shifting cultivation system, which implies rotation of land use with periods of farming and resting the soil, and sometimes the selective logging leaving some useful trees. They farmed in small fields or clearings in the forest, and from the neighboring forest they took medicine, food, and building materials. This whole system of management of the natural forest and itinerant agriculture was based on the knowledge of the phenological cycle of certain trees. They also practiced horticulture and fruit growing in a multi-story system [4, 5].

It is estimated that in Latin America (LA) the AFS reaches an area between 200 and 357 million ha, including 14–26 million ha in Central America (CA), the most prominent are the commercial Silvopastoral Systems and the AFS of perennial crops under shade including coffee and cocoa plantations [6]. Although, these figures may have changed today given that the SPS has increased due to climate change mitigation actions and the AFS with coffee and cocoa may have decreased. An updated LA inventory of agroforestry areas would be valuable to land planners, resource managers, and decision-makers. This limits the amount of data that can be useful for multi-scale efforts.

A conceptual controversy may arise about whether agroforestry is a forestry activity or an agricultural one. Agroforestry as a concept should not be confused with other related terms, such as forest farming, which covers all the effects of forests and trees on the environment and agriculture, particularly the related socio-economic aspects. So not any kind of random combination of forest, fruit trees, ornamental trees, or service trees with crops or pastures is defined as an agroforestry system. It is also required that their combination be intentional, carried out systematically, and to produce various types of products; the system is the result of an important interaction, both ecological and economical between various types of crops; and that the system maintains or, as far as possible, improves the productive capacity of the land. There are three essential conditions to define an AFS: (1) at least two plant species interacting biologically; (2) at least one of the plant species is a tree or woody perennial; and (3) at least one of the plant species is managed for crop production (annual or perennial) or forage [2, 3, 7].

2. Historical development

One of the first documents on agroforestry in CA (CA) was possibly that of Cook in 1901 [8] who recognized several beneficial effects of shade trees, particularly legumes, on coffee plantations. Later, Holdridge in 1951 [9] described the use of *Alnus acuminata* (alder) associated with grasslands in the highlands of Costa Rica (CR). This type of land use system was also described by Budowski in 1957 [10], who reported the success of *Cupressus lusitánica* as a windbreaker, in the highlands of dairy regions and *Cordia alliodora* as a shade tree in grasslands in humid lowlands, both in CR.

According to Holdridge [11], there are three major basic land uses agricultural, grazing, and forestry, and while other human activities occupy land (such as for industrial purposes, urban developments, and transportation infrastructure), they do not directly use the soil resources in the sense of the three major uses. Agroforestry activity arises when one of the main uses, agriculture or grazing overlaps with forestry. The mixture of species with different requirements also allows an enhancement of the interception of radiation by vertical stratification of the components and better use of horizontal space [12].

Combe in 1979 [13] identified three main fields of hypotheses related to AFS within the framework of economics, ecology, and forestry.

Economic hypothesis: it is assumed that AFSs allow obtaining net income higher per unit area in the long term than the possible income with each isolated component.

Ecological hypothesis: it is assumed that trees in an AFS contribute to the conservation of the environment and particularly of the soil, especially when the induced combination represents a simulation of the types of vegetation that would occur in natural successions. In addition to the effects on the soil, important impacts on the microclimate, the fauna, and other factors that affect the biological balance are assumed.

Silvicultural hypothesis: it is assumed that the trees in an AFS can and should be managed according to the principles of classical forestry, always considering the particular requirements of the associated crops. Adequate silvicultural treatment is an indispensable condition for achieving and optimizing the positive economic and ecological results exposed in the previous hypotheses. In CA, there was a historical process, which had its beginnings with the definition of Combe and Budowski [7], presented that year in the First Workshop of Agroforestry Systems held in Turrialba, CR that can be summarized as follows:

It is the set of land use and management techniques that involves the combination of trees with crops (annual and/or perennial), with animals, or with both at the same time, in a plot, either simultaneously or successively, to obtain advantages of the combination.

These combinations can be simultaneous or staggered in time and space, and their objective is to optimize the production of the system and ensure sustained performance [7, 14].

With the creation of the International Centre for Research in Agroforestry-ICRAF (Currently World Agroforestry Centre) in Nairobi, Kenya in 1977/78, a space for discussion and analysis of agroforestry issues was established. Within this framework of internal debates, the initial ideas were refined, and a definition was agreed upon in which the criterion of "deliberate association" and that of "significant ecological and/or economic interactions between its components" was highlighted [12, 15]. In the decade of the 80s, there was agreement that agroforestry is a modality of integrated land use that seeks greater production, especially under conditions of marginal land or low level of inputs in the same area, and some cases of AFS in CA are exemplified, such as the coffee plantations or shaded cocoa plantations of *Erythrina* and *Cordia* and in turn the concept of "agroforestry practices" is introduced as operational aspects of an AFS, for example, the pruning of the trees of the system [16, 17]. Nair's definition [18] summarizes the concept as follows: "*Agroforestry is a land-use system in which woody species are grown intentionally in combination with crops or cattle on the same land, either simultaneously or in a sequence. The objective is to increase the total productivity of plants and/or animals in a sustainable manner, especially under levels of low technical inputs and in marginal lands. It involves the social and ecological integration of trees and crops*". Simultaneously, in CR, was conceptualized a complementary definition includes requirements or conditions: *"Agroforestry is a form of land use for multiple crops in which some fundamental conditions are met: (1) There are at least two components that interact biologically; (2) At least one of the components is a perennial woody; and (3) At least two species are managed for "agricultural" purposes in the broad sense of the word".* [2].

Initially, most studies in agroforestry were descriptive from a biophysical point of view, in addition, it was accepted that agroforestry was a new name for a set of old practices; but much attention was paid to socio-economic aspects [18, 19], which have been widely discussed by other authors [20], and include a great diversity of products such as wood, foliage, fruits, resins, fuel and fodder; and numerous environmental services (climatic, hydrological, soil, ecological) and human (ethical and esthetic).

