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Perspective

Agroecosystem management in the 21st century: It is time for a paradigm shift*

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Abstract

The success of modern agricultural and forestry production can largely be attributed to monoculture systems using a few select species and heavy chemical inputs. This drive for maximizing yield and profit has caused serious environmental problems such as land- and water degradation and increased land-clearing. Modern agriculture is thus threatening its own foundations: land, water, forests, and biodiversity. During the past thirty years, however, the positive benefits of integrated land-use systems such as agroforestry to the producer and the environment have gradually been recognized. Combining trees and crops in spatial or temporal arrangements has shown to improve food and nutritional security and mitigate environmental degradation, offering a sustainable alternative to monoculture production. By providing supportive and complementary roles with a flexible approach, agroforestry offers specific social and environmental benefits across a range of landscapes and economies. It is time for us to eschew the artificial dichotomy between agriculture and forestry, embrace the values and benefits offered by time-tested traditional land-use systems such as agroforestry, infuse scientific investments for their development, and encourage their incorporation into agricultural development paradigms.

Keywords: Agroforestry, Biodiversity, Carbon sequestration, Ecosystem services, Sustainability.

Introduction

During the second half of the 20th century, the world witnessed dramatic changes in population as well as agricultural productivity. While the world's population more than doubled from 2.5 billion in 1950 to 6.1 billion in 2000, world grain production tripled from 640 million tonnes (1 tonne = 10^6 g = 1 Mg) in 1950 to 1,855 million tonnes in 2000. Of this 190% increase in grain production, only 30% was the result of increases in area under cultivation; the remaining 160% was made possible by increases in yield per unit area. These increases in agricultural production were brought about mainly by development and adoption of modern agricultural technology. Nobel Laureate Norman Borlaug has articulated that without the involvement of the new agricultural technologies, 1.1 billion ha more land would have been needed to produce the total quantity of food grains produced today (http://www.usda.gov/oce/forum/speeches/borlaug.pdf; last accessed on 5 Oct 2008). Borlaug argues that modern agricultural technologies have helped save more than a billion ha of forestland from clearing (Fig. 1).

These increases in agricultural production are significant accomplishments, indeed. An important point to consider, however, is the long-term sustainability of these gains. Without going into a discussion on the much-discussed and yet not-well-defined term sustainability, suffice it to say that sustainability is about meeting today's needs without compromising the ability of future generations to satisfy their needs, and it strives to achieve a balance between ecological preservation, economic vitality, and social justice. It is not a new

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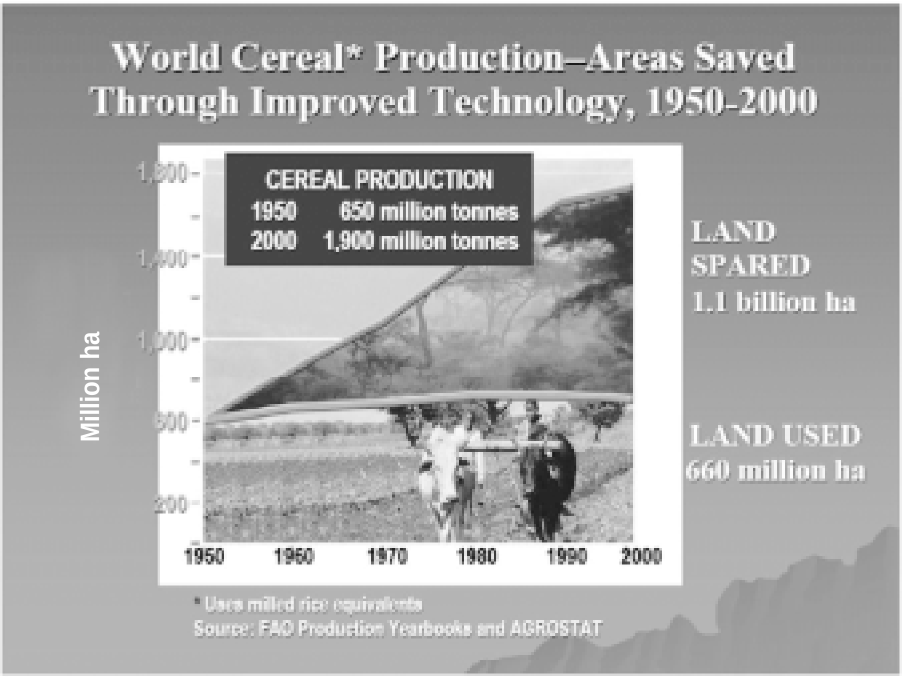

Source: http://www.usda.gov/oce/forum/speeches/borlaug.pdf

Figure 1. Areas saved through improved technology-World serial production. (source: http://www.usda.gov/oce/forum/speeches/borlaug.pdf; last accessed on 5 Oct 2008).

concept, simply the retrieval of ancient wisdom “you don’t eat your seed corn.” The question here is, are the modern agricultural technologies causing increasing damage to the ecological foundations of land-use, such as land, water, forests, biodiversity, and atmosphere? In other words, in our efforts to provide for the needs of the present, are we compromising the ability of future generations to provide for them?

