FUNCiTREE

REPORT

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1 Executive summary

Based on tree attributes, FUNCiTREE has addressed the functional roles of trees in the Sahel and dryland regions in Central America based for the design of locally adapted multi-functional agroforestry. In these regions, farmers are heavily dependent on trees in agroforestry, natural dry forests and savannas to provide them with dry season fodder production, shade provision, soil stabilization, soil fertilization, food and fuel production, and the potential for adaptation to climate change. However, agroforestry technologies proposed are often based on a small number of widely disseminated tree species, reducing the stability and adaptability of these systems to climate uncertainty and impoverishing the diversity of uses the farmers make from the trees.

Do trees enhance or reduce pasture productivity? Two distinct patterns have emerged when comparing the sites in Nicaragua and the Sahel. Trees in Nicaragua appear to have varying, but consistent negative effects on grass productivity, particularly during the rainy season when forage production is probably not the major production constraint. In contrast, the effects observed in Senegal are generally more positive. Whether the effects are positive or negative, is associated with site productivity, and in agreement with ecological theory that predicts more facilitation of trees on grasses with higher environmental harshness. This knowledge is critical for the design of agroforestry system in sub-humid and dry areas because whether the effects of trees on grasses and crops are positive or negative will determine different roles of trees in the farm.

Strategies of water use and adaptation to climate seasonality. Common trees in the agroforestry systems in Central America and the Sahel mainly rely on soil water stored in intermediate (<0.5 m) to deep (1 m or deeper) soil layers during drought periods, but the trees change soil water sources between seasons. Water sources are usually shallower in the rainy- compared to the dry season. Stable isotope analyses permitted to explore the mechanisms of how the trees in these areas control water loss. They indicate that despite differences in water availability, trees in these areas have the capacity to affect more strongly the processes involved in the water cycle (the amount and source of water absorbed and transpired), than the carbon cycle (the amount of atmospheric CO_2 captured). This knowledge is important to understand and model hydrological and bio-geochemical cycles, and the changes that may occur with shifts in the climate and in the composition of trees if agro-sylvo-pastoral systems.

Trees for cattle feed In all sites, interventions need to focus on dry-season forage which remains one of the most limiting factors for mitigating the effects of seasonal droughts in the region. Particularly in the Central American site, the role of trees as providers of forage in the dry season appears to be undervalued. Particularly in Nicaragua, species that farmers suggested had little forage potential were both found to be nutritious as well as preferred by livestock. This finding opens opportunities to explore new roles of trees in these systems. Also, the combination of species enhances overall nutrition value, and trees and shrubs with different characteristics suit in a different way cattle and goats.

Communicating functional diversity. The three sites have conducted field trials and promoted tree planting with particular aims adapted to the local context and needs. In Senegal and Mali the activities were planned in cooperation with the Millennium Villages Programme and integrated within their out-reach activities. In Senegal the focus is on the production of a variety of foods, forages, firewood, timber and many other products for domestic use. In Mali, the activities are based on tree production techniques of a diversity of species, and the plantation and the management of the plants by the farmers. A second activity is a program of restoration of degraded agroforestry parks through Assisted Natural Regeneration. In Nicaragua we have demonstrated how multi-functionality in paddocks can be enhanced, and have used participatory scenario modelling of farm multi-functionality based on the production preferences of farmers.

2 FUNCiTREE context and objectives

Modern agro forestry systems (AFS) are evolving due to the need to increase the productivity, stability, and adaptability of small and medium farmers in seasonaly-dry landscapes. To meet these goals, a portfolio of regionally available tree and shrub species whose functional cultural, ecological, and production traits are known is critically needed.

Cattle farmers of both semi-arid Sub-Saharan Africa and dryland regions Central America are faced with similar problems, particularly ensuring sufficient forage availability during prolonged dry seasons, and decreasing their vulnerability to climatic uncertainty. In both Sub-Saharan Africa and Central America, farmers are heavily dependent on AFS to provide them with a variety of services ranging from dry season fodder production, shade provision, soil stabilization, soil fertilization, food and fuel production, biodiversity conservation, and now adaptation to climate change. However, the majority of recommended AF interventions or improvements are based on a very small number of widely disseminated tree species, reducing the stability and adaptability of these systems to climatic change and uncertainly. Designing modernized AFS with built in resilience to climate change requires not only of the production needs of farmers, but also necessitates a strong working knowledge of the relationship between the attributes or traits of individual plant species and the capacity of these species to provide specific AFS functions.

FUNCiTREE proposed that species should be understood by their attributes or traits, including those related to drought tolerance and water use efficiency. Farmers should be able to review a portfolio of locally available species, and to select species based on their capacity to perform specific, or multiple functions. The specific objective of FUNCiTREE has been to understand how the traits of AFS trees can be arranged and managed to maximize the provisioning of critical farm level ecosystem functions including increased productivity, increased resistance to drought, and increased adaptability to climate change. Specifically, we proposed a portfolio approach where tree species are classified functionally, based on their capacity to provide specific management needs (functions), including drought tolerance and water use efficiency in dry conditions, competitive interactions with under-storey vegetation, and palatability and fodder value for livestock. We anticipated that this trait-based approach will permit the selection of species, or of particular combinations of species suited to local conditions, and more importantly to the specific management needs of the cattle farmer in question. When a single function is desired, a single species may be best suited to provide that function, however when multiple functions are desired from AFS, there is little doubt that multi-species assemblages with specific trait assemblages will be more effective. In addition, climate uncertainty in conjunction with other human-induced environmental changes calls for the maintenance of a broad resource base to face uncertainty and buffer periodic variability.

FUNCiTree has explicitly focused on the traits of native plant communities and have argued that introductions of exotic species may not be necessary. Species introductions are commonly an alternative to improve agroforestry (Maranz et al. 2008) and other managed ecosystems. Introduced species may have several advantages, such as higher growth rates and other desirable attributes (Maranz et al. 2008). Introductions can have a considerable potential for evolutionary adaptation to new conditions (Siemann & Roger 2001, Wang, D'Eon & Dong 2006), but can also be problematic in various ways. Rapid adaptation to new environments is probably not common in all species (Franks et al. 2008) and poor adaptation may lead to lower performance and increase risk for pest outbreaks since there is a correspondence between pest attacks and other stress factors (Rolland & Lemperier 2004). Furthermore, promoted exotic species may have lo capacity to adaptation to harsh environments, unless growing under controlled conditions (such as in research stations and pilot farms). Massive plantation of a single species further increases the risk for pest outbreaks. Additionally, genetic attributes that confer rapid adaptation appear at the same time to be related to the degree of invasiveness of the introduced species (Prentis et al. 2008). Therefore, the primary focus of FUNCiTree has been the native species pools, althought well-established introductions and species with unique capacities to perform particular functions have been considered in the functional assessment.

2.1 Why Plant Functional Traits?

The field of functional ecology opens new avenues to explore the question of indicators of ecological function in AFS. The approach aims to characterize species according to traits that correspond closely with eco-physiological functions such as those involved in carbon and nutrient acquisition in plants. Exploring eco-physiological similarities among species enables to identify emergent properties in species that can be linked to particular responses to the environment, for example strategies to cope with drought and/or nitrogen scarcity. Furthermore, these traits are often linked to specific effects on other organisms, through food webs and through changes in bio-geo-chemical processes that affect, for example, carbon storage and nutrient mineralization and availability in soils, all of these with a clear bearing on the provision of ecosystem services. Although currently most of the focus in this field has been on traits as indicators of plant persistence and recruitment, the approach has been applied to other problems, for example the functional characterization of pollinating insects and of river sediment micro-fauna. By analogy, and widening the scope in the approach, the relationship between structural characteristics of organisms and/or organism groups, and particular functions of AFS with importance for farmers can be explored. The trait-based approach proposed by FUNCiTREE has permitted to enhance the understanding of synergies between the multifunction components of agro-forestry systems including the relationship between ecological and cultural classifications of trees by traits. The research has modelled how specific trait combinations (species combinations) can maximize the provisioning of multiple functions including soil, production, animal nutrition and conservation functions.

The focus on functional traits of trees and other forage plants also enables the identification of commonalities and differences between adopted agro-forestry systems worldwide and therefore enables to explore the potential for the transfer of agro-forestry technologies, practices and recommendations across areas within a region and among ecologically similar areas across continents. The main research objectives of FUNCiTREE are related to plant functional traits (PFT's and farmer adoption of AFS include (1) the identification, analysis and characterization of the main factors influencing the adoption/non-adoption of agro-forestry in arid regions of Central America, and the Sahel in Africa; (2) identification of universal farmer selected traits for use in semi-arid AFS ; (3) elucidation of the relationship between specific species level traits and farmer decision making; and (4) understanding of the primary agro-ecosystem functions that farmers consider when making management decisions on the adoption or lack of adoption of an AFS.

2.2 Why South-North-South Collaboration?

Latin America and Sub-Saharan Africa have experienced distinct development trajectories due to a variety of factors including, the severity of the climate and an increasing pressure on the natural resources in Africa linked among other factors to uncertainty in land-tenure regulations. However they share similar environmental and production challenges. By focusing on a South-North-South collaboration, the shared experiences between the two regions can be used for the advancement of both regions. South-North-South collaboration has permitted us to focus on shared barriers, and solutions but also on the areas where region-specific constraints need to be attended. For example, the difference of organisation in production systems particularly in land-tenure: private against collective with different kinds of rights for the use of trees. The South-North-South collaboration is particularly interesting in light of the focus on plant functional traits, rather than on specific species. The focus on the trait-ecosystem function relationship in two continents permits to make management proposals that use tree species with shared traits, but that are native to the region. At the same time, regional differences in eco-physiological tree traits are likely indicators of different adaptations to clearly dissimilar environments and growth conditions. The cross-continental comparison is the back-bone of the contrast functional vs. species diversity hypotheses, which is the most essential and novel agro-ecological contribution of the study and adds a higher degree of universality to the study.

2.3 The sites

FUNCiTREE has worked in three focal sites, two in sub-Saharan Africa and the third in western Nicaragua. The two African sites are Tiby, Mali and Potou, Senegal. All three sites are characterized by their semi-arid to sub-humid environment, with a distinct dry season of three months or more between the months of October and April. Climate models predict that the severity and length of the dry season will increase with the impact of climate change. The dry season is also one of the primary barriers to sustainable production and food security in the three study areas. Agro-forestry systems of the three sites include a strong livestock production component. The two African sites are designated Millennium Villages (http://www.unmillenniumproject.org/), a collaboration between the Earth Institute at Columbia University, USA with the United Nations Development Programme (UNDP) and the UN Millennium Project.