Most definitions highlight the interactions among plant or animal components and their local environment and the spatial and temporal patterns of productive activities. Furthermore, open the possibility of considering and planning the social relations of production, and the interactions between communities and the outside world. Most of these aspects have been contemplated by Montagnini et al. [21, 22] in their comprehensive books on agroforestry.

3. Interactions among components in AFS

The functioning and adaptability of AFS depend on a dynamic relationship between plant species (a woody component with annual or perennials crops) and their abiotic environment (soil and water), as well as physical and chemical interactions in the environment (rainfall, temperature). These interactions and processes are of great importance for the long-term sustainability of the system. While the interactions are complex and interrelated simultaneously, they can be simplified from the point of view of the biological relationship between the two basic populations of an AFS, the woody component, and a crop; they may benefit or damage each other; or in other cases, the relationship may be neutral, all this depending on species and density of the tree component, the type of shade it produces according to the type of, type of canopy, tree crown, its branching habit, all of which have a fundamental role in AFS. After all, and since an AFS is an agroecosystem, which according to Hart [23], is an ecosystem that includes an agricultural or livestock productive component (crop populations, domestic animals, or both), an AFS can be syncretical defined as an agroecosystem with a woody perennial or tree component (**Figure 1**).

The effects of the woody component (trees, shrubs, palms, and bamboos) of an agroforestry system on soil and crops of an agroforestry system on soil and crops are very important because AF can increase farm productivity in several ways; first, the total output per unit area of tree/crop/livestock combination is greater than any single component alone; second, crops and livestock protected from the damaging effects of wind are more productive; and third, new products make the financial operations of

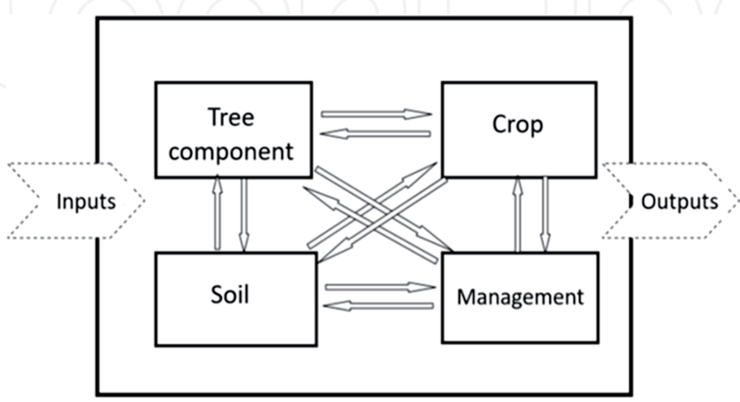

Figure 1.
Interaction among components of an agroforestry system, with limits, inputs, outputs, components, and interaction among components. Inputs are solar radiation, rainfall, fertilizers, and money invested in the system. Outputs are agricultural products, wood, and firewood from the tree component and ecosystem services. Management is what the farmer does with the components and inputs.

a small agricultural enterprise more diverse. These effects are shown both on the soil and in crops and are outlined in **Table 1**.

4. Canopy effects in agroforestry systems

The canopy is a set of crowns and branches of the trees; it is like a filter that intercepts the photosynthetically active radiation (PAR) or light that reaches the associated crops under the canopy and modifies it in quantity and quality. This interception projects a shadow, with physical effects (light/shadow, absorption efficiency, spectral modification of the transmitted light), and physiological actions are also triggered, such as photocontrol of germination, elongation of internodes, leaf expansion, and the development of the photosynthetic structure in the associated crops (**Figure 2**).

The canopy is characterized by having a structure and a floristic composition that can be managed, thus regulating the amount of shade depending on the crop's needs and the farmer's objectives. To measure the density of the agroforestry canopy, the Leaf Area Index (LAI) can be used, which represents the sum of all the existing leaf areas in a soil area. The LAI is an indicator of the canopy's ability to intercept solar radiation and predict the type of shade it produces dense, medium, or light shadow. The type of shade that the canopy produces can also be expressed in the percentage of coverage of the cups, in expressions such as 50% shade; although it is not necessarily an accurate indicator because the shadow is a dynamic process that moves on the floor of the AFS as the sun makes its apparent movement on the horizon. The position, shape, and accumulation of tree shadows, in different places and at different dates and times of an agroforestry plot, can be calculated with *software* designed in CATIE called *ShadeMotion*, which requires supplying the number of trees, location, shape, size, and density of foliage of the trees; as well as, the size of the land, degree of slope, and geographical latitude where the plot is located [24–26]. In response to shade, most plants produce less dry matter, retain photosynthates in the shoot at the expense of root growth, develop longer internodes and petioles, and produce larger and thinner leaves. The net photosynthesis (NP) of the crop increases with the Leaf Area Index (LAI) but reaches a ceiling when LAI is around 3 and could be plotted like the adjunct one attached. LAI is defined as the relationship between the sum of green leaf areas of

Effects of the woody component	
On soil	**In crops**
The leaf litter is the source of organic matter	Shade avoids excessive exposure to radiation
Nutrient supply	Intercept and mitigate wind
Improves soil structure	Attenuate the impact of rains
Controls erosion	Shade reduces air temperature
Favor water infiltration	Increase relative humidity
Limit runoff	Reduces weed dispersion
Reduces soil temperature	The positive effect of shadow

Table 1.
Effects of the woody component (trees, shrubs, palms, and bamboos) of an agroforestry system on soil and crops.