Modern agriculture has vast and adverse impacts on earth. For example, more than two-thirds of human water use is for agriculture; crop and livestock production is the main source of water pollution by nitrates, phosphates and pesticides; and agriculture, forestry and fishing are the leading causes of loss of the world’s biodiversity. Thus, agriculture affects the basis for its own future through land degradation, salinization, overextraction of water, and reduction of genetic diversity. The long-term consequences of these are difficult to quantify.

On the forestry front, we have seen several development issues and paradigms during the past 50 years as summarized in Fig. 2. The major emphasis has been on raising a selected few timber species in single-species plantations. Admittedly that strategy has paid rich dividends: at present, forest plantations that cover only 5% of forested areas provide 50% of world’s timber (FAO, 2007), and all indications are that plantations will continue to be the major focus of forestry development activities in years to come. In addition to plantation establishment, several issues and initiatives have also taken place in tropical forestry during the past few decades (Fig. 2), mostly resulting from an increase in awareness about the role and value of forests in the society in the context of increasing interest in the environment. Today, forestry is caught between the strong and opposing pulls and pressures of the conservation – production dilemma such that it seems to have lost direction in defining the scientific paths for future development.

These impacts of the intensive agricultural and forestry

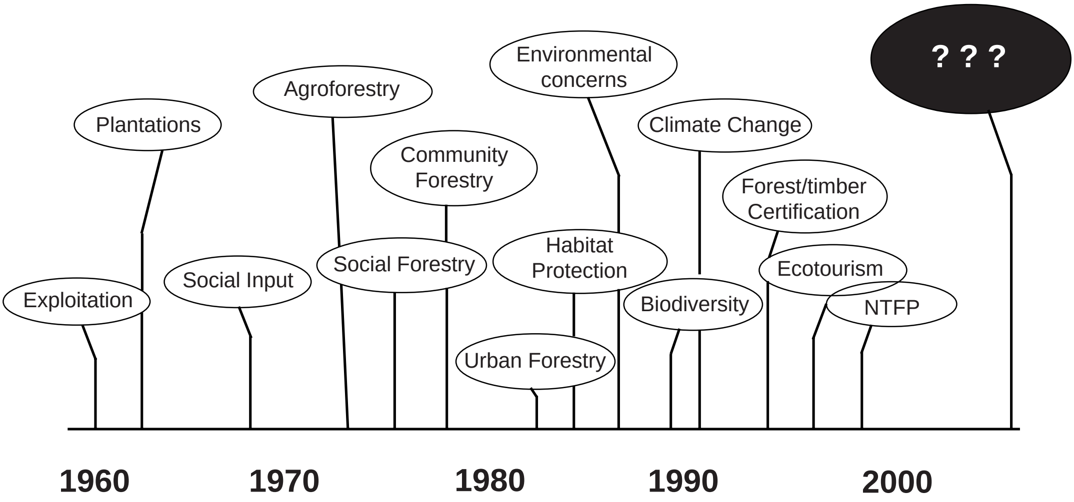

Figure 2. A pictorial presentation of the major issues, concerns, and paradigms in tropical forestry during the past nearly 50 years. Plantation establishment was the first major forestry development initiative; it continues to be the main one even today and is expected to be so in the immediate future. The period during the 1970s and 1980s saw substantial social input into forestry and consequent initiatives such as agroforestry, social forestry, and community forestry in a big way. The last two decades of the 20th century marked considerable appreciation of the environmental values and services of forests and initiation of a number of activities centering around those themes. No such major new programs and thrust areas seem to have sprung up so far in the 21st century. This makes one wonder if forestry, under the influence of strong and opposing pulls and pressures of the conservation – production dilemma, is at a cross roads in terms of directions for future development.

practices on the ecology and environment have become very conspicuous during the past few decades. A case in point is land degradation, which signifies the temporary or permanent decline in the productive capacity of the land (FAO: www.fao.org/ag/agl/degradation; last accessed on 25 Nov 2008), in developing countries. The UN Environment Programme (UNEP) has estimated that 23% of all usable land in the tropics (excluding mountains and deserts) has been affected by degradation. According to UNEP (2004), the main types of land degradation (with percentage figures in parentheses) are water erosion (56), wind erosion (28), chemical degradation (12) and physical degradation (4); overgrazing, deforestation, agricultural activities, and overexploitation of vegetation (http://www.grida.no/publications/other/geo3/?src=/geo/geo3/english/141.htm; last accessed on 25 Nov 2008).