The Potou, Senegal MV cluster includes a population of 30,000 residents and is located at the northern west of Senegal. The cluster consists of two zones: the Niayes zone, bordering the maritime fringe and the continental Diéri zone. Among the MVPs, the Potou cluster represents the coastal-traditional fishing farming system, where the majority of the inhabitants practice agriculture (96%), including a strong dependence on livestock production (60%). The Niayes zone is characterized by a succession of dunes and depressions where market gardening is undertaken. The vegetation of Potou is Sahelian parkland. Deforestation, overexploitation and natural disasters including drought events and desertification have all contributed to shaping the vegetation of the region.

The Tiby, Mali MV cluster encompasses 55,000 residents, and is located in the southern region of Segou. The combined effects of high human and animal population, exploitation of natural resources (foods, fuel, fodder, shelter, etc), and unfavourable climatic conditions, have put the soils under unprecedented pressure. The naturally poor soils have been further impoverished through nutrient extraction. The vegetative cover has seriously declined since the early 1970s, resulting in a loss of soil fertility and agricultural productivity. More than 75 percent of the villagers are subsistence farmers, growing mostly rain-fed sorghum and millet cereals with low yields—between 500 and 700 kg/ha.

Rivas, Nicaragua is located in western Nicaragua but faces many challenges similar to the African sites. The local population is dedicated to agricultural production and livestock production with pastures occupying more than 60% of the landscape. Though the landscape was historically comprised of continuous forest, less than 10% of the landscape remains in forest cover. The elevation oscillates between 100 to 200 m.a.s.l. The main economic activities are agriculture (sugar rice, beans, maize, wheat, cane and bananas) as well as dual purpose cattle ranching (beef and dairy). The pastures of Rivas are largely degraded as a result of over-exploitation and unsustainable land use.

2.4 FUNCiTREE objectives

The overall objective of FUNCiTree was to improve the understanding of the socio-cultural, economic and ecological characteristics of AFS in order to expand and improve the practice of socio-economically and ecologically sustainable livestock production in marginal seasonally-dry areas. FUNCiTREE specifically:

1. Assessed the commonalities and differences of socio-cultural and economical causes for adoption/non-adoption of agro-forestry practices in 3 semi-arid areas in Sub-Saharan Africa and Central America.
2. Assessed farmer perceptions of the AFS tree traits and the services provided by them.
3. Identified and quantified AFS tree ecological functions based on tree functional traits, and the synergies and trade-offs among them.
4. Produced a cross-regional synthesis of functional trait portfolios and modelling of modern multifunctional AFS based on tree functional diversity in relation to local and household needs.
5. Established the socio-economic implications of the adoption of tree functional portfolios at the household and local scales.
6. Developed demonstration sites of AFS tree functional portfolios utilizing existing participatory frameworks for the improvement of AFS technologies.

3 Main FUNCiTREE results

3.1 The benefits received from agro-silvo-pastoral trees

FUNCITREE gathered and analysed the different benefits or the ecosystem services that the rural communities in Rivas, Potou and Segou, receive from by the tree cover in pasture lands, and compared this benefits across a range of farming conditions. The extent to which agroforestry systems (AFS) provide ecosystem services depends on local context and management practices. There is a paucity of information about how and why farmers manage their farms in the way that they do and the local knowledge that underpins their decisions.

Farmers were presented with the regional species pool and were asked to make general comments on these species with a particular focus on the traits of the species and their perception of the functions in the farm and the benefits obtained. Through a series of semi-structured interviews, farmers were asked to describe the capacity of these species to provide benefits. During the interviews, farmers were encouraged to describe the reasons for which a species is well-suited or not for the provisioning of specific services. At a second stage, the relationships between locally important species traits and the capacity of the species to provide specific services were identified, and species were clustered by traits. Traits that farmers consistently identify as being related to the capacity or inability of a species to provide a particular service were highlighted.

A total of 429 species were identified in the local species pools (146 in Potou, Senegal; 220 in Tiby, Mali and 193 in Rivas, Nicaragua. Of the total number of species potentially found in the three case study areas, 11 of them were present in the 3 sites. The proportion of common species between the 2 sites in the Sahel is 39%, which is not surprising as the ecological conditions and the floras of the two sites are quite similar. Common species between the site in Rivas, Nicaragua and the two African sites is much lower, i. e. 6% with Potou and 5% with Tiby, respectively.

In Rivas, farmers ranked the importance of the products from the trees, such as timber, firewood, and human-edible fruit, but they had also detailed knowledge about how trees affected regulating ecosystem services such as soil formation, erosion control, provision of wildlife habitat and water conservation. Links between trees and biodiversity, and micro-climate regulation were understood; based on these stated preferences, species could be classified according to their role in both provisioning and regulating services. Farmers valued trees with multiple functions, such as *Enterolobium cyclocarpum* and *Albizia saman*.

In the Sahel trees play very important and diverse functions as well. They provide a variety of wood and non-wood products, with significant impact on people's lives but the intensive exploitation of timber resources and the lack of tree regeneration have led to a degradation of agroforestry parklands for years. The socio-economic analysis in Segou emphasizes a wide variety of uses of the trees. In addition, the same species does not fulfil the same functions for all user groups (farmers, pastoralists and women) and also uses vary with the environmental and socio-economical contexts (activities, knowledge, means and practices). The surveys reveal common perceptions between farmers of certain functional traits linked to strategic functions, but also of specific knowledge associated to the farmer's activities.

From the analysis of joint data from Rivas and Segou, we find some important differences and similarities between the sites. For instance in Rivas, the uses that the farmers make of the trees was rather similar across the whole population; although the producers that have had direct contact with extension services had more knowledge regarding fodder banks, cattle nutrition, and milk production. An important message that emerges from the studies in the Sahel is that the use of trees by the different social groups is the large variety of benefits that local communities derive from the trees. Regarding production functions, the number of species involved in the two sites for each production function is similar except for income, pharmacopeia and other uses (domestic, religious) with none or very few species being used in Rivas. With respect to service functions, farmers in Rivas mentioned fewer species except for live fences and biodiversity conservation which might show more specific uses and more awareness in the region about the importance of the AF trees for biodiversity conservation. On the other hand, socio-cultural functions are important in Africa but of no importance in the Nicaragua case study.

However, in both regions, despite many trees being multi-functional, no single tree fulfills all functions. Many trees have various uses, only a few fill single functions, and these are often related to medicinal use (Ickowicz et al. 2013). However, even if many tree species are multi-functional, their uses are often complementary to each other, and no single tree species fulfills all functions. For instance, in Senegal, several trees are used to feed livestock, but the species that provide good fodder for cattle differ from those that provide fodder to goats (Rusch & Pugnaire 2013, Carmona et al. 2013). Also, different social groups, including farmers, pastoralists and women, value the tree species differently and make different uses of them (Cisse et al. 2010, Clinquart et al. 2010). Consequently, it is critical that modern agro-silvo-pastoral systems are viewed and designed as functionally diverse systems.

These results emphasize that the functions and specific uses of tree species must be taken into account when the aim is to improve the management of agroforestry systems, and essential in the process of up scaling and adopting agroforestry technologies. The analysis has also highlighted the specific interest groups and has showed the extent of the scope attributed to agroforestry species and priority functions. The results obtained can be useful to improve the adaptation of current agroforestry practices in livestock farms of seasonally-dry tropical lands. Future research should focus on a better understanding of interactions between benefits and functions. Better diagnosis and understanding of the constraints and risks of actual practices are also necessary to increase the likelihood of practice improvement.

3.2 Analysis of factors underlying adaptation and change of AF technology

The factors that affect the adaptation of current agroforestry technologies by the rural communities in the FUNCiTREE case study areas in the Sahel have not been well known. In the Sudano-Sahelien zone in the intervention zone of the Millennium Villages project, which covers rural communities of Dioro and Farakou Massa, in Ségou, Mali we conducted enquiries at village group and household level in order to discuss issues related to agroforestry practices and technologies and the factors determining these decisions. The agroforestry technologies considered in the analysis were: food storage, hedgerows protection (defensive hedges against animals), village groves, household groves and hedges bordering properties. The latter is a local practice used by the local communities with the purpose of demarcating property rights over parcels of land. However, access to and use rights of plants depend on the rules that govern the community, and are subject to evolution. The variables taken into consideration in this study were the age of the head of the household, labour (availability of abled workers), affiliation to a village association, contact with village leaders, access to plots, livestock size, level of soil erosion of the land, and access to villages during the rainy season.

Two different and complementary methodological approaches were used in the analyses. First, a logistical regression model was used to determine factors of adoption and implementation of agroforestry technologies. The analysis revealed that *the adoption of agroforestry practices and technologies depends on several factors which vary from one technology to another, and according to the socio-economic characteristics of households and villages*. In other words, the economic status of households, their affiliation to village association, the degree of contact with village leaders, the state of soil degradation and the access to the village in all seasons are factors associated with higher levels of adaptation to new agroforestry technologies. Holding large numbers of livestock (cattle) tended to be associated with higher level of adoption of village groves, which are easy to supervise and protect against animal divagation. Contrary to our expectations, the variable “age” is not a determinant factor in the capacity for adaptation to new agroforestry technologies (Cisse et al. 2010).

We further modelled these data using a Bayesian Belief Network (BBN) approach to model household level data on adoption of agrosilvopastoral practices in Ségou (Barton et al. 2013). The analysis of agricultural adoption practices using categorical (logit/probit) regression models focuses on a single technology or practice at the time, explained by a number of household and farm characteristics. BBNs enable modelling of more complex data structures, including (i) multiple practices implemented jointly on farms, (ii) correlation between probabilities of implementation of those practices, and (iii) correlation between household and farm characteristics. Our studies have demonstrated the use of BBNs for ‘deductive’ reasoning regarding adoption practices, answering questions regarding the probability of implementation of combinations of practices, conditional on household characteristics. As such, BBNs can be used as a complement to logistic regression analysis, also exploring causal structures in the data before deciding on a reduced form regression model. More uniquely, we showed how BBNs can be used ‘inductively’ to answer questions regarding the likelihood of certain household characteristics conditional on certain practices being adopted. Finally, we have discussed the potential of BBNs to complement the toolkit of agricultural extension.