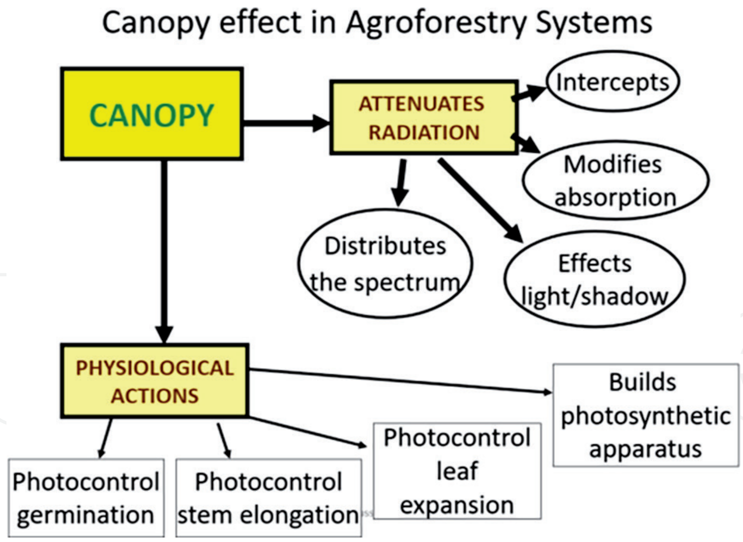

Figure 2.
Effect of the canopy on agroforestry systems.

the canopy of shade trees per unit ground surface area (LAI = Σ leaf area/ground area, m^2/m^2; in broadleaf canopies).

5. Classification and characterization of agroforestry systems

Classifying agroforestry systems including their environmental and site variants took a long time, without reaching a consensus or a global classification. In this context, ICRAF conducted a global inventory of AFS between 1982 and 1987, the results of which resulted in a classification scheme that is generally accepted today [16–18]. This inventory was designed to collect, synthesize, and disseminate information on existing AFS in developing countries. As a result of it, Nair in 1993 concluded that "*irrespective of the sociocultural differences in different geographical regions, the major types of agroforestry systems are structurally similar in areas with similar ecological conditions. Thus, agroecological regions can be taken as a basis for the design of agroforestry systems*." [18]. This project also made it possible to generate a list of the main herbaceous and woody perennial plants reported as components of existing systems and their main uses in different regions. Among the first classifications [7, 16], AFS were grouped into (a) sequential, (b) simultaneous; and (c) linear systems, according to the sequence of the tree component and the crop, and by the type of accompanying crop (annual or perennial). Sequential AFS include *shifting cultivation* and *Taungya* systems (annual crops combined in a forest plantation). In simultaneous AFS, all those combinations are grouped at the same time and placed trees with crops (annual or perennial), or with pastures; while on the live fences, hedges, and windbreaker curtains are grouped. Nair [18] made a grouping of agroforestry classifications into four groups: (1) For its structure; (2) For its functions; (3) Ecological; and (4) Based on socio-economic criteria; although, the first two have prevailed. Knowing the existing classifications allow identifying those AFS most appropriate to recover degraded areas through their restoration. However, when an AFS is used to stop deforestation and the recovery of degraded forest areas, the results may not be satisfactory unless forecasts are taken for the social welfare of the people involved. The known agroforestry classifications are hierarchical and arbitrary because the objective is defined by the user, and organized by components (trees, crops, livestock), temporal arrangements (sequential or simultaneous), and spatial arrangements, among others. Since there is a relationship between the concepts of the definition and the construction of classification, it is important to consider other aspects such as management, forestry, planting densities, establishment and maintenance costs, environmental services provided, and forest production associated with AFS, to avoid ambiguity when classifying it. Some examples of traditional AFS in CA are presented in **Table 2**.

6. Sequential agroforestry systems

Sequential AFS occurs at a site where there is a chronological succession between a period with annual crops and another with a forest component; that is, annual crops and regeneration of the natural forest or tree plantations follow each other over time. This category includes modalities of migratory agriculture with fallow management and taungya systems, where annual crops are made interspersed between rows of trees in the stage of establishment of a forest plantation until the foliage of the trees is developed (**Figure 3**).

Classification of traditional AFS	**Type of AF system**	**Example of agroforestry systems**
Sequential	Shifting agriculture	The traditional agriculture of cutting and burning trees practiced since ancient times.
	Taungya Systems	A temporary combination of a forest plantation during its initial phase, with the production of annual crops until the shade of the canopy allows it.
Simultaneous	Trees with annual crops	*Alley cropping*, rows of a woody nitrogen-fixing plant are associated with an annual crop.
	Trees with perennial crops	Growing coffee or cocoa under shade trees such as *Erythrina poeppigiana* y/o *Cordia alliodora*.
	Agroforests	Management of secondary forests, in association with one or more tree species of economic utility. Systems Quesungual o Kuxum-Rum.
	Silvopastoral systems	Association of trees with pastures and livestock. Grazing in forest and fruit plantations.
	Mixed home gardens.	Characterized by their complexity, are multi-specific, combine various forms of life and maintain production throughout the year.
Linear systems or in alignment	Live fences	Fences with live poles to which the wire is fixed and periodically pruned.
	Live hedges	A row of tree species was established at very close distances.
	Windbreak curtains	Multiple rows of tree species are planted perpendicular to the direction of prevailing winds.

Table 2.
Examples of traditional Agroforestry Systems in CA. Source: modified from Combe y Budowski [7] and Nair [16].

