Service functions of agroforestry systems

J Beer[1], C A Harvey, M Ibrahim, J M Harmand, E Somarriba, F Jiménez

Key words: biodiversity, cacao, carbon capture, coffee, soil conservation, sustainable livestock systems, water quality.

Abstract

This article presents a brief review of the main environmental service functions that are provided by agroforestry systems (AFS): 1) maintenance of soil fertility/reducing erosion *via* organic matter inputs to the soil, N fixation and nutrient recycling; 2) conservation of water (quantity and quality) *via* greater infiltration and reduced surface runoff that could contaminate water courses; 3) carbon capture, emphasizing the potential of silvopastoral systems; and 4) biodiversity conservation in fragmented landscapes. These service functions complement the products that AFS provide (commercial and home use; e.g., fuel wood, timber, fruits) but farmers are rarely rewarded for them. More research is needed on the possible tradeoffs between the different service functions when the tree component of agricultural systems is increased; e.g., maximizing carbon capture with high-density tree monocultures will have negative effects on biodiversity conservation. Methods for managing financial incentives, as rewards to farmers who provide these services by adopting/improving AFS, in order to leverage better land use, also have to be developed and tested in different socio economic frameworks. A major limitation to the promotion of AFS is the dearth of economic analyses that include valuation of these service functions.

[1] Author for correspondence John Beer, Apartado 44, CATE, Turrialba, Costa Rica. Fax (00506) 5561576. E.mail: jbeer@catie.ac.cr. Department of Agriculture and Agroforestry, Centro Agronómico Tropical de Investigación y Enseñanza, Turrialba, Costa Rica.

Prepared for the World Forestry Congress, Quebec, Canada September 2003

Introduction

The formal study and promotion of agroforestry systems (AFS), a method of land management used since time immemorial throughout the "old" as well as the "new" Worlds (see references to ancient Greek and other writers in Robinson 1985), started at the end of the 1970´s (De las Salas 1979; Steppler and Nair 1987). Initially the focus was on the description and inventory of traditional AFS, mostly in the tropics (Nair 1989). This was followed by evaluations of productivity of both existing and novel AFS and more recently studies on the interactions between the component species with a view to improving management and profitability (or reduced risk) (Schroth and Sinclair 2003). At the end of the 1990´s, increased international concern about environmental issues led to new treaties (e.g., Kyoto Protocol) and emphasis on the environmental service functions of alternative land uses. It was rapidly recognized that AFS had many advantages over monocultures respect the increasing demand for multi-functional agriculture and that AFS provide important environmental services. Other recognized potentials of AFS include aesthetic values (e.g., city parklands and tree Savannahs), buffering of protected areas and agroecotourism (e.g., guided tours of indigenous cacao AFS in Costa Rica and Belize).

The payment of incentives to farmers whose land use protects natural resources and hence provides a service to the local, national and global community is a new option, which could contribute to the financial viability of farms. The title of this congress "Forests, source of life" offers an opportunity to emphasize and review this important new focus in agroforestry programs; i.e., the quantification and valuation of service functions of tree-crop and/or tree-animal production systems. The main service functions of agroforestry systems (AFS) considered in this paper are soil conservation, conservation of water quality, carbon capture (climate change) and biodiversity conservation.

How AFS can reduce soil erosion and maintain soil fertility

The concepts of soil amelioration by trees in AFS have been reviewed by Young (1989) and Buresh and Tian (1998) among other authors. Soil improvement in AFS is linked to the growth of N-fixing trees or deep-rooted trees and shrubs, which increase N availability through biological fixation, recycle plant nutrients from depth (especially in dry zones) and build up soil organic matter (Charreau and Vidal 1965; Beer 1988; Kessler and Breman 1991; Rao et al. 1998).

Formal AFS research (especially in Africa) initially focused on ways of maintaining soil fertility in annual cropping systems by using leguminous shrub species; e.g., in alley cropping (Kang and Reynolds 1989) and tree improved fallows (see below). Less research has been carried out on "barrier" AFS (alley cropping along the contour of slopes), though the use of strips of grass and other annual species to trap sediments and nutrients, slow runoff and increase infiltration has been widely promoted by NGO's in Central America and Asia. Although many of these AFS studies gave promising results on-station or in researcher managed on-farm trials, for productivity and soil fertility parameters, adoption of alley cropping systems was disappointing due to: high labor and land requirements; in some cases because of the lack of commercial or home use products from the tree/ shrub component; and the long time required to show positive changes (Carter 1995).