In Potou and Rivas, we also modelled the agroforestry practices and technologies currently in use by farmers and then, the factors determining the tendency to change and adapt current practices and local knowledge as conditional probabilities in a causal chain using a Bayesian Belief Network approach. The questionnaires contained a large number of questions on socio-economic background, characteristics of the farm production system and agrosilvopastoral practices (ASP). The survey was exploratory and aimed at providing data for testing the integration of socio-economic farm characteristics with biophysical characteristics. A small sample approach was used to test whether BBNs provide useful information for sample sizes typically lower than what is used in econometric models representing the population. In Potou, our preliminary data analysis found that very few socio-economic characteristics of the farm and farmer could explain the specific adoption of ASP or the selection of specific tree species. This may have been due to the small sample size combined with the large heterogeneity resulting from the spatial sampling strategy. To illustrate the BBN analysis, we used two of the key variables from the survey: agroforestry practice and uses / provisioning ecosystem services of trees. ASP included ‘live fences’, conserving ‘trees in field’, ‘plantations’ and ‘natural regeneration’. Uses included ‘firewood’, ‘forage’, ‘pharmacopeia’, ‘construction’, ‘food’, ‘live fence’, and ‘fertilization’. The most probable combinations of uses of trees and ASP practices found in the sample were forrage associated with plantations and trees in field. Forrage is by far the most common of the uses of trees in the sample with 53% of respondents reporting the use of some type of forage. In Rivas, we developed an expert system using Bayesian belief networks for the design of ideal livestock pastures using combinations of trees in live fences and on pastures. The tool was created with information on types of farmers and their preferences, local farmer knowledge about tree species and their benefits, and scientific knowledge about functional traits in the design of silvopastoral systems. The costs and benefits predicted by the model were validated in a follow-up survey in the study area. The model identifies combinations of multifunctional trees which improve ecosystem services provision. Also, it permited the comparison of results obtained with different silvopastoral systems that provide similar services (Barton et al. 2013).

Participation and learning as processes determining change

The results described above help to understand the conditions that would enable up-scaling of AF technologies and practices. However, the challenges to incorporate change go beyond the expressed interest by the farmers. A study in a related Sahelian case study site (in Cameroon) on Apple-ring acacia

(*Faidherbia albida* (Del.) Chev.), an iconic tree species for Sahelian agro-foresters, illustrates the value of participatory demonstration activities, and the recognition of the farmers' interest to promote change. Traits and functions of Apple-ring acacia are well-known by agro-pastoralists farmers and scientists. Traits include a deep taproot system that reaches the water table on alluvial soils, inverted phenology, with leaves being present in the dry season and absent during the rainy season and therefore assumed low competition with crops and grassland; and its ability to reproduce vegetatively (root suckers, coppices of stumps and branches). The main functions widely valued by agro-foresters are its general positive impact on the associated crop, and the production of forage (leaves and fruit) and firewood. However, the area extension of *Faidherbia* agroforestry systems (parklands) is still far below what it could be, despite the isolated actions of many extension services. Research on crop productivity under *Faidherbia* helped changing the perception of this tree by techicians involved in agricultural development, in the 1990s. Then it was possible to "boost" the restoration of these parklands on a large scale, mobilizing public funding, associations and farmer organizations and subsidizing (even at a low level) Assisted Natural Regeneration. The results of the socio-economic surveys and pruning trials, conducted in 2012, confirm, at least, the interest of farmers for pruning the trees and for a sustainable extraction of fire-wood using this method. These concerted actions have resulted in that the demand of farmers on the right of pruning trees and to freely use the wood harvested has been taken into account in the draft amendment to the Law on the forest regime, introduced in 2012, to the Cameroon parliament. These studies on *Faidherbia albida* have helped Cameroonian farmers keep more than one million young trees, but also have helped to change the law in the sense of increasing the rights of peasants to use trees, including planted trees, which are often exotic, but also native tree species maintained by farmers, such as shea-butter tree (*Vitellaria paradoxa*) and many other multipurpose species.

The necessity of a direct involvement of the local communities in all the aspects that affect their decision-making on how they manage the farm resources is also highlighted by the application of the community capitals framework (CCF). CCF can be used in agro-ecological research on one hand to include, analyse, and process socioeconomic data and on the other hand to open spaces where farmers and other interest groups (key stakeholders) can be part of a participatory research and learning process, and can start thereby the adaptation and improvement of AFS based on evidence and a deep and systematic contextual analysis. Research in the sociology of adoption and diffusion of agro-pastoral practices and technology highlights the disparity between agricultural and natural resources research efforts on one side, and their relevance and application (so called adoption) by the local farmers. In this context, CCF enables to bridge this gap between science and practice, through an analysis of AFS based on evidence and a deep and systematic contextual analysis. The results from Rivas, Nicaragua highlight the fact that producers have local knowledge (cultural capital) to identify functions and ecosystem services from trees within the pastures: i. e., timber and wood production; feed resources and shade for livestock; soil, water and biodiversity conservation, carbon sequestration and others. This local knowledge (cultural capital) combined with relationships with neighbours', family and friends (social capital) are a starting point to promote the development of multi-functional silvopastoral systems (SPS) toward the improvement of productivity of livestock farms. The experience gained in FUNCITREE along with studies within the Mesoamerican Agroenvironmental Program (MAP) with farmer field schools (FFS), have shown a key role of these efforts of capacity building (human capital) toward the generation of a learning environment in which participants can learn, share and apply more and better knowledge and skills to improve their farms. Knowledge sharing or *wisdom dialogue* (cultural capital) within FFS, allow participants to build and strengthen relationships (social capital) and conserve the ecosystem services (natural capital) through the use of innovative sustainable land use practices, such as AFS. Additionally, the process seeks to empower participants to increasingly take part in local and national decision making structures (political capital). Finally, there is also an enhancement of the productive infrastructure (physical capital) and an increase of income and/or savings (financial capital) coming from the improvement of the productivity.

A democratic and inclusive strategy has been used in FUNCiTREE when implementing the field trials and when incentives have been provided for particular actions. In Segou, the overall development objective is to improve the socio-economic and environmental conditions of rural populations in the project area by the Millennium Villages Project. The results from FUNCiTREE stress the importance to enhance the multi-functionality of the tree cover in the area. Specificic development objectives for this area are to conduct planting of priority woody species in cropping systems to increase the production of forage, wood, and improve soil fertility and food security, and to enrich the parklands with trees by promoting Assisted Natural Regeneration (ANR). The out-reach work has consisted on the enrichment of village lands by planting woody species. General meetings were held in the villages to determine the preferences of farmers in terms of plant species, to identify the households willing to engange in planting, and to allocate species and number of plants to be planted by each household.

3.3 Tree traits as indicators of ecological and eco-physiological functions in seasonally dry agroforestry systems

Coping with drought and plant water use

Unraveling belowground processes, especially root-soil interactions whereby plants acquire water and nutrients, remains one of the greatest challenges in plant ecology. Stable isotopic composition of xylem water and leaf tissues coupled with soil and different water sources provide valuable insights on fundamental ecological processes such as plant water sources, and plant water and nutrient use efficiency, among others. Our results show that multiple-isotopic analyses of AFs trees and water provide a unique way to explore the relationships between water and carbon fluxes in the plant-soil-atmosphere continuum, and provide evidence on the diversity of water-use and drought coping strategies in AFS in seasonally-dry areas. We determined stable isotope composition in 21 species per site and in two contrasting periods in terms of water availability: dry and wet seasons. The analysis of δ^2H and $\delta\ ^{18}$O composition of xylem sap, soil and well water, and the composition in δ^{13}C, δ^{15}N and δ^{18}O of dry leaves revealed high plant functional diversity in the FUNCiTREE AF systems. Trees of agroforestry systems in Rivas, Nicaragua and Potou, Senegal – from where isotope analyses are already available- mainly relied on soil water stored in intermediate (<0.5 m) to deep (1 m or deeper) soil profiles during drought periods. Plants changed soil water sources between seasons and these water sources were usually shallower in the rainy season compared to the dry season. Time-integrated intrinsic Water Use Efficiency (WUE) was usually related to the source of water that trees relied on in AFs in Nicaragua, but not in the Sahel. In AFs from Nicaragua, trees relying on deep or more permanent water sources displayed the lowest WUE values while those that had to withstand pulsed resource availability (surface soils) displayed the highest WUE. Plant WUE changed among seasons. During the rainy season plant WUE of Central America tree species was lower, and plant WUE in sahelian species was higher than during drought periods. Sahelian trees displayed a positive relation among WUE and discrimination of 18O in leaves which may be related to differences in stomatal conductance (gs) and/or transpiration (E); that is, the higher the WUE of a plant the lower E and gs. This means that there was a tight control of plant E and gs rates when soil water was less available for plants, also reflected by the relationship between WUE and stem water potentials; the less negative the water potential (had more water available) the lower the WUE of the species. *Overall, our results show that multiple-isotopic analyses of AFs trees and water provide a unique way to explore the relationships between water and carbon fluxes in the plant-soil-atmosphere continuum, and provide evidence on the diversity of water-use and drought coping strategies in AFS in seasonally-dry areas.*

FUNCiTREE conducted various complementary studies to gain knowledge about how trees in tropical seasonally dry AFS cope with water shortage and rainfall seasonality in the different environments they grow. We did this through the analysis of plant attributes and functional traits because they correspond to the environmental conditions the plants have to withstand and thus can be used to assess species tolerance to stress. We studied the physiological responses to drought along abiotic gradients of nine woody species dominant in the tropical semiarid savannah AFS in the Sahel, where scattered trees grow in a matrix of seasonal grasslands and crops. The species were *Acacia tortilis*, *Adansonia digitata*, *Balanites aegyptiaca*, *Combretum glutinosum*, *Celtis integrifolia*, *Faidherbia albida*, *Neocarya macrophyla*, *Sclerocarya birrea*, and *Tamarindus indica*. In five contrasting seasons differing in water availability – dry or rainy season – and mean temperatures – relatively cold or hot seasons – we measured predawn relative water content (RWC), predawn leaf water potential, specific leaf area (SLA) and leaf area index (LAI) on 6 mature trees per species. *Our data show contrasting physiological responses and tolerance to drought in these species, which allow us to classify them into different functional groups. These results can be used as input to models predicting the effect of dominant woody species on ecosystem functioning and its evolution in a context of climatic change*.