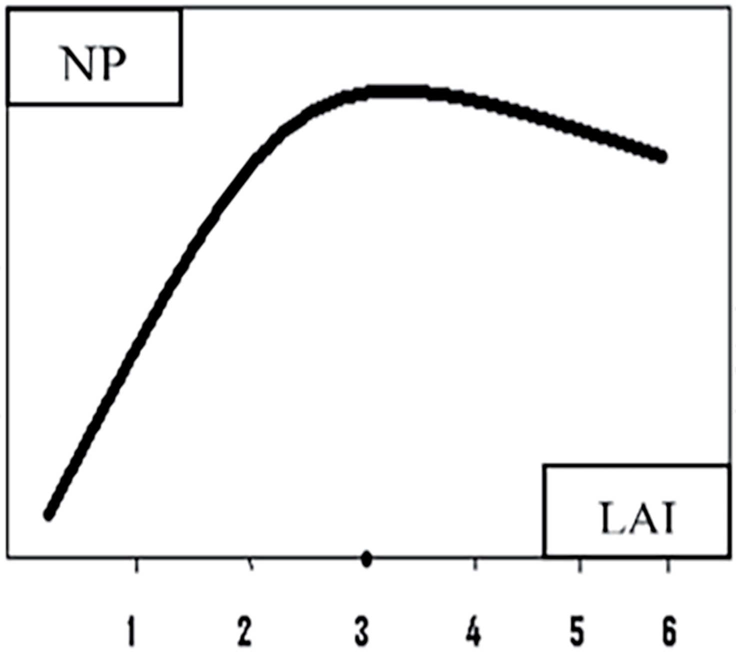

Figure 3.
Relation between Net photosynthesis (NP) and Leaf Area Index (LAI). (Russo, R. Agroforestry Course).

6.1 Shifting agriculture

The migratory agriculture also called itinerant, nomadic, or "*shifting cultivation*" is possibly the oldest of the agricultural systems and consists of the slash and burn of natural vegetation with the option of clearing the land to cultivate. On the other hand, it has been an important source of subsistence for rural populations in the tropics. Its application has varied according to the site and local conditions, but several practices are almost universal; among them is the rotation of cultivation sites or milpas (rotation of trees and crops), the cleaning of land by burning (slash-grave-burn in Mexico), the exclusion of chemical fertilizers, the exclusive use of manual labor, planting by hand and short periods of cultivation alternated with long periods of fallow. The system was developed in conditions of low population density, oriented towards subsistence, with a high concurrence of forests and simultaneous production of several crops with different harvest times. Fertility is restored through a long fallow period, and during the first production season little or no weeding is needed [27]. In addition, slash, grave, and burn fallows serve as habitats for wildlife, corridors between patches of forest and as shields against edge effects such as extreme temperatures, desiccation, and fires [28].

6.2 *Taungya* system

The *Taungya* system (TS) is a reforestation method that allows the temporary combination of a forest plantation in its establishment phase with the production of short-cycle crops, such as maize and beans, or horticultural crops (**Figure 4**). Under certain conditions, the TS works better than pure reforestation, since there is an intermediate use of the land in agriculture, which if it did not occur could proliferate weeds that compete with the plantation [17]. The word *taungya*, which means "hillside terrain" is Burmese (Burma, today Myanmar from where the system migrated in 1870). In India, that same practice was called "kumri". In Java, the TS was used to plant 40,000 ha

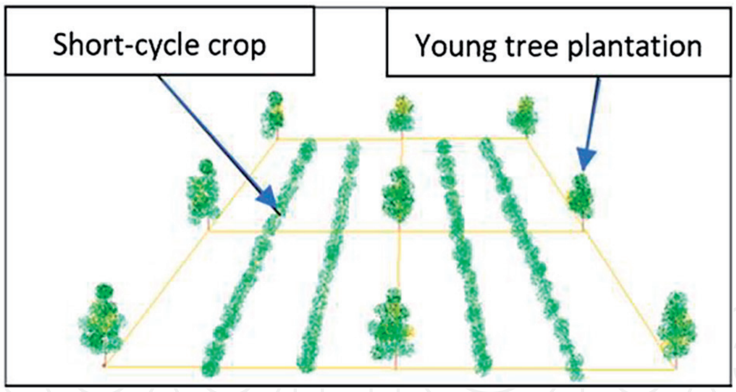

Figure 4.
Taungya system: a young tree plantation with a short-cycle crop between rows (Russo, Agroforestry Course).

of *Tectona grandis* (teak) in the late 1800s; in 1920 there was 190,000 ha, in 1952 312,000 ha and currently exceeding 700,000 ha [29, 30]. Annual crop yields in *taungya* combinations are usually lower than in pure crops, but they produce income that covers planting costs and can be considered an added value to reforestation, which would not otherwise be obtained. To be successful, TS must be applied in places where there is a need for land; soils are suitable for producing food crops with reasonable temporary yields, without causing excessive soil deterioration; tree species in demand are of proven adaptability; there is a peasant population, and local staff is trained to operate the system [27]. The TS has been very successful to establish forest plantations under different conditions. In the dry areas of what is now Myanmar, with 450–1100 mm of annual rainfall, communal forests were established using taungya systems for 2–3 years to provide firewood from *Acacia* spp., *Albizia lebbek*, *Senna siamea*, *Dalbergia sissoo*, *Melia azedarach*, *Prosopis* spp. and *Eucalyptus* spp.; and to produce pulpwood. An example is the *Gmelina arborea* plantations in Jari in southern Brazil, established through the *taungya* system; rice and beans have been harvested for 2 years in plantations of *Cunninghamia lanceolata*; rice, cotton, and corn with *Eucalyptus.* In addition, among the ecosystem benefits that TS provides, it is a restoration tool, combining afforestation actions with agricultural activity during the early stages of tree establishment, which represents an economic and social benefit, while preventing the establishment of weeds and contributing organic matter to the soil with crop stubble (**Figure 5**).

7. Simultaneous agroforestry systems

Simultaneous AFSs occur at a site where there is a simultaneous and continuous combination of an agricultural component with a forestry component, whether timber, fruit, multi-use, or service trees. These AFSs include all kinds of tree associations with annual or perennial crops, mixed home gardens, agroforests, and silvopastoral systems.