Planted tree fallows are a potential solution to declining fertility due to shortened fallow periods (Anderson and Sinclair 1993; Harmand and Njiti 1998; Ganry et al. 2001). Relative to herbaceous fallows, greater accumulation of organic material and nutrient storage in biomass, increased root density as well as greater vertical extension of tree roots in tree fallows (especially in drier areas) help maintain nutrient stocks by reducing leaching losses or by taking up nutrients from deep layers. N availability, determined by inorganic soil N or aerobic N mineralisation at 0 to 20 cm depth, and crop yields can be significantly higher under the N fixing trees than under other tree species or grass fallows (Harmand and

Balle 2001). Fast-growing leguminous trees can accelerate restoration of N, P and K stocks in the crop layer but may not restore completely Ca and Mg stocks (Szott and Palm 1996).

The benefits of perennial crop (e.g., coffee and cacao) shade trees include reduced soil erosion as natural litter fall or pruning residues cover the soil and reduce the impact of raindrops, improve soil structure, increase soil N content and enhance nutrient retention (Beer et al. 1998; Fassbender et al. 1991).

Although economic analyses of all the above mentioned systems are available (e.g., Sullivan et al. 1992) they do not take into account all the short and long term benefits of including the trees, such as improvements or maintenance of soil fertility, nor the possible impact on profitability of service function incentives.

How AFS can contribute to maintaining water quantity and quality

The potential of AFS to help secure water supplies (quantity and quality) is the least studied service function. The trees in AFS influence water cycling by increasing rain interception, transpiration and retention of water in the soil, reducing runoff and increasing infiltration. For example, Bharati *et al.* (2002) reported that infiltration in areas cultivated with maize or soya, or under pastures, was five times less than under riparian strips cultivated with a variety of plant and tree species, suggesting that the latter had a much higher potential to avoid surface runoff (containing contaminating substances) reaching water courses. Moreover, trees in AFS can cycle nutrients in a conservative manner preventing their loss through nutrient leaching (Imbach *et al*. 1989). Hence, AFS can reduce ground water contamination by agrochemical residues such as nitrate and other substances that are harmful to the environment and human health. As a result, micro-watersheds with forest cover or AFS, which cover a high percentage of the soil surface, produce high quality water (Stadtmüller 1994).

A series of studies in Costa Rica have illustrated some of these interactions. For example, rain interception was 16 and 7.5% in coffee (*Coffea arabica*) plantations associated with *Erythrina poeppigiana* (555 trees/ha) or *Cordia alliodora* (135 trees/ha), respectively (Jiménez 1986). Nitrate losses through leaching were higher from unshaded coffee plantations than from those containing shade trees in areas where high coffee yields had been achieved through large additions of N from chemical fertilizers (Babbar and Zak 1995) probably because of higher rates of transpiration in the AFS (Avila 2003). In this country, legislation recognizes the environmental services of AFS as well as from forested land but once again economic analyses that take into account the medium long-term environmental benefits are needed to determine the true value of the AFS.

How AFS can sequester C and reduce emissions of green house gases

Highly productive AFS, including silvopastoral systems, can play an important role in C sequestration in soils and in the woody biomass (above and underground). For example, in Latin America, traditional cattle management involves grass monocultures, which degrade about 5 years after establishment, releasing significant amounts of carbon to the atmosphere. Veldakamp (1994) estimated that the cumulative net release of CO_2 from low productivity pastures (*Axonopus compressus*) varied from 31.5 (Humitropept soil) to 60.5 Mg C ha^{-1} (Hapludand soil) in the first 20 years after forest clearing. Well-managed silvopastoral systems can improve overall productivity (Bustamante *et al.* 1998; Bolivar *et al.* 1999), while sequestering C (López *et al*. 1999, Andrade 1999), a potential additional economic benefit for livestock farmers. Total C in silvopastoral systems varied between

68 – 204 t ha^{-1}, with most C stored in the soil, while annual C increments varied between 1.8 to 5.2 t ha^{-1} (Table 1).

The amount of C fixed in silvopastoral systems is affected by the tree/shrub species, density and spatial distribution of trees, and shade tolerance of herbaceous species (Nyberg and Hogberg 1995; Jackson and Ash 1998). On the slopes of the Ecuadoran Andes, total soil C increased from 7.9% under open *Setaria sphacelata* pasture to 11.4% beneath the canopies of *Inga* sp. but no differences were observed under *Psidium guajava.* Soils under *Inga* contained 20 Mg C ha^{-1} more in the upper 15 cm than under open pasture (Rhoades *et al*. 1998).

Few studies have been conducted to determine how payments for C sequestration will affect farm income and land use changes on livestock farms (Ruiz 2002). An *ex-ante* analysis showed that farmers could increase income by more than 10% when 20 % of grass monoculture pastures are transformed into silvopastoral systems (e.g., fodder banks and dispersed trees in pastures) and secondary forest. This economic analysis, conducted on dual purpose cattle farms, suggested that gross potential income generated from carbon stored in the trunks of trees was 253 US\$ yr^{-1} for a 70 ha farm (C price 7 US\$ ton^{-1}) (Pomareda 1999). Incentives for farmers to adopt silvopastoral systems that store more carbon and prevent pasture degradation are being developed and tested in Colombia, Costa Rica and Nicaragua (CATIE coordinated GEF project) but a lot more work is needed to realize the full potential of this approach.