In Rivas, in addition to the stable isotope analyses, a total of 20 traits were measured to characterize six tree species. *Albizia saman*, *Guazuma ulmifolia*, *Coccoloba caracasana, Tabebuia rosea*, *Crescentia alata* and *Enterolobium cyclocarpum* were studied with the aim of identifying further differences in how the trees use resrouces and cope with water shortage. A Principal Components Analysis (PCA) based on canopy and leaf traits helped to identify two axes of functional differenciation related to tolerance to drought and to strategies of resource acquisition. Along the first PCA-axis canopy traits distinguished species according to drought tolerance and avoidance strategies. The second PCA-axis reflected the resource capture strategy of the plant, distinguishing between conservative vs. acquisitive strategies (leaf traits such as size and tensile strength). *Our findings suggest not only that the trees show different responses to climatic stress, but also of general resource use strategies, which need to be considered when designing agro-silvo-pastoral systems in the future.*

The use of different water sources and the strategies, and the way trees cope with water seasonality and shortage is closely linked to the tree root system. FUNCiTREE evaluated root traits as a step to further identify the strategies adopted by tree species to tolerate or avoid climatic variations in cycles of drought and rain in six tree species: *Albizia saman*, *Guazuma ulmifolia*, *Coccoloba caracasana*, *Tabebuia rosea*, *Crescentia alata* and *Enterolobium cyclocarpum.* The study explored fine root density (g m^{-3}), specific root length, and length volume (cm^3) using soil samples along with the software program WinRhizo. The tree species differed significantly in root traits and their distribution in the soil profile, and root traits were correlated with above-ground traits such as crown density, leaf water content, both absolute and relative, and specific leaf area (SLA). Based on root traits in the dry and in the wet season, species could be clustered (Ward, Euclidian distance) into three and four functional plants types (FPT), respectively. For instance, in the rain season, FPT 1 was characterised by high specific root length and low root bulk density, whereas trees in FPT 2 had the very long roots. FPT 3, on the other hand had the lowest specific root length and root length. The species with longest roots and highest root density density was *C. caracasana*, which appears to have a strategy of using conserved resources during the dry season based on the patterns of root distribution in this period. *E. cyclocarpum* and *A. saman* are associated with greater root diameter and lower crown density. *This study provided evidence for a diversity of root functions in terms of concentration of fine roots, the relative volume of soil explored, the distribution of roots along the soil profile, and the seasonal shifts in these patterns*.

One very evident difference in how trees cope with rainfall seasonality is whether they are evergreen or deciduous. Differences in leaf phenology are critical to many functions and services trees fulfil in AFS, affecting functions such as the timing of shading for crops and the provision of shade and fodder for animals. The co-occurrence of trees with deciduous and perennial crowns in AFS is therefore particularly important because each growth form fills different functions and provides different services. FUNCiTREE explored other techniques to help disentangle the various mechanisms through which trees in tropical seasonally dry climates cope with water shortage. In the Sahel parklands, trees can provide fodder during the dry season if they keep functional foliage in this period. In such conditions, the xylem vessels (that conduct water and minerals from the roots to the leaves) sustain high tension which can induce cavitation, decrease the conduction of sap and lead to branch mortality. Therefore, xylem resistance to cavitation is a good index of tree tolerance to water stress. However, information about this parameter remains scarce in Sahel tree species. In addition, its measurement is difficult and requires specialized equipment limiting its feasibility in field conditions. FUNCiTREE measured the vulnerability to xylem cavitation in 10 tree species with fodder potential in North Senegal, also aiming to assess whether this physiological trait can be correlated to morphological traits easier to measure such as wood density, xylem anatomy, and vessel length. We used the Cavitron spinning technique to construct cavitation vulnerability curves and to compute the P50 (water potential inducing 50 % loss of conductivity), but this technique seems to be of limited use in these species. Due to the long xylem vessels in most species (except for *Tamarindus indica*), vulnerability to cavitation could not be assessed using the Cavitron spinning technique.

Tree traits, fodder provision and other functions related to animal keeping

Farmers in arid and sub-humid regions traditionally know trees and shrub species with fodder and medicinal interest, and ecologists, agro-forestry and livestock scientists have applied standardized analytical methods and further advanced in the knowledge about fodder properties of woody species. Particularly, the regular occurrence of droughts in these areas has prompted investigations to characterize, quantitatively and qualitatively, forage provision by trees and preferences by animals. Exotic species have also been tested. However, despite much descriptive and analytical data, there has been little effect on the management of forestry and tree species in agro-pastoral rangelands. The new research that has been stimulated by the increase pressure on these resources due to climate and demographic changes must therefore integrate local knowledge on practices (past and current), the multi-functionality of the use of trees, their use according to growth rates and regeneration capacity of the species; together with the socio-economic contexts that determining management practices. FUNCiTREE has advanced in some of these areas. Within this overall framework, the functional traits related to forage function must express:

- productivity of foliage and reproductive organs
- availability of forage for livestock following simultaneity between phenological cycles and major nutritive needs of animals
- palatability of species
- nutritional value expressed by concentration of digestible nutrients (nitrogen, minerals, fiber)
- capability of re-sprouting after browsing or pruning both in the rainy and dry seasons
- content of tannins or other characteristics that deter herbivores
- propagation, which is in turn related to the capacity to re-sprout after browsing
- the balance between competition and facilitation of the pasture

These traits are related to tree demography, phenology, morphology, anatomy, chemical composition, animal browsing behaviour and intake and much data exist. It must be organized so that they are accessible and linked to their agro-climatic and socio-economical environments. During the course of the project, data on chemichal properties of tree species were retrieved and prepared for the FUNCiTREE database.

In addition to chemical tests, one way to assess the potential to provide fodder is through trials and observations using livestock. Also in seasonally-dry areas of Central America woody plants are an alternative forage for cattle feed, particularly in the dry season when grasses dry out. FUNCiTREE conducted studies to assess the preference by animals of local AF tree species. In Rivas, preference was determined in ten species by cafeteria testing in pairs of, using five cows. The combination of ten species in pairs originated a total of 45 events for each cow, each lasted three minutes. The descending order of consumption was *Samanea saman*, *Leucaena leucocephala*, *Albizia niopoides*, *Cordia dentata*, *Moringa oleifera*, *Guazuma ulmifolia*, *Gliricidia sepium*, *Brosimum alicastrum*, *Mimosa pigra* and *Acacia farnesiana*. The preference by cows was associated with several whole-tree and leaf traits. The first three species are legumes which generally have higher leaf nitrogen content; the leaves are large and soft. However, the least consumed trees were also legumes. The low preference in these cases is due to the presence of thorns and high concentration of condensed tannins. Many forages species present condensed tannins that can poison livestock if consumption is high (Mueller-Harvey 2006). This usually occurs when cattle have this only food in the diet and it is difficult that this happens in a pasture where there is a variety of forages. Preference studies give us guidance on the preferred livestock species, although silvopastoral system designs must consider other attributes such as ease of propagation, re-sprouting capacity, forage yield, and tolerance to frequent pruning.

Our studies indicated that species like *Leucaena leucocephala*, *Cordia dentata*, *Gliricidia sepium*, and *Guazuma ulmifolia* have important advantages as on-farm feed resources. The combined use of the species such as *A. saman* + *C. dentata*; *L. leucocephala* + *C. dentate*; *A. niopoides* + *C. dentata* to supplement the basal diet in the dry season (*Pennisetum purpureum*, molasses and minerals) can improve an average milk production of 6.5 kg / cow / day when based only on grazing of dry grassland and with supplement of manure, molasses and mineral salt, to between 6.7 and 7 kg / cow / day. The best response is due to the associative effect of mixed browse material (at least 2 woody species such as *L. leucocephala* + *C. dentata*) that enhances nutrient availability.

In addition to fodder quality, biomass production and regrowth capacity after harvesting or browsing are important traits in trees supporting the fodder production function. Six species common in AFS in Rivas were studied, using 6 replicates for each, in total 36 observation units. The selected trees had not been managed with pruning close to the start of the experiment. *Cordia dentata* and *Pithecellobium dulce* had the highest of edible biomass 5,95 $\pm$ 1,43 and 3,20 $\pm$ 1,12 Kg dry matter (DM) / tree respectively; while *Albizia niopoides* showed the lowest yield 0,53 $\pm$ 0,14 Kg DM / tree. In descending order the average production of sprouts per tree was *Pithecellobium dulce* (260,5), *Cordia dentata* (147,83), *Guazuma ulmifolia* (69,0), *Albizia saman* (54,0), *Gliricidia sepium* (24,33), and *Albizia niopoides* (17,33). In terms of functional traits, it was determined that a lower leaf area seems to be related to a higher reservoir of meristems and axial buds which improves the capacity to resprout and productivity, as in the case of *Pithecellobium dulce* (4171,9 mm^2) and *Cordia dentata* (4212,1 mm^2). Both species have potential for cattle feeding in the dry season, either under the cut-and-carry system or by cutting and offering the fodder on the ground near the tree. However, to propose these species for fodder provision, the effect of prolonged pruning on the response of *Cordia dentata* and *Pithecellobium dulce* needs to be determined. This study made an important contribution by widening the knowledge about the fodder value of several woody species that currently occur in paddocks in the area of Belén, Rivas, but that are undervalued, such as *Cordia dentata, Gliricidia sepium, Guazuma ulmifolia, Albizia saman and Albizia nipoides*.

In sub-saharan Africa animal feeding depends mainly on free grazing on rangelands and also in this region, pastoralists have to deal with fodder shortages during the dry season. During the lean season, trees and shrubs represent the only source of green fodder available on rangelands. FUNCiTREE aimed to identify fodder species and their functional characteristics as animal feed on the specific conditions of Sahelian rangelands with a focus on the Louga area in Senegal. This context is characterized by high anthropogenic pressure and a particularly low biodiversity of the tree layer. We analysed the behaviour and the feed preferences of cattle for the available woody species on rangelands. Regular monitoring of cattle herds was done during the dry season. Food preferences were determined by direct observation method of the woody plants intakes and the results were compared with biological aspects of consumed species. *Guiera senegalensis* and *Boscia senegalensis* appeared to be the most important woody species consumed as they represent 60% to 100% of the feeding time on woody plants. Differences in behaviour were partially explained by differences in morphological characteristics and phenology stages among the fodder species. One reason for the preference of these two shrubs in this area could be that the rangelands have undergone a process of degradation of the biological diversity and the fodder resource, and only a few easily accessible shrubs species remain in considerable amounts. The most consumed species, *Guiera senegalensis* and *Boscia senegalensis* are used for medicinal purposes, which could indicate that these species may contain high levels of anti-herbivore substances. In order to identify particular traits impacting the food choices of woody plants, chemical analysis of the consumed trees and shrubs need to be performed in the future. In addition, and in order to strengthen the diagnostic of the qualities of these species to provide fodder, the results from the FUNCiTREE site must be compared with others obtained in other more diverse sahelo-sudanian agro-pastoral rangelands.