7.1 Trees with annual crops

7.1.1 Alley cropping

Alley cultivation is a simultaneous AFS of trees with annual crops, consisting of rows of trees, usually 4–6 m apart between rows x 2 m between trees, interspersed with annual crops between rows of planting (**Figure 6**). Trees are pruned before

Figure 5.
Taungya system: Left: Young plantation of Eucalyptus deglupta (eucalyptus) and Araucaria hunsteinii (klinki) intercropped with Zea mays (freshly harvested corn) between rows, in Guácimo, CR; and, Right: New plantation of Swietenia macrophyla (mahogany) intercropped with Eryngium foetidum (coriander) between rows, in Turrialba, CR. Photos: Rolando Camacho.

Figure 6.
Left: Alley Cropping of banana (Musa paradisiaca) with rows of Moringa oleifera, Caribbean region of CR; and Right: Organic banana system, rows of Musa AAA subgroup Cavendish) intercropped with a nitrogen-fixing tree (Erythrina berteroana), a timber tree (Cordia alliodora), and cocoa (Theobroma cacao), Caribbean region of CR. Photos: R. Russo.

planting and branches are left in alleys to incorporate organic matter into the soil and in turn suppress weeds. In this AFS, conveniently, the trees are of nitrogen-fixing species (Fabaceae such as *Erythrina* spp., *Gliricidia sepium,* and *Leucaena leucocephala*), mainly in soils of low fertility, where the nitrogen content (N) is low. The main intention of alley cultivation is the recycling of nutrients to maintain or increase crop yields through soil improvement, weed control, and erosion control.

Reminding that the main mechanisms of gain of N in the soil are: (a) N contributed with the rainfall; (b) N from non-symbiotic fixation; (c) N from symbiotic fixation; (d) N provided by organic fertilizers; and e) N from the mineralization process from fresh remains (vegetable and animal), in this case, the fallen leaves and branches from the trees. Therefore, this is a production system that adapts well to low fertility soils in degraded areas and to dry and semi-arid areas, since it favors the restoration of fertility and physical conditions of the soil. In addition, producers can obtain from trees other products such as poles, firewood, fodder, green manure, and atmospheric nitrogen fixation. The latter has current importance because the action of reducing nitrogen fertilization is a way to reduce nitrous oxide emissions into the atmosphere, so it is considered a way to mitigate climate change. In areas, with steep slopes, the rows of trees can be established in contour lines as a living barrier for water conservation and to deter erosion. In addition, they are a way of conserving the soil that does not require physical conservation structures.

7.1.2 Crops under the cover of forest curtains

This category includes any form of short-cycle agricultural monocultures or polycultures such as corn, beans, onions, celery, lettuce, tomatoes, coriander, and other horticultural species, in association with windbreaker curtain-like trees in windy areas, multiramified live fences, or rows of trees in contour lines in hillside areas. All these alternatives that integrate crops with the planting of trees are a form of conservation and restoration of degraded areas, which contribute to conserve biodiversity and water resources. Crops undercover, forest.

7.1.3 Trees with perennial crops

The simultaneous association of trees and perennial crops is a common practice in CA. The most prominent examples are coffee and cocoa crops under shade. The beneficial effects of shade trees, particularly *Fabaceae*, on coffee were recognized and described at the beginning of the last century [8]. Cocoa, unlike coffee, adapts to fertile inshore sites (from 0 to 700 meters above sea level); while coffee is a crop in higher areas. These AFSs with shading trees are more sustainable alternative to perennial monocultures because they give added value in terms of diversifying production, providing habitat for greater biodiversity, favoring soil conservation, and serving as protection of water resources. All these elements are important when contemplating the recovery of degraded areas.

7.1.4 Coffee and cocoa plantations under shade

These systems simultaneously combine trees with perennial crops, such as *Coffea arabica*. The main crop is interspersed with the trees that contribute with environmental services, additional products, soil improvement, microclimate beneficial to the crop, and serves as a tutor or support for vine crops such as *Piper nigrum* or *Vanilla planifolia*.

Coffee (*C. arabica*): Shaded coffee is perhaps the oldest and most important crop, as it is estimated that it covers seven hundred thousand hectares in CA, of which more than 80% are AFS and most of it is grown by small-scale farmers on farms no larger than 5 ha [31–33]. Permanent shade trees can be timber (*C. alliodora*, *Cedrela odorata, Swietenia macrophyla, Dalbergia retusa*, *Tabebuia donnell-smithii*, *Schizolobium parahybum, Grevillea robusta*, also*, Terminalia amazonia*, *Gmelina arborea, Eucalyptus* spp., among others; also fruit trees (*Citrus* spp., *Inga edulis, I. vera, Persea americana*, *Macadamia* spp., *Psidium guajava*), or multipurpose trees (*Erythrina poeppigiana*, *E. fusca*, *Gliricidia sepium*; *Leucaena leucocephala*), *among others* (**Figure 7**) Also, the temporary shade of banana and plantain (*Musa* spp.) is in the early stages of the establishment of the system. In all cases, shade trees play an important role, in light regulation by the various layers or strata of crown trees. Aspects such as planting densities of shade trees, and regulation of shade by pruning or pollarding of branches have sound importance; given that coffee cultivated under excessive shade produces fewer coffee grains and increases in production can be favored with the management

Figure 7.
Left: A coffee plantation (Coffea arabica) shaded with a nitrogen-fixing tree (Erythrina poeppigiana) just totally pollarded, in Tres Ríos, CR; and Right: View of a coffee crop associated with Eucalyptus deglupta located in Juan Viñas, CR.

of the shade, through pruning of the trees, which allows air circulation and greater penetration of light [34]. A coffee AFS with shade trees of *E. poeppigiana* annually pollarded (pollarding is the pruning of all branches at a certain height of the tree trunk) located in Tres Rios, CR and a SAF of coffee associated with *Eucalyptus deglupta* located in Juan Viñas, CR, are presented in **Figure 7**.