How AFS can contribute to the maintenance and management of biodiversity in agricultural landscapes

AFS can play an important role in the conservation of biodiversity within deforested, fragmented landscapes by providing habitats and resources for plant and animal species, maintaining landscape connectivity (and thereby facilitating movement of animals, seeds and pollen), making the landscape less harsh for forest dwelling species by reducing frequency and intensity of fires, potentially decreasing edge effects on remaining forest fragments and providing buffer zones to protected areas (Schroth et al. in press) (Table 2). AFS cannot provide the same niches and habitats as the original forests and should never be promoted as a conservation tool at the expense of natural forest conservation. However they do offer an important complementary tool for conservation and should be considered in landscape-wide conservation efforts that both protect remaining forest fragments and promote the maintenance of on-farm tree cover in areas surrounding the protected areas or connecting them; e.g., in the Central American Biological Corridor .

The degree to which AFS can serve conservation efforts depends on a variety of factors, including the design and origin of the AFS (particularly its floristic and structural diversity), its permanency in the landscape, its location relative to remaining natural habitat and the degree of connectivity within the habitat, as well as its management and use, particularly pollarding, use of herbicides or pesticides, harvesting of timber and non-timber products and incorporation of cattle, goats, etc. (Table 2). In general, the more diverse the AFS, the lower its management intensity and the nearer it is to intact habitat, the greater its ability to conserve native plant and animal species. Certain AFS, which closely mimic natural ecosystems (for example, home gardens, agroforests as well as rustic coffee and cacao AFS), provide a variety of niches and resources that support a high diversity of plant and animals, though usually less than that of intact forest (Perfecto et al. 1996; Rice and Greenberg 2000). However, even AFS with low tree densities and low species diversity may help in maintaining biotic connectivity (Harvey *et al*. in press).

Equally important is the attitude of local people towards biodiversity conservation and the perceived resulting benefits (products, services) and losses (e.g., crop damage or raiding, loss of animals), which in turn cause local people to favor or discourage native plants and animals. When hunting intensity is high, populations of game species within AFS are unlikely to be viable regardless of whether there is appropriate habitat available.

While there is a growing literature on biodiversity within AFS, important questions still remain about the long-term viability of animal and plant populations in AFS and what will happen to these populations if the surrounding landscape is increasingly deforested. Most studies to date have monitored or inventoried biodiversity within landscapes that still retain some forest cover, have focused on a few taxa and have been conducted on small spatial and temporal scales. Multi-taxa, multi-scale and long-term studies are needed before the true value of AFS for conservation is known.

Despite these limitations in our current knowledge, there is already sufficient evidence that AFS offer more hope for conservation of plant and animal species than the monoculture crops they usually replace. This finding has led to exciting new initiatives to use AFS as tools for conservation in already deforested and fragmented landscapes. Many of these initiatives include either the direct payment to farmers for biodiversity conservation (e.g., GEF silvopastoril project led by CATIE; payment for environmental services for AFS in Costa Rica) or the certification of products stemming from these AFS as biodiversity or ecologically friendly (e.g., bird-friendly coffee [Smithsonian Migratory Bird Center 1999]).

Conclusions

The service functions provided by AFS, such as soil conservation, carbon capture, water quality and biodiversity conservation are gaining the attention of researchers, planners and politicians. Although some results are already available on the environmental services of selected AFS in selected sites, more research is clearly needed on the potential tradeoffs between the different services involved and on the valuation and financial mechanisms required to directly benefit farmers who provide these services. Complex integrative studies, which focus on the possible changes in all the service functions when the tree component of agricultural systems is increased, as well as on productivity and profitability of AFS, are going to be needed to achieve optimal land use. Without doubt, conceptual, process and other models will have to be used to achieve this goal. Solid base line studies, monitoring and evaluation, to validate and demonstrate to different levels of our societies the positive impacts of AFS on the long term ecological and financial sustainability of these multifunctional agricultural production systems, are also needed.

Bibliography

Anderson L.S. and F.L. Sinclair, 1993. Ecological interactions in agroforestry systems. Agroforestry Abstracts 54: 57-91.

Andrade C., H.J., 1999. Dinámica productiva de sistemas silvopastoriles con *Acacia mangium* y *Eucalyptus deglupta* en el trópico húmedo. Tesis Mag. Sc. CATIE, Turrialba, Costa Rica. 70 p.

Avila H. E., 2003. Dinámica del nitrógeno en el sistema agroforestal *Coffea arabica* con *Eucalyptus deglupta* en la zona Sur de Costa Rica, Tesis M.Sc., Turrialba, Costa Rica, CATIE. 89 p.