Besides the role of AF trees in fodder production, trees provide shelter and shade for the animals, ameliorating in this way heat stress, and affecting foraging behaviour. Using geographic information systems, the effects of tree cover on the movement patterns and behaviour of dairy cows was studied in 13 pastures in Rivas. Cows mainly used trees at noon for protection and preferred functional groups of trees that best reduced radiation and temperature under the crowns. The study showed that daily variation in behaviour is higher than seasonal changes for all the variables studied. However, it was observed that cows used trees more during the rainy season than in the dry season, which is likely related to the fact that several tree species in these AFS are deciduous and lose their leaves in some periods of the dry season. It could also be attributed to the fact that the pastures provide little forage during the dry season, and the cattle therefore need to forage over a larger area and move more. Depending on the activity of the cow and the time of day, the animals visit different functional groups. Cows use trees with less coverage to graze and those with denser canopy coverage for protection. When deciduous trees regain their leaves in the rainy season they are visited by cows while during the dry season these trees are not visited. For the design of silvopastoral systems the presence of both deciduous and evergreen trees is recommended, because the different functional groups are utilized by the cows during different seasons. In the rainy season, the effect of both evergreen and deciduous groups is the same; however cows prefer deciduous trees in this period. In the dry season, the evergreen trees offer greater protection than the deciduous trees which lose their leaves, and cows switch their preference to evergreen trees. One practice that could be tested is to prune the evergreen trees in the rainy season when both groups of trees offer similar protection, because too much canopy coverage can affect grass growth and cows prefer deciduous trees during this time.

Tree traits and the interaction with grasses

In savannas, wooded meadows and similar systems with trees in a matrix of herbaceous vegetation, trees and herbaceous plants interact in several ways. Through the effects of trees on soil water, nutrients and light reaching the soil, as well as on vegetation, trees have a large impact on understorey growth conditions. Tree responses to drought conditions involve not only plant adaptations to water limitation but also interactions with soil and soil biological communities, in addition to livestock and understorey vegetation. Such characterization is needed to identify tree species suitable for agro-forestry systems in dry and marginal areas.

Tree species traits monitored along several seasons in target areas of Latin America and Africa evidence contrasting responses to water shortage as well as different relationships between tree functional traits and understorey productivity. For instance, several physiological traits are associated with tree size; larger trees have higher pre-dawn water potential (ψ_{pd}) (higher water status) in both wet and dry seasons, which are in turn related to traits influencing resource use by the plants such as specific leaf area (SLA), leaf relative water content (RWC), water use efficiency (WUE), and related measurements. However, trees with dense foliage (high LAI) and therefore with more evaporative surface area show lower ψpd (lower water status). In general, the more water is available the less efficient are plants in the use of that water. *We found that tree attributes have an impact on understorey vegetation. Trunk diameter and height negatively influenced understorey biomass and cover, and taller trees were associated with fewer species in the understorey. Trees with dense foliage showed less grass productivity and cover in the understorey.*

The conditions of the environment on which trees grow are also important for the understorey and the soil. We found significant differences among sampling sites in Potou regarding several measured variables such as understorey species richness and grass productivity, nutrient availability, pH, soil salinity, and the presence of mycorrhizal fungi. Soil pH was strongly correlated with species richness, and the higher the pH the higher the number of species. Soil salinity also influenced productivity; low salinity in the soil was associated with more species. Grass richness and fungi also depended on water availability (indirectly measured through tree RWC) and more species and more fungal spores were present with greater availability of water. These results show aconsiderable within-site variability in terms of the environmental conditions and of the responses of the vegetation and the trees. These differences need to be considered when designing and recommending AF practices.

In addition, trees may suppress grass growth through direct competition for water, light, and nutrients but trees may also facilitate understorey growth by directly or indirectly improving environmental conditions for understorey growth. Therefore, tree-grass interactions encompass both competition and facilitation at the same time. Current knowledge supports the idea that the balance between facilitative and competitive processes is a function of environmental harshness, with higher facilitation effects towards more extreme environments (e.g. drier and/or with higher salinity) while competition predominates in benign conditions. FUNCiTREE studied the effects of trees in seasonally-dry tropical agro-pastoral systems on understorey herbaceous vegetation along a gradient of environmental productivity in the Sahel and in Central America. We used above-ground productivity (ANPP) of areas of open grassland as an integrative index of site productivity, thereby encompassing a range that was affected by soil properties and rainfall. *Site productivity explained a large portion (42%) of the effect of trees on understorey ANPP. The effect of trees growing in more productive sites was predominantly negative, resulting in a decrease of ANPP compared to open patches, while the facilitative effects of trees increased with decreasing productivity.* The relationship between the effect of trees and site productivity was monotonic, indicating the absence of thresholds and showing a steady decrease in the importance of facilitation with site productivity. The effect of trees on understorey ANPP was negatively associated with tree size, as larger trees had stronger negative effect on pasture growth than small trees.

We also observed species-specific responses. For instance, *Celtis integrifolia* in Senegal, showed a considerably negative effect on the understorey that would be expected from the general site productivity. *Celtis integrifolia* occurred in relatively low-producitivity sites, where a predominant facilitative effect would have been expected, but this species showed strong negative effects on its understorey. Allelopathic effects or other attributes of leaves affecting the quality of litter incorporated into the soil could explain such differences, and possibly stronger competition, although we would expect less intensity of competition in more stressful environments.

In contrast, *Faidherbia albida*, also one of the species growing in Senegal, had a net facilititave effect considerably larger than expected from site productivity. *Faidherbia albida* is a species highly valued in AF systems in the Sahel as it promotes an increase in crop yield and pasture growth. This effect could be associated to the "inverted" phenology of the species. It retains foliage during the dry season and shed it during the rain season; therefore most likely below- and above-ground competition is low as other species are not active during its growth period, thus escaping from competition. Since the species drops its foliage at the start of the rainy season, the input of fresh litter implies an important addition of nutrients for crop growth, particularly because *F. albida* is a legume.

Opposite to Nicarauga, most individuals and species studied in Senegal had a net positive effect on understorey ANPP, and there was also a trend of more net facilitative effects than expected from site producitivity.

The *net* effect of trees on grass ANPP, positive or negative depending on site productivity, was unrelated to changes induced by trees in soil C, N and pH, indicating a predominance of direct (tree-grass biological interaction) compared to indirect (through changes in soil properties) effects of the trees on the pasture. Trees in tropical agro-pastoral systems fulfil many important functions and both trees and grasses are vital for system productivity. These functions may be in conflict with each other at times, particularly in the most productive sites, where competition prevails. However, facilitation effects were more frequent in less productive sites.

In conclusion, and although there are site-specific effects, particularly dependent on site productivity, there are parallelism between Latin American and African AFS, where different tree species have different access to resources and affect understorey productivity in different ways, providing tools for improvement of agro-forestry systems. Generally in AFS, it should be expected that trees will tend to reduce pasture productivity as the amount of resources (water, nutrients) available increase, but, interestingly, trees will promote pasture growth as environmental harshness increases.

The effect of AF trees on the soil

The decline in soil fertility limits agricultural productivity with consequences for food security and rural poverty across the semi-arid and sub-humid tropics where low-input agriculture and husbandry is practised. Thus, AF is increasingly used to restore soil fertility and raise agricultural productivity, since solitary trees in addition to many other services, enhance soil characteristics and change the cycling of C and nutrients in their vicinity. However, the success of an agroforestry system depends largely on the tree species. FUNCiTREE studied the influence of 14 woody species in the Sahel, 11 trees (*Acacia senegal, A. tortilis var. raddiana, Faidherbia albida, Celtis integrifolia, Combretum glutinosum, Adansonia digitata, Balanites aegyptiaca, Neocarya macrophylla, Tamarindus indica, Zizyphus mauritiana* and *Sclerocarya birrea*) and 3 shrubs (*Annona senegalensis, Boscia senegalensis* and *Maytenus senegalensis*) (***i***) on some soil fertility indicators, (***ii***) herbaceous diversity and biomass production in four villages of Leona Rural Community (Region of Louga, Senegal). The soil fertility indicators used were pH, electrical conductivity, total carbon, total nitrogen, available phosphorus and density of mycorrhizal fungal spores. The results showed that all species increase electrical conductivity and slightly acidify the soil except *C. integrifolia* and *A. senegal*. *C. glutinosum, S. birrea, T. indica, B. senegalensis, N. macrophylla* and *B. aegyptiaca* increased soil electrical conductivity more than 200%. *T. indica A. raddiana, F. albida, A. senegal* and *N. macrophylla* increased total carbon more than 150%. However, only nitrogen-fixing trees (*A. raddiana, F. albida* and *A. senegal*) increased total nitrogen over 150% and only *F. albida* increased over 100% the available phosphorus.

The density of fungal spores was lower under tree cover than in the open grassland except for *C. integrifolia, S. birrea* and *M. senegalensis*. Herbaceous total cover was higher under tree cover than in the open grassland cover except for *C. integrifolia, Z. mauritiana* and the three shrubs. Based on these variables, *F. albida, N. macrophylla, A. raddiana, T. indica* and *A. senegal* were the species that had the most important positive effect on soil fertility and herbaceous biomass production while *C. integrifolia* seemed to have a depressive effect.

In Nicaragua, we were particularly interested in testing the effect of legume species, since species of this group are often recommended in agro-silvo-pastoral systems due to its potential to improve soil fertility through symbiotic fixation of atmospheric nitrogen. We quantified the effects of trees on soil nutrient and C stocks and assessed differences on the effects between legume (*Albizia saman; Enterolobium cyclocarpum*) and non-legume tree species (*Tabebuia rosea; Guazuma ulmifolia*). The results showed that soil organic C and N, available P and extractable K^+ and Ca^{2+} were higher under the tree canopy than under paired open grassland. Also stable isotope analysis of soil organic matter indicated a strong role of trees in soil formation, showing a significant input of tree biomass and debris (signal related to C_3 photosynthetic pathway) under the trees, compared to the open pasture (showing a signal corresponding to C_4 metabolism, characteristic of the grasses in the region). The basal area of trees was positively related with the canopy effect on soil variables, thus suggesting that the age or sizes of the trees are relevant factors associated with the content of soil C and nutrients. On the other hand, no specific effects related to the legume species group were detected. *Our results indicate that in fertile seasonally-dry subtropical pastures, scattered trees have an overall effect on soil fertility, and that the magnitude of the effect depends more on the tree characteristics (i.e. basal area, crown area) than on whether the species is a legume or not*.