Cocoa (*Theobroma cacao*) farming in CA is practiced by small farmers extremely poor (indigenous people, Afro-Caribbean, and mestizo), living in remote zones. Cocoa is cultivated at 100–800 m altitude in small plots (1.2 ha/farm) with low yields: 75–150 kg/ha/year in zones with frosty pod rot (*Moniliophthora roreri*) and with poor management; and 200–350 kg/ha/year where there is frosty pod rot and minimal management (**Table 1**). Cocoa trees are typically spaced at 4 × 4 m (625 plants/ha) in most countries. Most farmers have two or more cocoa plots per farm. Cocoa trees are 4–6 m tall and are associated with shade trees at a density in the range of 85–166 trees/ha. Most shade trees are planted, and some species are selected from the natural regeneration. Shade trees are used for timber (*Cordia alliodora, Cedrela odorata*), fruit (*Musa spp., Citrus spp*., avocado (*Persea americana*), coconut (*Cocus nucifera*), peach palm (*Bactris gasipaes*), mango (*Mangifera indica*), and shade providers (*Inga* spp., *Gliricidia sepium*). Shade tree canopies usually have three vertical strata (low <10 m, medium 10–20 m tall, and high >20 m tall) [35, 36].

7.1.5 Agroforests

The concept of agroforests, despite being traditional systems, has been incorporated more recently into the definitions and classifications of FAS. Agroforests are areas with a predominance of trees and shrubs or communities that resemble forests, where there are plots or clearings with agricultural practices along with structures typical of natural forests due to their floristic composition and their multiple stratifications. An example is the so-called *Quesungual* agroforestry system (SAQ), or *Kuxur Rum*, an agroforestry modality that was practiced ancestrally by the Mayan cultures and is still carried out in some regions. This system is reported to be practiced in countries such as Guatemala, El Salvador, Honduras, and Nicaragua. It consists of pruning selected trees in an area of natural forest (usually secondary) up to the middle of the trunk, without damaging the roots, and planting corn in the clearings or gaps with greater solar radiation [37]. It should be noted that in the case of Honduras, after Hurricane

Figure 8.
Cocoa (Theobroma cacao) agroforest in rehabilitation with a shade of numerous tree species, Changuinola, Panama.

Mitch, in the areas where SAQ was practiced, such intense damage was not observed. Studies carried out in southeastern Honduras, on hillside land with slopes greater than 12% (approximately 80% of the country's area); have shown this system reduces the vulnerability to climate change of smallholder subsistence farmers, and that it has great potential to improve livelihoods and help to adapt climate changes on tropical slopes; it is a good option to mitigate greenhouse gases, and in turn, it performs other services for a better sustainable agricultural use [38]. Other examples are cocoa agroforests in the area of the binational Sixaola River basin between CR and Panama (**Figure 8**).

7.1.6 Silvopastoral systems

Silvopastoral Systems (SPS) are agroecosystems in which a tree component is deliberately associated with an herbaceous one (natural or improved pastures) and a livestock production component (domestic animals) in the same site so that there are biological interactions between both to maximize the land use. In other words, they temporarily and spatially combine the maintenance of pastures (natural or cultivated ones) with livestock production activities, along with tree species. To this the silvopastoral practices can be added, in which the woody component does not need to be in the same site as the animal component because forage can be transported; such as the case of forage banks or living fences, which are pruned, and the forage produced by the pruning is supplied to confined animals [39, 40]. The limits, inputs, outputs, components, and interactions are shown in **Figure 9**. Silvopastoral systems found most frequently in CA are: (a) trees in pasture lands, including grazing in secondary forests and fallows; (b) grazing in forest and fruit plantations; (c) living fences; (d) perimeter shelterwood; and (e) fodder banks or crop and utilization of forage trees and shrubs. Tree species identified in pasture lands in CA are diverse and are according to the characteristics of vegetation, climate, and altitude of each region. In most cases, the trees are from natural regeneration and have been allowed to grow in densities that do not affect pasture growth, in a range from 10 to 70 trees per hectare but can reach up to 100 trees; with a basal area (BA) ranging from 1 to 7 m^2/ha, although some authors mention that is possible to have up to 200 trees/ha [42]. Among the most frequent tree species found in animal production systems is *Cordia alliodora, Cedrela odorata, Enterolobium cyclocarpum, Pithecolobium saman,*