Avila V., G., 2000. Fijación y almacenamiento de carbono en sistemas de café bajo sombra, café a pleno sol, sistemas silvopastoriles y pasturas a pleno sol. Tesis Mag. Sc. CATIE, Turrialba, Costa Rica. 98 p.

Babbar, L. and D. R. Zak, 1995. Nitrogen loss from coffee agroecosystems in Costa Rica: leaching and denitrification in the presence and absence of shade trees. Journal of Environmental Quality 24 (2): 227-233.

Beer, J., 1988. Litter production and nutrient cycling in coffee (*Coffea arabica*) or cacao (*Theobroma cacao*) plantations with shade trees. Agroforestry Systems 7:103-114.

Beer, J., R. Muschler, D. Kass and E. Somarriba, 1998. Shade management in coffee and cacao plantations. Agroforestry Systems 38:139-164.

Bharati, L., K.H. Lee, T.M. Isenhart and R.C. Schultz, 2002. Soil-water infiltration under crops, pasture and established riparian buffer in Midwestern USA. Agroforestry Systems 56:249-257.

Bolívar, D., M. Ibrahim, D. Kass, F. Jiménez and J.C. Camargo, 1999. Productividad y calidad forrajera de *Brachiaria humidicola* en monocultivo y en asocio con *Acacia mangium* en un suelo ácido en el trópico Húmedo. Agroforestería en las Américas 6 (23):48-50.

Botero, J.E. and P.S. Barker, 2002. Coffee and biodiversity; a producer-country perspective. In: Coffee Futures, CENICAFE, Colombia, pp.2-11.

Bustamanate J., M. Ibrahim and J. Beer, 1998. Evaluación agronómica de ocho gramíneas mejoradas en un sistema silvopastoril con poró (*Erythrina poeppigiana*) en el trópico húmedo de Turrialba. Agroforestería en las Américas 5(19): 11-16.

Buresh R.J. and G. Tian, 1998. Soil improvement by trees in sub-Saharan Africa. Agroforestry Systems 38 : 51-76.

Carter, J., 1995. Alley farming: have resource-poor farmers benefited. ODI-Natural Resource Perspectives 3. London UK.

De las Salas, G. (ed), 1979. Agroforesty systems in Latin America (Proceedings) CATIE, Turrialba, Costa Rica, 220 p.

Charreau C. et Vidal P., 1965. Influence de l'*Acacia albida* Del. sur le sol, nutrition minérale et rendements des mils Pennisetum au Sénégal. Agronomie Tropicale 20: 600-626.

Fassbender, H.W., J. Beer, J. Heuveldop, A. Imbach, G. Enriquez and A. Bonnemann, 1991. Ten year balances of organic matter and nutrients in agroforestry systems at CATIE, Costa Rica. Forest Ecology and Management 45:173-183.

Fischer, J. and D. B. Lindenmayer, 2002. The conservation value of paddock trees for birds in a variegated landscape in southern New South Wales. 2. Paddock trees as stepping stones. Biodiversity and Conservation 11: 833-849.

Forman, R. T. T. and J. Baudry, 1984. Hedgerows and hedgerow networks in landscape ecology. Environmental Management 8(6): 495-510

Fritz, R. and G. Merriam, 1993. Fencerow habitats for plants moving between farmland and forests. Biological Conservation 64: 141-148.

Fritz, R. and G. Merriam, 1996. Fencerow and forest edge architecture in Eastern Ontario farmland. Agriculture, Ecosystems and Environment 59: 159-170.

Ganry F., C. Feller, J.M. Harmand and H. Guibert, 2001. Management of soil organic matter in semiarid Africa for annual cropping systems. Nutrient Cycling in Agroecosystems 61:105-118.

Guevara, S. , J. Laborde and G. Sanchez, 1998. Are isolated remnant trees in pastures a fragmented canopy? Selbyana 19(1): 34-43.

Guevara, S. and J. Laborde, 1993. Monitoring seed dispersal at isolated standing trees in tropical pastures: consequences for local species availability. Vegetatio 107/108: 319-338.

Harmand, J.M. and P. Balle, 2001. La jachère agroforestière (arborée ou arbustive) en Afrique tropicale. In: C. Floret and R. Pontanier (eds.), La jachère en Afrique tropicale: Rôles, aménagement, alternatives. De la jachère naturelle à la jachère améliorée. Le point des connaissances. Libbey, Paris, pp. 265-292.

Harmand, J.M. and C.F. Njiti, 1998. Effets de jachères agroforestières sur les propriétés d'un sol ferrugineux et sur la production céréalière. Agriculture et Développement, Spécial Sols Tropicaux 18: 21-30.

Harvey, C. A, 2000. The colonization of agricultural windbreaks by forest trees: effects of windbreak connectivity and remnant trees. Ecological Applications 10: 1762-1773.

Harvey, C.A. and W. A. Haber, 1999. Remnant trees and the conservation of biodiversity in Costa Rican pastures. Agroforestry Systems 44: 37-68.