Additionally, we explored possible differences among tree species in processes related to carbon storage and cycling. We studied the effects on soil respiration between *Guazuma ulmifolia* (Guácimo) and *Crescentia alata* (Jícaro). The results show that in addition to differences between the species soil type was an important variable affecting most of the soil properties assessed in the study. Soil bulk density was affected by soil type (P = 0.011), tree species (P<0.001) and whether the soil was under the tree canopy or in the open grassland (location, P<0.001), with higher bulk density values in Vertisol soils, under Jícaro and in the canopy and leaf litter deposition zones. Soil C content (g C m-2) was higher in Vertisols (P<0.001) and under the trees (P<0.001), and decreased with soil depth (P<0.001), but it was not affected by tree species. There was, however, a significant tree species × location effect (P=0.008) with higher C contents under the canopy and leaf litter deposition zone of Jícaro. All carbon fractions (Soil C present in the "free labile" and "occluded" fractions, and the mineral-associated C fractions) were lower in the sub-soil (P<0.001), but otherwise not affected by tree species, location or soil type. Soil N content was, just as C, higher in Vertisols (P<0.001) and under the trees (P<0.001), but decreased in the sub-soil (P<0.001). There was also a significantly higher content under the canopy and leaf litter fall zone of Jícaro (P=0.012). Nitrogen in soil fractions followed similar trends as in the case of C. Soil P content was marginally higher in the Mollisols (P=0.053) but was not affected by tree species or relative location to the trees. Soil C:N, C:P and N:P were higher in Vertisols (P<0.001), but these ratios were not affected by location, and only C:P was higher under Jícaro (P=0.023). Soil respiration, measured as CO_2 efflux at the soil surface, was highest in the leaf litter zone, intermediate in the pasture and lowest under the canopy (P<0.001), while average respiration was higher under Guácimo (P=0.013). *We infer that high soil C storage is promoted by Vertisol soils, due to higher clay % (P<0.001) and impeded drainage, and by the canopy and leaf litter zones of Jícaro trees. The latter corresponds well with the observed higher respiration rates under Guácimo*. *The observed species effect on C:P, but not on C:N, may indicate increased uptake of P under Jícaro and a possible growth limiting role of P.* By looking at the free labile and occluded fractions, the early stages of soil C stabilisation processes do not seem to be affected by tree species or location, or may be obscured by the rapid turn-over of organic matter and its high spatial variability. However, *the most stable mineral associated fraction, which makes up ~ 89% of total soil C, is about one-and-a-half times larger under Jícaro than under Guácimo or pasture. Carbon sequestration as an ecosystem service may therefore be promoted by the use of Jícaro in silvopastoral systems*.

As the previous studies demonstrate, litter deposition from tree leaves and roots are important sources of nutrients and carbon in soil. Additionally, trees may add nutrients to the soil through through-fall, i. e. leaf exudates and nutrients in particles captured in the leaves that are washed by rainfall and thereby incorporated in the soil. Trees can also affect the amount and distribution of rainfall water that reaches the soil. We hypothesized that the amount of water and of nutrients washed by rainfall would differ between AF tree species and that these differences would depend on whole plant and leaf properties of the tree species. In Rivas, we studied six species: *Albizia saman*, *Coccoloba spp.*, *Crescentia alata*, *Enterolobium cyclocarpum*, *Guazuma ulmifolia* and *Tabebuia rosea* and assessed the proportion of rainfall throughfall that reaches the ground, and on its content of NO_2^-, NO_3, total P total, K^+, Mg^{2+} y Ca^{2+}. We evaluated 27 isolated trees located in paddocks in 9 livestock raising farms in the department of Rivas, Nicaragua. Rainfall samples were collected in 324 rain gauges, 12 for each tree. The data were collected after 20 rainfall events during the rainy season, from May to September 2011. Thirty-nine samples (28 composite samples under the tree, and 11 in the open grassland) were analysed chemically. There were significant inter-specific differences in the proportion of throughfall, which was in turn associated with leaf size. *Enterolobium cyclocarpum* was the species with highest proportion of throughfall (84%). Leaf tensile strength, peciole length and leaf size were traits associated with the amount of nutrients captured in the throughfall. *Coccoloba* spp. was the species group with highest nutrient contents (mg/l) in the throughfall. *We can conclude that the effect of the trees on soil chemistry and on the availability of resources for the understorey vegetation is not only a function of the quality and amount of the litter incorporated to the soil, but that mineral nutrients can be directly incorporated by through-fall. In addition, rainfall interception by the tree canopy appears to be an important factor determining the amount of water that reaches the soil*.

Multiple functions of trees in AFS

The ecological processes that underpin functions that are essential for humans are known as ecosystem services (ES). Frequently, different ES are interlinked, which translates into positive or negative co-variation between ES, meaning that some functions may be synergetic while trade-offs may occur among others. Despite the capital importance of understanding how these functions are maintained and how they are affected by management decisions, little is known about which are the processes that regulate the provision of the different ES, about the effects that different management practices can have on the capacity of natural systems to produce ES or about the trade-offs between different ES. In order to deal efficiently with these broad challenges, it is critical to better understand the relative effect of environmental and land-use factors on the species present at a given site, as well as its feedbacks to ecosystem functioning. In this context, given that methods based on functional traits provide a more mechanistic approach than the use of species identities alone, FUNCiTREE used plant functional traits as indicators of key ecological functions in the AFS in the case studies. Based on functional traits that are known to influence, or be influenced by, the studied ecosystem processes, we constructed plant functional groups (PFG), i.e. groups of species with similar trait characteristics or attributes. To date, most studies in trait-based ecology have focused only on differences among species, considering only a single mean trait value for each species, thus neglecting the importance of intraspecific variability in trait values. Considering only interspecific variability assumes that intraspecific differences are much smaller than interspecific differences, but this point of view has recently been challenged by several studies indicating that intraspecific variability can have a considerable importance. We took intraspecific variability into account by creating individual-tree-based PFGs instead of the classical species-based PFGs. According to this framework, trees belonging to the same PFG are expected to have similar responses to changes in the environment, and/or similar effects on ecosystem functioning. In this way, PFG can be linked to specific effects on other organisms and on the physical environment, with direct consequences on ecosystem functioning and on the provision of ES. With the data set from Potou, Senegal, we explored the use of Bayesian Networks (BN) to represent the probabilistic relationships between traits of trees and three service provision functions (grassland productivity, soil formation under the trees and fodder quality of trees). Based on eco-physiological traits (specific leaf area, and maximum and minimum annual values of the leaf area index), phenological traits (leaf phenology) and chemical components of leaves (for fodder quality), we classified trees into functional groups (PFG), estimated the linkages between these groups and the studied functions, and evaluated the influence of environmental characteristics on these linkages. At a later stage, the BN approach allowed us to assess the trade-offs between different ecosystem functions.

Different PFGs had various effects on the different functions, and these effects were, in turn, strongly modulated by the environment. There were marked differences in the productivity of the understorey vegetation between different PFG both within and across environments, which indicates that the particular eco-physiological and phenological attributes of the tree played an important role determining the effect of trees on understorey vegetation, an effect that was strongly dependent on the environment. These results are in agreement with those from the analyses about the factors affecting the relationships between tree eco-physiological attributes and the response of understorey grasses using parametric statistics presented in earlier sections. For example, considering the effect of trees in a PFG with deciduous habit, grass productivity under the tree canopy was generally enhanced if the trees occurred in salty soils, but in non-salty soils, trees in the same group decreased grass productivity. These results contrasted with those observed for the effect of trees on soil properties, which were generally positive regardless of the PFG and the environmental characteristics, suggesting the absence of trade-offs between the understorey productivity and soil properties functions. The lack of correspondence between these functions was later confirmed with the correlation analysis among the different indicators of the two functions. Finally, regarding the fodder provision function, we found a trade-off between trees preferred by cattle and goats but synergy between trees preferred by goats and sheep.

We also used an online platform for Bayesian Belief Network to demonstrate how farmer knowledge of tree multi-functionality could be made available in a compact form to a wider community of researchers. Knowledge from in-depth interviews regarding tree multi-functionality in Mali were collected and coded into a BBN model which was then distributed online. Users unfamiliar with BBNs can access the data through the online interface and discover the multi-functional profiles of different species. They can also identify portfolios of species that fulfil functional profiles.

In Rivas, Nicaragua we assessed the importance of trees in pastures in providing the following ecosystem services (ESs): habitat (for others species), carbon storage, and food for livestock. An index for each service ranging between 0 and 1 was developed and used to calculate the capacity of 35 pastures with tree cover were to provide ESs. The pastures were classified into four groups based on the capacity to provide habitats and the density of woody cover. In addition, the weighted functional diversity (WFD) index for measuring range, value and abundance of functional traits in a community was calculated. Four multidimensional indices were used including functional richness (F Ric), functional equity (FEve), and functional divergence (FDiv). Pastures with more species of trees and greater tree density showed higher tree biodiversity (0.54 to 0.61) and larger amounts of stored carbon (0.37 to 0.39). Pastures that had the majority of trees with moderate or light crown (allowing light transmission to the pasture) had a low value of the index that indicated shading of the pasture, thus indicating limited negative effect on pasture productivity. Pastures presenting low tree diversity (0.34 to 0.40) showed the lowest values of the index of shade for grass (0.05 to 0.10). Therefore, pastures where light and moderate tree foliage predominates provided a better contribution to the productivity of pastures. Likewise, pastures with a high density of trees can affect pasture productivity. It is worth mentioning that the main use of trees in pastures in Rivas, Nicaragua is for the production of timber and firewood, however there is potential for forage (grass, leaves and fruits) that has been hardly used by farmers as part of their feed supplementation strategy during the dry season.

3.4 Concluding remarks

Traditionally, recommendations on agroforestry promote the cultivation of 'multi-function/multi-purpose species', namely, single species, usually exotic to the area but potentially with several uses and of which the biology, particularly its propagation, is relatively well-known. A key message from the studies in FUNCiTREE is that farm and ecological multi-functionality requires a diversity of species with a variety of functional characteristics. Most species satisfy several functions, but they are also complementary of each other, because no species fulfils all functions. This functional diversity refers to the strategies of the trees to cope with climatic seasonality and droughts, and the shorter-term provision of services in the AFS such as the provision of dry season fodder for the animals, of firewood and timber, human and animal pharmacopoeia, human nutrition, and understorey crop and pasture yield. These findings derive both from studies that gathered the local ecological knowledge and the farmers' preferences in their production system, and from the ecological studies and highlight the importance of maintaining high biological diversity in agro-pastoral ecosystems.

4 FUNCiTREE potential impacts

FUNCiTREE has used several communication channels to disseminate and communicate the findings from the research conducted in the project to four main potential users of the results: i) the scientific community, ii) professionals and practitioners in tropical agro-ecosystems in the case study countries and the EU, iii) local decision-makers and iv) farmers and local communities.