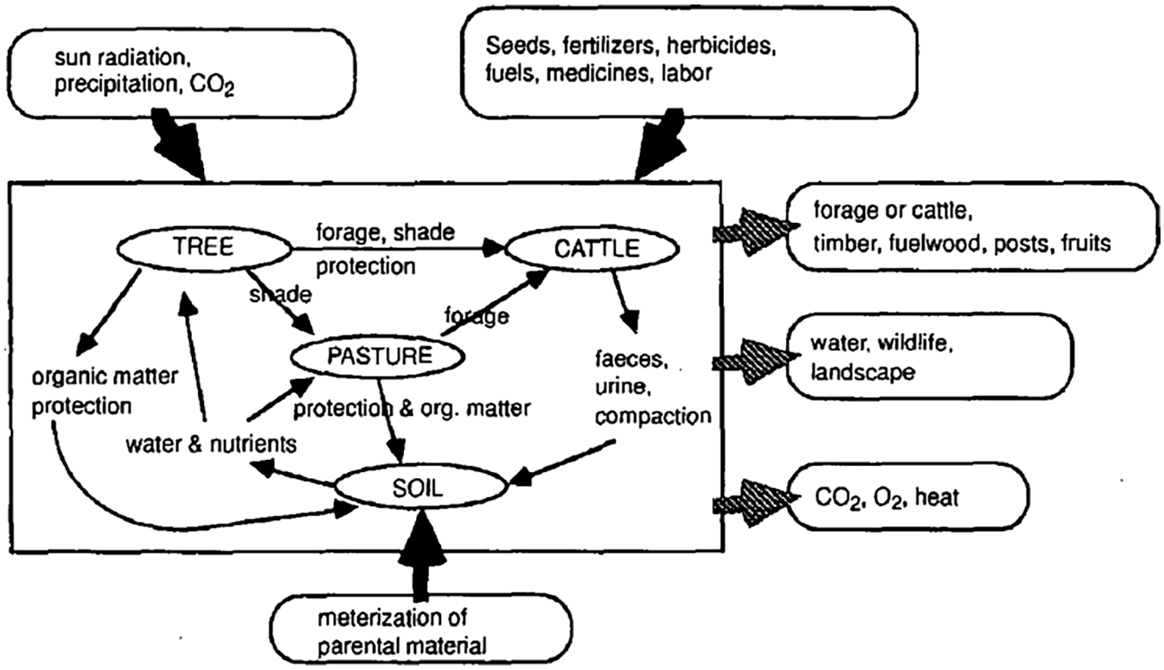

Figure 9.
Interactions in a silvopastoral system. Source: taken from [41].

Guazuma ulmifolia, Tabebuia rosea, Pterocarpus rohrii, *Pentaclethra macroloba, Mangifera indica*, *Gliricidia sepium* in the lowlands (up to 600 masl); and *Citrus* spp., *Platymiscium dimorphadrum, Persea americana, Inga* spp., *Psidium guajava*, *Bursera simaruba, Brosimum alicastrum, Alnus acuminata;* in midlands and uplands (600–2000 masl).

8. Linear agroforestry systems

Linear or alignment systems are tree plantations in rows of one, two, or more rows, such as live fences, hedges, living barriers, tree, and shrub lines (timber, fruit, multi-use), and windbreak curtains, usually associated with an agricultural crop or grasslands. They are useful especially on small farms because they offer many opportunities for the production of goods and services of interest to the farmer and are one of the most commonly promoted agroforestry technologies in forest and agroforestry extension and development programs in CA [43, 44].

8.1 Live fences

A living fence is made up of live poles in a row of trees or shrubs that delimit a property, or you can divide or parcel it out internally. Depending on the species used, it can produce firewood, wood, fodder, flowers for honey, fruits, and poles among others. They are very common in the countries of CA and one of their most important functions is the delimitation of farms, or paddocks (**Figure 10**). The most commonly used tree species as living poles are *Gliricidia sepium, Bursera simarouba, Erythrina berteroana, E. costaricensis, Spondias* spp., *Mangifera indica, Ficus isophlebia, Pochote quinata; Delonix regia*, *M. indica*, and *Simaruba glauca*, among others. The fences can be established with a single species (mono-specific), or with more than two species (multi-specific) [43–45].

Figure 10.
Left: Mono-specific living fence with Erythrina berteroana poles in Sarapiquí, CR; Right: Multi-specific living fence in Bonanza, Nicaragua.

8.2 Windbreaker curtains

A windbreaker is a linear tree plantation, which forms a barrier, to mitigate the negative effects of winds and regulate microclimate conditions, which consists of spinning multiple lines of trees, established perpendicular to the direction of the prevailing winds. They are included in the AFS when they are associated with an agricultural or livestock production system. The trees are planted in several parallel rows, and the protection depends on the height of the curtain and the compactness of the tree crown to stop the wind. It is generally accepted that a windbreaker curtain provides services and benefits to agricultural establishments. In addition, a well-managed curtain also produces timber and fuel wood. Several aspects must be considered for the design of a curtain, among them are (a) Orientation; (b) Distance between trees and between rows of trees; (c) Density; and (d) Height of trees. The height of the curtain trees is the most important factor to consider in your design, as it determines the area it protects. The maximum wind mitigation distance of a curtain varies between 15 and 20 times the height of the trees. That is, if a curtain is 10 m high, it will protect up to a distance of 150–200 m. For instance, in León, Nicaragua, curtains of three strata and five lines of *Eucalyptus camaldulensis, Leucaena leucocephala,* and *Tecoma stans* were established to protect the soil in cotton (*Gossypium hirsutum*) fields during the dry season [46]. In CR, the cases of curtains of *Cupressus lusitánica*, from Mexico are known in high altitude areas of the Central Valley in the provinces of Heredia and Cartago (personal observations] (**Figure 11**).

9. Attributes and characteristics sought in agroforestry systems

There are desirable attributes and characteristics of AFS in different aspects: (a) As for the selection of the woody species, keep in mind that it is easy to establish and grow quickly; (b) Regarding the architecture, phenology, and compatibility of the woody species with the associated crops, it is desirable that they make little competition for water and nutrients; that they have an open and narrow crown with small leaves; that they have a strong root system and as far as possible deep; no allelopathic effects; with branches and stems that are not brittle and that do not host pests or diseases. (c) Regarding the management and physiology of the woody component, it

Figure 11.
Left: Windbreaker curtain of Cupressus lusitanica (cypress) associated with horticultural crops in Ochomogo, CR. Right: Agroforestry landscape of windbreak curtains associated with horticultural crops and pastures, Cartago, CR.

Attributes	Desirable characteristics of agroforestry systems
Productivity	The system produces goods, merchandise, and services required by producers
Sustainability	Maintains or increases productivity over time: producing while preserving and conserving producing
Adoptability	It is accepted, even under socioeconomic and biophysical constraints prevailing locally

Table 3.
Desirable attributes and characteristics of agroforestry systems. Source: Modified from [47–49].

is desirable that: they tolerate full exposure to the sun; have self-pruning of branches; tolerate frequent pruning; regrow easily; be easy to handle (without thorns or stinging latex); and that if possible, fix nitrogen. (d) As for ecological functions, they are desirable attributes that have functional biodiversity and promote biological control; provide habitats for avifauna and other non-harmful animals; encourage soil conservation and fertility and maintain foliage in the dry season. The main three groups of attributes and characteristics (**Table 3**) that farmers expect from an AFS are (a) productivity; (b) sustainability; and (c) adaptability [47–49].