Harvey, C. A., C.F. Guindon, W. A. Haber, D. Hamilton DeRosier and K. G. Murray, 2000. The importance of forest patches, isolated trees and agricultural windbreaks for local and regional biodiversity: the case of Monteverde, Costa Rica. XXI IUFRO World Congress, 7-12 August 2000, Kuala Lumpur, Malaysia, International Union of Forestry Research Organizations, Subplenary sessions, Vol 1: pp 787-798.

Harvey, C. A. , N. Tucker and A. Estrada (in press). Live fences, isolated trees and windbreaks: tools for conserving biodiversity in fragmented tropical landscapes? In: . Schroth, G., G. A.B. da Fonseca, C. A. Harvey, H. L. Vasconcelos and A. M. Izac (eds.) Agroforestry and Biodiversity Conservation in Tropical Landscapes. Island Press.

Hietz-Seifert, U., P. Heitz and S. Guevara, 1996. Epiphyte vegetation and diversity on remnant trees after forest clearance in southern Veracruz, Mexico. Biological Conservation 75:103-111.

Holl, K.D., M.E. Loik, E.H.V. Lin and V.A. Samuels, 2000. Tropical montane forest restoration in Costa Rica: overcoming barriers to dispersal and establishment. Restoration Ecology 8:339-349.

Ibarra-Nuñez, G., J. A. Garcia and M. A. Moreno, 1995. Diferencias entre un cafetal orgánico y uno convencional en cuanto a diversidad y abundancia de dos grupos de insectos. In: Memorias de la primera conferencias internacional IFOAM sobre café orgánico. Universidad Autónoma de Chapingo, México. pp. 115-129.

Imbach, A. C., H.W. Fassbender, R. Borel, J. Beer and A. Bonnemann, 1989. Modeling agroforestry systems of cacao (*Theobroma cacao*) with laurel (*Cordia alliodora*) and *Erythrina poeppigiana* in Costa Rica. Water balances, nutrient inputs and leaching. Agroforestry Systems 8:267-287.

Jackson, J and A. Ash, 1998. Tree-grass relationships in open eucalypt woodlands of northern Australian: influence of trees on pasture productivity, forage quality and species distribution. Agroforestry Systems 40: 159 –176.

Jiménez, F., 1986. Balance hídrico de dos sistemas agroforestales: café-poro y café laurel en Turrialba, Costa Rica. Tesis MSc. UCR-CATIE, Turrialba, C.R. 104 p.

Kang B.T. and L. Reynolds (eds), 1989. Alley farming in the Humid and Sub humid Tropics. Proceedings. IDRC, Ottawa, Canada. 251 p.

Kessler J.J. and H. Breman, 1991. The potential of agroforestry to increase primary production in the sahelian and sudanian zones of West Africa, Agroforestry Systems 13: 41-62.

Lavelle, P., B. Sencapati and E. Barrios, 2003. Soil macrofauna. In: G. Schroth and F. L. Sinclair (eds). Trees, crops and soil fertility concepts and research methods. CABI, Wallingford, U.K. pp. 303-323.

López M., A., A. Schlönvoigt, M. Ibrahim, C. Kleinn and M. Kanninen, 1999. Cuantificación del carbono almacenado en el suelo de un sistema silvopastoril en la zona Atlántica de Costa Rica. Agroforestería en las Américas 6 (23):51-53.

Martinez, E. and W. Peters, 1996. La caficultora biológica: la finca Irlanda como estudio de caso de un diseño agro ecológico. In: Trujillo, J, F. de León-González, R. Calderón and P. Torres-Lima (eds.). Ecología aplicada a la agricultura: temas selectos de México: Universidad Autónoma Metropolitana, México, D.F. pp.159-183.

Moguel, P. and V. M. Toledo, 1999. Biodiversity conservation in traditional coffee systems of Mexico. Conservation Biology 13(1):11-21.

Molano, J.G., M. P. Quiceno and C. Roa (in press). El papel de las cercas vivas en un sistema de producción agropecuaria en el pidemonte llanero. In: Sánchez, M. and M. Rosales (eds.) Agroforestería para la producción animal en América Latina II. Memorias de la segunda conferencia electrónica de la FAO. Estudio FAO de Producción y Sanidad Animal, Rome.

Mora C.V., 2001. Fijación, emisión y balance de gases de efecto invernadero en pasturas en monocultivo y en sistemas silvopastoriles de fincas lecheras intensivas de las zonas altas de Costa Rica. Tesis Mag. Sc. CATIE, Turrialba, Costa Rica. 92 p.

Nair, P. K. (ed), 1989. Agroforestry systems in the tropics. Kluwer, Dordrecht, The Netherlands, 664 p.

Nyberg G. and P. Hogberg, 1995. Effects of young agroforestry trees on soils in on-farm situations in western Kenya. Agroforestry Systems 32: 45-52.