4.1 Scientific community

Training of young scientists

Seven PhD students and post-docs have been involved in the project from Spain, Senegal, Nicaragua and Mexico. During the course of the project young scientists have had the opportunity to gain on-job research experience and/or attend advanced courses in the following discipline-specific areas: i) stable isotope analysis in plant eco-physiological research, ii) eco-physiology of plants in systems with water shortage, iii) plant functional traits databases, iv) local knowledge data bases, v) qualitative survey methods applied to natural resource management vi) statistical mixed-models analysis, vii) Bayesian Belief Networks models and viii) methodological frameworks for the analysis of ecosystem services (ES).

Scientific publications and thesis

14 Published articles in Journals

- Niemeyer, R.N., et al. (accepted for publication) Vegetation canopy cover increases hydraulic conductivity across a soil texture gradient in dry tropical riparian forest of Nicaragua. Vadose Zone Journal.
- Casals, P. et al. (accepted for publication). Soil organic C and nutrient contents under trees with different functional characteristics in seasonally dry tropical silvopastures. Plant and Soil.
- Mulder, C., Ahrestani, F.S., Bahn, M.B., Bohan, D.A., Bonkowski, M., Griffiths, B.S., Guicharnaud, R.A., Kattge, J., Krogh, P.H., Lavorel, S., Lewis, O.T., Mancinelli, G., Naeem, S., Peñuelas, J., Poorter, H., Reich, P., Rossi, L., Rusch, G.M., Sardans, J. & Wright, I.J. (in press). Connecting the green and brown worlds: Allometric and stoichiometric predictability of above- and below-ground networks. Advances in Ecological Research, 49.
- 11 articles, FUNCiTREE special volume "Revista Agroforestería de las Américas" published August 2013.

59 contributions in the following scientific conferences:

- I Annual Norwegian Latin America Research Conference: "Contributing to a better future? The role of Norway based Latin America research", Oslo, Norway, Nov-12-15 2009.
- I Conference Norwegian Ecological Society, Trondheim, Norway, March 2013.
- FUNCiTREE Final Conference: "The role of functional diversity for ecosystem services in multi-functional agroforestry", Trondheim, Norway, May 2013.
- VI International Congress on Agroforestry for Sustainable Husbandry, Panamá City, Panamá, September 2010.
- VI Henry Wallace Conference: Agrobiodiversidad en Mesoamérica: De genes a Paisajes. Turrialba, Costa Rica, 2010.
- VII International Congress on Agroforestry for Sustainable Husbandry, Belém, Pará, Brazil, November 2012.
- VII Henry A. Wallace Conference: "Climatically Intelligent Territories in the Tropics", CATIE, Turrialba, Costa Rica, Sept 30th to Oct 4th 2013.

19 MSc and MPh theses by students from Central and South America (various countries in the Region), France, the Netherlands, Norway, Mali and Senegal.

1 PhD dissertation (ongoing)

10 FUNCiTREE Reports and 12 technical briefs

Ca 25 scientific articles in preparation for submission to international journals

- Featured issue on Tree traits and AFS Functions
- Ca 10 articles, tentative journals: "Agroforestry Systems" and "Agriculture, Ecosystems and Environment"
- Featured issue on Bayesian Belief Networks issue and online publication of interactive models in HUGIN - EXPERT Demo site.
- Seven articles in progress, tentative journal: "Ecology and Society". FUNCiTREE has an agreement with HUGIN EXPERT A/S to make available 6 models that will be part of the 7 publications. Four models and 1 manuscript are already completed.
- Five to ten publications in specialized journals on: Eco-physiology of water use in seasonally dry AFS, models and indicators of ecological/eco-physiological function (traits),

The FUNCiTREE plant trait data base

FUNCiTREE has gathered and systematized the data collected in WP 4 into a database of tree functional traits with a structure that is compatible with the global trait data base, TRY (Kattge et al. 2011) with the aim to contribute to TRY in the future. TRY is a network of vegetation scientists headed by DIVERSITAS, IGBP, the Max Planck Institute for Biogeochemistry and an international Advisory Board with the main objectives of providing a global archive of plant traits, promoting trait-based approaches in ecology and biodiversity science and to support the design of a new generation of global vegetation models.

4.2 Professionals and practitioners

Capacity building

FUNCiTREE has built capacity of young professionals and future practitioners in Central America, Senegal, Mali, France, the Netherlands and Norway, supporting MSc and MPh theses, in total 19, in the research areas of biodiversity and functional ecology in agro-pastoral ecosystems, ecosystem functions and ecosystem services (the benefits perceived by society from life-systems), and farmers' knowledge integrated into farm and/or community level decision-making.

In addition to the formal education received under the MSc and MpH programs, young professionals in the project have received training on research methods, imparted through three methodological workshops and on-job training: **1**) on the "Agro-ecological Knowledge Tool-kit (AKT)", a method developed by the University of Bangor to collect and systematize ecological knowledge of farmers (Dixon et al. 2001). **2)** FUNCiTREE used a second approach to capture knowledge into so-called "Hugin Knowledge Bases" and used "Bayesian Belief Networks (BBN)", a graphical probability model for reasoning about uncertainty. BBN have been increasingly used in recent years as a decision-support tool due to advances made in algorithms and theory. **3)** FUNCiTREE has contributed to the development of the free-share online training to conduct qualitative surveys used in the social sciences to complement other survey methods: from constructing the problem statement up to the processing and interpretation of data, and including the design and conduct of semi-structured interviews (available in English, French and Spanish https://enquetes-cirad.iamm.fr/). **4)** FUNCiTREE conducted methodological workshops in Nicaragua and in West Africa, developed common protocols for data collection and performed field demonstrations and on job-training on plant eco-physiological and other functional-trait measurements. The experience gained by young professionals in Central America in this field has led, for instance, to the establishment of a research program in Agro-forestry/silvopastoral systems in the National Research Centre for Research in Agriculture in Colombia (CORPOICA, Corporación Colombiana de Investigación Agropecuaria).

FUNCiTREE held local meetings with the participation of professionals and practitioners at the end of the project. In Nicaragua, approximately 30 participants attended a workshop held on June 26th at the premises of the Ministry of Agriculture and Forestry (MAGFOR) with affiliation to the UN - Food and Agriculture Organization (FAO), the National Institute of Research in Agriculture (INTA), the National Agriculture University (UNA) and national and international research institutes (NITLAPAN, CIAT).

Based on the studies by MSc students in Rivas, Nicaragua, FUNCiTREE produced a technical bulletin in Spanish with 7 articles and an interview with the local government authorities about the condition of the tree cover in cattle farms and its contribution to sustainable production in Rivas, Nicaragua. Sánchez, D., Villanueva, C., Rusch, G. M., Ibrahim, M. and DeClerck, F.(eds.) 2013. Serie Técnica CATIE, Boletín Técnico no.60.

4.3 Decision-makers

- National decision-makers attended FUNCiTREE local meetings. The meeting in Nicaragua at MAGFOR had the participation of members of the Ministry of Agriculture and Forestry (MAGFOR) and from the Directorate of Climate Change (MARENA).
- Another meeting was organized at the municipality of Belén, Rivas on June 24th 2013 with participants from MAGFOR and the government of Belén Municipality, in addition to farmers from the area of the project and the local school of agriculture.
- Sánchez, D., Chávez, W., Rusch, G.M., Villanueva, C. & DeClerck, F. (2013) El papel de los bosques ribereños y sus servicios ecosistémicos en paisajes ganaderos: estrategia de conservación y restauración de la sub-cuencia Gil González, Belén, Rivas. Synthesis for Decision Makers – Policy Brief, PF17 CATIE, May 2013. ISSN 1659-3480
- FUNCiTREE has used Bayesian Belief Networks, a graphical probabilistic model, to represent the interconnections among farmers knowledge of the services (benefits) provided by tree species in the AFS they manage such as soil conservation, soil fertility, shade; and the preferences that farmers have for the different functions performed by the trees, indicating the production priorities. FUNCiTREE has used the HUGIN EXPERT software for this purpose, which offers a graphical interactive interface that enables to explore the consequences of different management decisions or options in terms of the kind of services that are promoted, the functional attributes of the different species, and whether there are trade-offs or synergies among the different functions and services. The software provider HUGIN EXPERT A/S, a Danish-based SME, offers the opportunity of publishing the models online, with the corresponding data documentation, from where decision-making scenarios can be explored. At the moment, two models have been uploaded, with data from the Mali case, one on stakeholder preferences for trees and one about functional group definitions according to rural stakeholder perceptions (ecosystem services). FUNCiTREE has an agreement with HUGIN EXPERT A/S to make available 6 models that will be published online when the featured issue is published. The models will be accessible online during one year after publication.

4.4 Farmers and local communities

The main activities directed to farmers and local communities have been the participation in field trials. For small, medium and large livestock producers in the dry Pacific Region of Nicaragua, and agro-pastoral communities in the case studies in Mali and Senegal, the least expensive way to feed their cattle is grazing in pastures and rangelands. However, this food source becomes critical during the dry season because the production of grasses almost completely stops, and there is no supply of fresh forage in this period (Ospina et al., 2012, Zapata et al. 2013). Only a few cases of cattle farms in the area of Rivas, Nicaragua have planning strategies to mitigate the effects of drought. To address the problem of forage shortage in the dry season, famers need strategies to stabilize forage supply throughout the year. The experiences and knowledge gained by the Center of Agricultural Tropical Research and Higher Education (CATIE) in Nicaragua and elsewhere in Central America show that farms retain several trees and shrubs species that maintain growth in the dry season with the potential to provide food (leaves and fruits) and to improve productivity and profitability of farms. The increase of the diversity and cover of live fences appears to be a feasible and acceptable way to enhance agroforestry multi-functionality in the farms in the case in Nicaragua. Also in the Sahel, shrubs and trees constitute a major source of energy and nutrition for sheep, goats and cattle in the dry season. The project FUNCiTREE explored, through specific studies, the different abilities of several woody species such as seasonality of growth and fruit production, forage quality, the preference by cattle, the ability of regrowth after pruning and the provision of other livestock feed (e.g. fruits), that can help cope with fodder shortage during the dry season.

FUNCiTREE contributed to establish trial plots of functionally diverse agro-sylvo-pastoral systems based on the lessons learnt from the research in livestock farms in the municipality of Belén in Rivas, Nicaragua, and in the two Millennium Villages.

Field trials are a tool to show agricultural innovations in participatory training processes in order to encourage the adaptation and improvement of technologies in farms. FUNCiTREE's most important messages have been to highlight the many functions that trees perform in AFS, to identify synergies and trade-offs among these functions ecologically, and from the farmers' perspective, and to demonstrate that in order to maintain multi- functions, a diversity of tree characteristics needs to be maintained. FUNCITREE has demonstrated the value of functional diversity in the farm in the AFS through the retention and the introduction of new species in paddocks selected through a participatory process by the farmer.