10. Current trends in agroforestry

At present agroforestry has become a significant issue in scientific research because the human face new challenges to ensure food security and climate change mitigation. The research interest in the field has boosted, and about 139 countries have been involved with the research in the field of AF and connected topics. These publications cover 66 subject categories and a great diverse research theme. The most used keywords in AF research have been changed from "Intercropping", "Alley cropping", and "Multipurpose trees" to "Carbon sequestration", "Ecosystem service", and "Climate change" [50, 51]. Other topics like Small-island agroforestry in climate change and sustainable development goals have been developed [52]. Also, extensive analysis and proposals to face the challenges of the new millennium by first-line researchers, covering topics of Biodiversity Conservation, and Food Sovereignty, Climate Change have been brought together in a work of vast value for researchers and students [53].

11. Conclusions

Agroforestry systems are a viable option to reduce land degradation and generate income for rural families. However, due to the cost structure and the return period, technical and financial assistance (payment for environmental services) should be considered for the adoption and empowerment of these systems to be successful in the long term. CAn farmers are familiar with a set of traditional AFS, including shaded coffee, shaded cocoa, silvopastoral systems (SSP), and row trees.

The different modalities of the AFS allow the diversification of family farming, the sale of surplus production, and the efficient use of the natural resources of the farm (water, land, biodiversity, energy); factors that are linked to the degree of development of the peasant economy and that would allow more comprehensive productive, food, and nutritional schemes. Due to the similarities in their structure, energy flows, and nutrient cycles with natural forest ecosystems, AFS is considered to be an alternative for ecologically sustainable use for climatic zones where natural vegetation is a forest.

Agroforestry systems, whether traditional or innovative, allow the development of strategies for the maintenance of productivity based on the regulation of nutrient recirculation through the choice of species, planting densities, and the management of canopy shade on crops through pruning. All this makes it possible to maximize income and minimize the loss of nutrients from the soil.

Although the advantages of the tree component (trees, shrubs, palms, and bamboos) are always highlighted, there can also be negative effects on crops and soil when planting density and shade are excessive and when the choice of species is not the most appropriate.

There are ancestral agroforestry modalities (*Quesungual* or *Kuxum-Rum*) that are very appropriate for tropical areas with a dry season and the recovery of degraded areas. Indigenous peoples and local communities (IPLC) own or manage a considerable area of existing forests in the CA region; consequently, they are related to agroforestry practices comprising subsistence crops such as maize, beans, bananas, plantain, and cocoa, managed through low-impact concepts and combined in agroforestry systems; where multiple crops are mixed with timber trees, and with permanent crops such as cocoa, they offer a different vision of what agroforestry systems and the ancestral management of the natural forest should be since they develop a sustainable production in which the soil is never left uncovered. After all, Agroforestry is a form of productive restoration of degraded areas because it improves soil fertility, increases resilience to climate change, and provides alternative sources of income to local people.

Agroforestry is part of the concept of the Nationally Appropriate Mitigation Action (NAMA) mechanism, which is based on a combination of public and market incentives for the implementation of greenhouse gas (GHG) mitigation measures. An example is the NAMA for the coffee sector of CR, which constitutes a broad platform for coordination and participation of the sector together with governmental, non-governmental, and international cooperation entities, covering an area of more than 90,000 hectares and 50,000 producers, for the improvement of competitiveness (cost savings and diversification of the coffee agroforestry system), and seeks at the same time the differentiation of the sector maintaining its access to markets and contributing to a low emission economy.

In a brief summary of the above, Guatemala has experiences and achievements in community forest management, with more than 20% of forests managed communally or municipally (380,000 hectares managed sustainably by community concessions in Petén); in Panama, 54% of forests and carbon are in indigenous territories and indigenous peoples organized under the National Coordinator of Indigenous Peoples of Panama (COONAPIP); Nicaragua has interesting approaches in the Autonomous Regions (21 titled territories with more than 3.6 million hectares, which are more than 62% of the forests in North and South Atlantic Autonomous Regions (RAAN and RAAS); in Honduras, more than 400,000 ha are in the hands of communities since the Forestry Law of 2007, there is titling of seven territories and 760,000 ha in the Mosquitía; while in CR, indigenous peoples, who constitute 2% of the population with 12% of the forests in the country, have Indigenous Development Associations (ADI) and from these rights the Payment of Environmental Services (PES) was established in indigenous territories with institutions consolidated by the National Forest Financing Fund (FONAFIFO).

Finally, Agroforestry is a possible alternative to receiving payment for the environmental services (PES) they produce. In the case of CR and Guatemala, there exist formal PES programs that incentive agroforestry; promote the incorporation of trees in agroecosystems; as an alternative for the recovery of forest cover, income generation, and also as a means for the reduction of greenhouse gas emissions. Honduras and Panama provide environmental services in their legislation, and Dominican Republic is in the process of formally implementing PES. In the case of mixed crops involving timber trees, it will undertake to increase and/or reorder the number of trees and reduce the impact of the crop on soils and waters and that its activity coincides with the capacity of land use; in addition, they could constitute an opportunity to strengthen the processes of conservation, sustainable use and poverty reduction in the CA region.

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I dedicate this review to the memory of Dr. Gerardo Budowski (1925–2014) with whom I was introduced to the concepts of agroforestry; also, to my colleagues in my initial experience (1981–1986) at The Tropical Agricultural Research and Higher Education Center (CATIE), where I took the first steps into this multi-disciplinary field that combines agriculture with forestry and livestock activities.

Conflict of interest

The author declares that the literature research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest, and without external funding.

Comments

The apparent limitation of the study would be that the author cited mainly old literature, but the author felt that the pioneering work of the researchers who laid the foundations of the AF both in the New and Old World could not fail to be recognized. However, it is recognized the mutual importance of both the pioneering and current researchers of these sustainable cultivation technologies.

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