Perfecto, I., R. A. Rice, R. Greenberg and M.E. Van der Voort, 1996. Shade coffee: a disappearing refuge for biodiversity. BioScience 46(8): 598-608.

Pomareda C., 1999. Perspectivas en los mercados y oportunidades para la inversión en ganadería. In: Pomareda C and H. Steinfeld (eds.) Intensificación de la ganadería en Centroamérica: Beneficios economicas y ambientales. CATIE/FAO/SIDE. Costa Rica. pp 53 -74.

Rai, P., R.S Yadav, K.R. Solanki, G.R. Rao and R. Singh, 2001. Growth and pruned production of multipurpose tree species in silvo-pastoral systems on degraded lands in semi-arid region of Uttar Pradesh, India. Forests, Trees and Livelihoods 11: 347-364.

Rao, M. R., P. K. R. Nair and C. K. Ong, 1998. Biophysical interactions in tropical agroforestry systems. Agroforestry Systems 38 : 3-50.

Rhoades, C.C., G.E. Eckert and D.C. Coleman, 1998. Effect of pasture trees on soil nitrogen and organic matter: implications for tropical montane forest restoration. Restoration Ecology 6(3): 262-270.

Rice, R. and R. Greenberg, 2000. Cacao cultivation and the conservation of biological diversity. Ambio 29:3.

Ricketts T.H., G.C. Daily, P.R. Ehrlich and J.P. Fay, 2001. Countryside biogeography of moths in a fragmented landscape: biodiversity in native and agricultural habitats. Conservation Biology 15:378-388.

Robinson, P.J., 1985. Trees as fodder crops In: Cannell, M.G.R. and J.E. Jackson (eds) Attributes of trees as crop plants. Institute of Terrestrial Ecology, UK. pp. 281-300.

Ruiz G., A. 2002. Fijación y almacenamiento de carbono en sistemas silvopastoriles y competitividad económica en Matiguás, Nicaragua. Tesis Mag. Sc. CATIE, Turrialba, Costa Rica. 106 p.

Schroth, G., G. A.B. da Fonseca, C. A. Harvey, H. L. Vasconcelos and A. M. Izac (in press). Agroforestry and Biodiversity Conservation in Tropical Landscapes. Island Press. Washington, D.C.

G. Schroth and F. L. Sinclair (eds), 2003. Trees, crops and soil fertility concepts and research methods. CABI, Wallingford, U.K.

Slocum, M. G. and C. C. Horvitz, 2000. Seed arrival under different genera of trees in neotropical pasture. Plant Ecology 149: 51-62.

Smithsonian Migratory Bird Center, 1999. El cultivo de café con sombra: Criterios para cultivar un café "Amistoso con las Aves". http://web2.si.edu/smbc/coffee/criteria/html.

Stadtmüller, T., 1994. Impacto hidrológico del Manejo Forestal en bosques naturales tropicales: medidas para mitigarlo. CATIE, Turrialba, C.R. 62 p.

Steppler, H.A. and P.K.R. Nair (eds), 1987. Agroforestry: a decade of development. ICRAF, Nairobi, Kenya.

Suarez, A. 2001. Aprovechamiento sostenible de madera de Cordia alliodora y Cedrela odorata de regeneración natural en cacaotales y bananales indígenas de Talamanca, Costa Rica. MSc. Thesis, CATIE, Turrialba, Costa Rica. 70 p.

Sullivan, G.M., S.M. Huke and J.M. Fox (eds.), 1992. Financial and economic analyses of agroforestry systems. NFTA, Honolulu, Hawaii.

Szott, L.T. and C.A. Palm, 1996. Nutrient stocks in managed and natural humid tropical fallows. Plant and Soil 186: 293-309.

Veldkamp E., 1994. Soil organic carbon dynamics in pastures established after deforestation in the humid tropics of Costa Rica. PhD dissertation, Wageningen Agricultural University, The Netherlands. 117 p.

Villanueva N., C., 2001. Ganadería y beneficios de los sistemas silvopastoriles en la cuenca alta del Río Virilla, San José, Costa Rica. Tesis Mag. Sc. CATIE, Turrialba, Costa Rica. 107 p.

Young, A., 1989. Agroforestry for soil conservation. C.A.B. International/ICRAF, Wallingford, UK. 276 p.