Field trials of multifunctional agro-sylvo-pastoral systems to promote adaptation of current practices in the seasonally-dry tropics

In Rivas, Nicaragua we selected two typical farms that were easily accessible, and where the famers were open to collaboration and willing to share the experience with neighbours and other stakeholders. In the first farm 0.7 hectares with SPS cut and carry fodder bank of *Gliricidia sepium* and *Cratylia argentea* was established. The incorporation of these trees into the pasture system constitutes an alternative of fodder supply throughout the year, and particularly in the dry season. The tree richness of the plot is 12 species, it has a density of scattered of 37 individuals/ha and a density of 23 trees/100 meters. In the second farm 3.1 hectares with SPS- *Andropogon gayanus*, *Cynodon plectostachyus*, *Digitaria decumbens* and *Panicum maximum (cv mombasa),* associated with *Leucaena lecucocephala* were established to be used for grazing and browsing of woody species. The tree richness of the plot is 33 species, and tree densities of 109 individuals/ha and 9 trees/100 meters. In both farms, scattered trees with light to moderate canopy cover predominate and will require pruning to reduce shading effect on the pasture. Also, the diversity of live fences was reinforced by increasing species richness and density (at least 25 individuals/100 meters, almost uniformly distributed). The woody component fulfils several functions as timber products, fruit for human consumption, feed resources, shade for livestock, soil conservation, carbon sequestration, provision of habitat for wildlife and others. The richness and abundance of species reflect the multi-functionality of the silvopastoral system, improving the productivity and ecological performance and the potential for adaptation to climate variability.

In Potou, Senegal, the rural communities in Leona use several agroforestry practices to manage soil fertility, control soil erosion (water and wind), produce fodder and food, for medicinal purposes, and for firewood and timber production. Thus, trees are very important resources in rural livelihoods. Cattle ranching is essentially the rule in the rural community of Leona, Potou, and the scarce grass vegetation in the dry season (8 months) forces the use of woody species. This situation leads often to an abuse of the tree fodder (pruning and sometimes immoderate cutting trees) that destroys the agricultural landscapes, thereby enhancing precarious living conditions of agro-pastoralists. The establishment of fodder banks could be a palliative to the sustainable use of natural resources in the village lands, therefore field trials on fodder banks have been one priority. Mixed fodder banks have been established at two sites. The installation of fodder banks was conducted with individuals practicing semi-intensive farming and the plots were arranged near water points. A plot of 0.5 ha per site has been demarcated and an experimental design with four blocks has been implemented. For each species (*Moringa oleifera*, *Ziziphus mauritiana*, *Bauhenia rufescens* and *Leuceana leucocephala*), 200 plants were planted in rows with 0.5 m spacing, and 1 m between rows. The analyses encompass evaluations of biomass every three months after the first 6 months, and maintaining the plants at about 50 cm. The leaves of the trees are harvested and dried before being distributed to animals in the form of balanced ratios composed of the fodder species for cattle and sheep. In both sites, seedling survival has been higher than 50%. The survival rate of *L. leucocephala* has been higher than that of other species (more than 98%) and that of *Z. mauritania*, the lowest (50% and 68% in each site, respectively).

Another important function of AF trees identified in Potou is soil erosion control and the protection of crops. In the communal production sites that have been promoted by the Millennium Villages Project (MVP) in the area, two main constraints have been identified, related to the exposure of soils and crops to wind erosion and damage caused by stray animals. The communities have expressed interest in setting up hedges (HV) and windbreaks (BV) using multiple drought-resistant species in 2 parcels mainly used for horticulture, one managed by the community (30 households) and one by a women group (70 households). In Wakhal Diam (2 ha) 400 plants have been planted (200 plants of each *Ziziphus mauritiana* and *Acacia mellifera*), and in Syer, ca. 700. During the establishment of the live-fences, leaders of peasant organizations were involved to ensure proper monitoring of irrigation and protection of plants to ensure survival. In both sites, survival rates were low and were therefore not evaluated in the participatory monitoring process. However, a nursery was installed in Wakhal Diam by the Millennium Villages Programme to establish the hedges during the rainy season 2013.

In Segou, Mali, the studies in FUNCiTREE have identified the preferences and needs of the communities in the project area. Within the Millennium Villages Project action area, and through community meetings, a planting scheme for 2012-2013 was established by which households decided about the species and number of trees to be planted. In total 1469 trees of 7 different species have been planted by 44 households in 7 villages. The majority of the trees were *F. albida* (45 %) and *Adansonia digitata* (38%). The uses of *F. albida* are the provision of fodder (leaves and fruits) and the improvement of crop yields. *A. digitata* is an important resource for human nutrition (leaves and fruits) and for the provision of fibres used in hand-crafting. By August 2013, 87% of the planted trees had survived, and approximately 3 800 new nursery plants of 6 species are ready to be planted. Fourteen species with a role in fodder provision during the dry season have been identified in the area.

Factors that contributed to the adoption and adoption risks: In Nicaragua, the use of incentives (seed, labour and technical assistance), and of field trips in communities where there are ongoing activities that promote practices in sylvo-pastoral systems are considered critical. Also, the selection and design of the sites and the AFSs established was done in conjunction with the farmer and in accordance with the specific benefits sought by that farmer. This process also provided the opportunity to build farmers' decision-making skills and ability to adapt information to his/her own needs. It is also important to stress that the production of fodder and feed for the animals provided by the AFS is one component of the production system and that needs to be improved alongside with other factors. For instance, in order to reach the best relationship between animal production and multi-functional SSP it is necessary to consider the animal genetic potential, animal health and water availability (quality and free access). If these factors are not considered, they become bottle-necks that will impair the benefits obtained from the new technologies proposed which could even show a lower performance than the traditional system.

The farmers take risks when they adapt their production system by incorporation new technologies. It takes also time before the improvements result in higher production, in addition to that some values of multi-functionality, such as the insurance against drought spells and climatic variability, increase resilience of the system but will likely not increase short-term productivity. Small-holder farmers may have limited economic capacity to take this kind of risks. These matters need to be taken into account when promoting new technologies to ensure that extension and demonstration activities take into account that the need of capital and labour, the long period of time expected since the establishment to production, and the erratic rainfalls during the year that may hamper the establishment of trees from seed or seedlings.

In Mali, determining the constraints and priorities of users of agro-silvo-pastoral system in the study area has laid the foundation for a sustainable exploitation of agro-forest parks, and has highlighted the need for an integrated approach that takes into account the interests of different focus groups. It has also shown the need for the implementation of accompanying measures, some of which fit into the overall policies or agricultural development programs. The factors determining the adoption of agroforestry technologies are socio-economic, technical, environmental and cultural, and vary depending on the kind of technology that is promoted.

Extension strategy: The field trials are representative of the conditions faced by producers in the area, so it can be used as a demonstration site to generate motivation among neighbouring farmers and as a centre of information exchange with public institutions and local universities. Neighbours and producer groups have come to know the process of the establishment, management and use of the sylvo-pastoral system, which is necessary to achieve the adaptation of current practices among other producers. It requires, however, monitoring by local institutions to help with questions from farmers and sustainable replication in time.

In Senegal, the trials are based on a principle of participatory approach in research and development, with the aim to enable farmers to learn about the positive effects of the including trees into their AFS, according to the trees' functional characteristics. The participatory approach will promote ownership of the results in the target populations with the intention of promoting a wider dissemination.

Both in Mali and Senegal, FUNCiTREE activities have been integrated into the Millennium Village Project (MVP) extension program. This concerns the improvement and enhancement of agroforestry technologies (TAF) including fodder banks, life fences and windbreaks, assisted natural regeneration, the domestication of fruit trees. MVP will contribute to the dissemination of research results by integrating into its program activities within "Sustainable Land Management" (SLM), "Agroforestry and land restoration". At the end of FUNCiTREE, MVP starts a major reforestation program, dissemination and consolidation of achievements in the field of agroforestry technologies.

In Senegal, ISRA, through FUNCiTree, has been heavily involved in the implementation of the reforestation program in the choice of species, seed collection, the domestication of trees. ISRA is also a prime contractor in the following programmes in the area of Potou: «Tree Seed Program, and partners in the «Planning Program for Economic Development in the Niayes Zone».

In Segou, Mali, it was demonstrated that factors that determine the adoption of agroforestry technology is the enhancement of production functions (wood, fodder, food) and service functions (fight against erosion, maintain soil moisture, soil fertility improvement), the organization of farmers in associations, the support to farmers by extension services, land ownership and the level of land degradation It is therefore necessary to take account of these factors in the development of agroforestry technologies to promote their adoption in these rural areas.

How can change be encouraged?

- Scale-up from plot to entire farms
- Identify farms with pastures that are highly multi-functional
- Farmers need to see concrete examples in order to trust new technologies
- Farmers need to see tangible results on animal production associated with multi-functional AFS
- It is important to recognize farmers' priorities, needs and access to resources
- Use of co-existing crops during the tree establishment period

Lesson learned

The transition from research to experimentation has positive outcomes with regard to demonstrating that more trees in pastures leads to increased benefit provision all year long. The adoption process is slow and gradual (step by step), but farmers recognize the value of the trees and the services they provide to the farm. There is growing interest among farmers to retain and manage trees in pastures, both as individual trees in pastures and as live fences.

To increase multifunctionality in sylvopastoral systems it is necessary: 1) to recognize priorities, needs and access to the resources of the producers, 2) to identify and learn how the producer manages a portfolio of species that offer various services according to the farm production objectives, 3) use of co-existing crops during the tree establishment period.

In Potou, Senegal, despite a difficult environment, agro-pastoralists remain receptive to the views and experiences gained through the project. They are determined to integrate into their farming operations production systems that not only improve their income and living conditions, but also to reduce the risk of environmental degradation. The communities in Leona, Potou, however are poorly armed for the sustainable management of agroforestry systems due to many technical limitations such as the choice of species and inadequate knowledge about their biology, including the best seed collection periods, how to produce saplings and not least the management of the AFS. In FUNCiTREE, the MVP and Institut Senegalese de la Recherche Agronomique (ISRA) cooperated in the holding a series of capacity building sessions on technical seed collection, nursery and plantations.

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Functional Diversity:
An ecological framework for sustainable and adaptable agro-forestry systems in landscapes of semi-arid ecoregions.

Based on the principles of functional ecology, FUNCiTREE addresses the provision of multiple services of silvopastoral systems (SPS) in semi-arid regions in Africa and Central America. FUNCiTREE aims to provide farmers in the regions with a portfolio of regionally suitable tree species that are capable of providing multiple services. The project integrates theories and concepts from agroforestry and ecological science and will provide a scientifically based model for the design of modernized SPS.

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