Table 1. Carbon storage and carbon fixation in some silvopastoral and pasture systems

Zone	Soil organic carbon[1]	Above-ground carbon[2]	Total carbon	Carbon fixation[3]	Reference
System (age in years)	(t ha^{-1})	(t ha^{-1})	(t ha^{-1})	(t ha^{-1} yr^{-1})	
Humid lowlands, Northern Region, Costa Rica					López *et al.* (1999)
Panicum maximum monoculture	233 ± 8		233		
P. maximum – Cordia alliodora (≤ 3)	177 ± 8	2.3	179		
P. maximum – C. alliodora (3-7)	196 ± 21	8.8	205		
P. maximum – C. alliodora (≥ 7)	175 ± 23	26.8	202		
Lower montane ecosystems, Ecuadorian Andes					Rhoades *et al*. 1998)
Setaria sphacelata pasture	69.0				
S. sphacelata – Inga sp.	87.3				
S. sphacelata – Psidium guajava	73.6				
Humid lowlands, Atlantic Zone, Costa Rica					Andrade (1999)
Brachiaria brizantha – Eucalyptus deglupta (2)		3.7		1.8	
B. decumbens – E. deglupta (2)		3.8		1.9	
P. maximum – E. deglupta (2)		4.7		2.3	
B. brizantha – Acacia mangium (2)		3.9		1.9	
B. decumbens – A. mangium (2)		3.9		1.9	
P. maximum – A. mangium (2)		4.2		2.1	
Humid lowlands, Atlantic Zone, Costa Rica					Avila (2000)
B. brizantha – A mangium (3)	86.6 ± 17.5	8.90 ± 0.03	95.5	2.20	
B. brizantha – E. deglupta (3)	87.3 ± 0.4	7.48 ± 0.26	94.8	1.80	
B. brizantha monoculture	66.2 ± 16.4	2.04 ± 0.16	68.3		
Ischaemum indicum monoculture	84.2 ± 11.1	0.12 ± 0.03	84.3		
Highlands, Volcanic Cordillera, Costa Rica					Mora (2001)
Pennisetum clandestinum monoculture	494.5 ± 34.6			5.16 ± 0.30	
P. clandestinum and trees	572.5 ± 29.5			5.14 ± 0.25	
Cynodon nlemfuensis monoculture	756.5 ± 54.1			4.79 ± 0.18	
C. nlemfuensis and trees	624.1 ± 65.1			4.91 ± 0.04	
Jhansi, India					Rai *et al*. (2001)
Mixed pasture[4]	0.47				
Mixed pasture – *Acacia nilotica* var. *cupressiformis*	0.67 ± 0.04				
Mixed pasture – *Dalbergia sissoo*	0.71 ± 0.04				
Mixed pasture – *Hardwickia binata*	0.71 ± 0.05				
Highlands, Volcanic Cordillera, Costa Rica					Villanueva (2001)
P. clandestinum monoculture	184.6 ± 32.2		184.6		
P. clandestinum – Alnus acuminata (2)	186.6 ± 46.2	1.07 ± 0.64	187.7		

P. clandestinum – A. acuminata (3)	195.5 ± 24.8	4.17 ± 1.71	199.6	
P. clandestinum – A. acuminata (4)	196.7 ± 9.1	6.20 ± 0.8	202.9	
Seasonally dry hillsides, Central Nicaragua				Ruiz (2002)
Naturalised grass monoculture	150.0 ± 14.7	1.37 ± 0.19	151.4 ± 15.6	
Naturalised grasses and trees	155.2 ± 13.3	9.1 ± 2.7	164.4 ± 14.2	
Improved grass monoculture	157.7 ± 14.7	1.65 ± 0.17	159.4 ± 15.7	
Improved grasses and trees	155.1 ± 15.3	15.0 ± 3.0	170.2 ± 16.2	

[1.] Soil organic carbon values correspond to the following soil depths: 0-50 cm (López et al 1999), 0-15 cm (Rhoades *et al*. 1998), 0-30 cm (Avila 2000), 0-100 cm (Mora 2001), 0-60 cm (Villanueva 2001) and 0-80 cm (Ruiz 2002).

[2.] Above-ground carbon values were estimated from carbon stored in trees only (López et al 1999; Villanueva 2001) or in trees and pasture (Andrade 1999; Avila 2000; Ruiz 2002).

[3.] Carbon fixation values correspond to carbon fixed in tree biomass (Avila 2000) and in soils (Mora,2001).

[4.] Pasture consisted of *Chrysopogon fulvus*, *Stylosanthes hamata* and *S. scabra*.

Table 2. General principles of how to enhance biodiversity conservation within agroforestry systems (AFS) and examples of studies illustrating the importance of each principle.

Principle	Examples
Maximize the floristic and structural diversity of the AFS by including a variety of plant species of different life forms (herbs, epiphytes, lianas, shrubs and trees) with different architectures (AFS with perennial crops are generally better than AFS with annuals or silvopastoral systems)	Bird, plant, mammal and insect species diversity and abundance are greater in AFS that have high floristic and structural diversity (i.e., rustic coffee systems) than in simple AFS or agricultural monocultures. 184 bird species were found in 'rustic' coffee systems in Mexico (Moguel and Toledo 1999), compared to only 6-12 species in sun-grown coffee (Martinez and Peter 1996). In naturally-regenerated live fences in Colombia, 105 bird species of 45 families were found, with older, more structurally complex live fences having more bird species and more birds typical of forest borders and secondary growth than younger, less complex live fences (Molano et al. in press).
Include native plant species (especially those that produce flowers, fruits or resources that are important for wildlife)	Trees and other plants within AFS provide important habitats and resources for many mammals, insect and other animal species-particularly arboreal species. In Veracruz, Mexico, 73 bird species visited four isolated fig trees (*Ficus yoponensis* and *F. aurea*) in pastures (Guevara and Laborde 1993). Similarly, isolated remnant trees in Costa Rican pastures were visited by at least 27 frugivorous bird species (Holl *et al,* 2000). In coffee AFS, trees with long fruiting and flowering seasons are particularly important for hummingbirds, tanagers and fruit and flower feeding bats (Botero and Barker 2002).
Ensure that tree cover is available year-round	Year-round tree cover is important to ensure permanent habitat and resources to both plants and animals, and to maintain a constant microclimate (Smithsonian Migratory Bird Center 1999).
Retain epiphytes, vines, lianas, weeds and other plants within the AFS that can provide niches for other organisms	Trees in AFS can retain a large number of epiphytes, lianas and other plants. 58 epiphyte species were found in silvopastoral systems in Mexico, representing 37% of the epiphyte flora of the region (Hietz-Seifert *et al.* 1996). These epiphytes, in turn, provide shelter, nest sites and resources for a variety of other organisms. The presence of weeds and shrubby vegetation within coffee AFS favors bird and butterfly diversity (Botero and Barker 2002).
Maintain a variety of microhabitats by retaining dead trees, fallen tree trunks, rocks and leaf litter within the AFS	AFS with a greater variety of microhabitats are likely to support a greater animal and plant diversity than those lacking these microhabitats. Leaf litter quantity and quality as well as the presence of dead and rotting wood may be particularly important for many invertebrate species (Botero and Barker 2002; Lavelle *et al*. 2003).

Minimize management, especially the frequency and intensity of weeding, pollarding and agrochemical use.	The use of pesticides, herbicides and fertilizers can negatively affect local plant and animal populations (both above and belowground), leading to drastic changes in species composition and abundance. In Mexico, twice as many insect species were found in an organic coffee AFS as in a conventional sun-grown coffee plantation where agrochemicals were used (Ibarra-Nuñez *et al,* 1995). While live fences with full canopies may attract large numbers of birds and bats, live fences that are pollarded are of little conservation value (Principle 1) and attract few animals because they have little foliage and few perching or roosting sites (personal observation). Frequent weeding of AFS eliminates the natural regeneration of plants, thereby reducing overall plant diversity. In cattle pastures, where the use of herbicides and manual weeding is common, tree regeneration is usually reduced (Harvey and Haber 1999)
When possible avoid entry into the AFS by domestic animals (an obvious exception to this rule are silvopastoral systems in which animals are a central part of the system)	Pigs, chickens and cattle may often trample or damage regenerating vegetation or the understory, creating a less diverse ecosystem (personal obs.). Soil compaction can also negatively affect soil biotic communities, although little is known about the soil fauna of AFS.
Encourage the natural regeneration that occurs within AFS	Natural regeneration within AFS is often considerable, as birds, bats and other seed-dispersing animals visit trees within the AFS and deposit seeds (Slocum and Horvitz 2000). If allowed to grow, this natural regeneration can considerably enhance plant diversity and farm productivity (Suarez 2002). The capacity of AFS to facilitate natural regeneration was observed in windbreaks in Costa Rica, which contained 91 tree species (including both primary and secondary forest species) occurring as seedlings in the windbreak understory just 5-6 years after the windbreaks were planted (Harvey 2000).
Position AFS in such a way as to increase landscape connectivity, by creating corridors and/or stepping stones	Linear AFS (such as windbreaks, hedges or live fences) can serve as corridors for a limited number of animal species, especially if they are structurally and floristically similar to forest habitats and connected to patches of suitable habitats (Fritz and Meriam 1993; 1996; Forman and Baudry 1984). AFS (patches) and individual trees within the agricultural matrix often serve as stepping stones for a variety of species (especially birds), facilitating their movement across large open agricultural areas (Guevara et al. 1998; Fischer and Lindenmayer 2002). Birds that undertake landscape-scale movements or migrations may use the isolated trees as stopover points for shelter and resting, as appears to be the case for Three-wattled Bellbird (*Procnias tricarunculata*) and the Resplendent Quetzal (*Pharomachrus moccino*) in Monteverde, Costa Rica (Harvey et al. 2000).

Locate AFS near natural habitats that can serve as sources for wildlife and plant propagules and such that the AFS can serve as a buffer to remaining forest patches or protected areas	AFS located close to natural forests are likely to retain a greater proportion of the original flora and fauna than those that are isolated from forests (Ricketts *et al*. 2001). Coffee AFS that are close to forest remnants support a higher diversity of forest birds than isolated AFS (Botero and Barker 2002).