Focus on a few selected species is another feature of modern agriculture and forestry. Such species are bred or otherwise improved and cultivated in monoculture stands to produce maximum quantities of preferred commodities. In this single-commodity paradigm, the age-old practice of growing crops and trees together is ignored or bypassed, leading, among other things, to serious biodiversity decline. For example, the Convention on Biological Diversity (CBD) has estimated that human activity is causing species extinction at a rate of 100 to 1000 times the natural rate of extinction (CBD, 2006). Furthermore, agriculture and forestry are treated separately in development activities although these two sectors are often interwoven on the landscape and share many common goals.

The conservation – production dilemma represented by agricultural production versus environmental integrity is really a complex issue. We certainly need to increase land productivity to meet the growing demands, for which focus on single species and use of nonrenewable inputs (fertilizers and pesticides) may be essential – at least according to our current thinking. We also need to view it as an activity embracing vast proportions of our natural resources and therefore strive to reduce the damage caused to the natural-resource base and protect ecological balance. In other words, agriculture should not be seen in a narrow sense as an activity for meeting the demands for food and fiber. We need a paradigm shift: we need to develop and promote land-management and land-care practices that make the best use of nature's goods and services. Agroforestry is one such approach to sustainable land-use, based on the age-old and time-tested practice of growing crops and trees together. Other forms of integrated land-use systems that embrace the concepts of agroforestry, but known by different names, are also available; for example: conservation farming, ecoagriculture, ecofarming, and farm forestry. In this paper I will use agroforestry as an example to represent all such integrated land-use systems irrespective of their local or regional names.

Agroforestry: An Integrated Science and Practice

Simply put, agroforestry involves growing of trees with crops, and/or sometimes animals, in interacting combinations in space or time dimensions (Nair, 2007; Nair et al., 2008). The practice has been prevalent for many centuries in different parts of the world, especially under subsistence farming conditions. During the late 1970s, efforts were initiated to bring these traditional practices into the realm of modern agricultural science (Bene et al., 1977). These initiatives arose from the frustrations arising from failure of the Green Revolution (Evenson and Gollin, 2003) to benefit poor farmers and those in less-productive agroecological environments. Escalating land-management problems, such as tropical deforestation, fuel-wood shortage, and soil degradation as well as increased awareness about the relevance of the age-old tree-and-crop integrated farming practices provided additional incentives to these initiatives (Steppler and Nair, 1987). That was the time when serious doubts began to be expressed about the relevance of the single-commodity strategies for providing the basic needs of the poorest farmers, and that a major cause of tropical deforestation was the clearing of more land to provide food and fuelwood for the rapidly increasing populations. The search for appropriate strategies to address these problems led to interest in the age-old practices based on combinations involving trees, crops, and livestock on the same land unit, and the recognition of their inherent advantages. The establishment of the World Agroforestry Centre, originally called the International Council (and later Centre) for Research in Agroforestry (ICRAF), in 1977, in Nairobi, Kenya (www.cgiar.icraf.org) signifies the institutionalization of agroforestry at the global level. Following these developments, agroforestry was incorporated into national agricultural and forestry research agendas in many developing countries during the 1980s and 1990s (Garrity, 2004).

Agroforestry has had a slower evolution as a science and practice in the temperate regions, than in the tropics (Garrett et al., 2000). Faced with the environmental consequences of agricultural and forestry practices that focused on the economic bottom line, the general public in developed nations started demanding greater environmental accountability of land-use practices and the application of ecologically and socially compatible management approaches. As a result, the concept of agroforestry gained acceptance in the industrialized nations during the 1990s. Agroforestry systems and their application are also prevalent in countries and regions such as the United States, China, Australia and New Zealand, and southern Europe. These developments have clearly demonstrated the range of conditions under which agroforestry can be successfully applied and the myriad of benefits that can be derived (Nair et al., 2004; Nair et al., 2008; Jose and Gordon, 2008; Rigueiro-Rodríguez et al., 2008).

Agroforestry systems in different parts of the world vary in nature, complexity, and objectives (Nair, 1993). The economic advantage of diversified income is a major motivation for practicing such systems in both tropical and temperate regions. In general, subsistence farming and emphasis on the role of trees in improving soil quality of agricultural lands are characteristic of tropical agroforestry systems. Environmental sustainability is a major driving force for the development and adoption of agroforestry in the industrialized nations, where monocultural production of agriculture and forestry commodities has led to reduced biodiversity and loss of wildlife habitat, increased non-point source pollution of ground and surface water, and deterioration of family farms. Such problems are the legacy of maximizing production of agricultural products without sufficient knowledge of, or regard for, impacts on future productivity, the environment, and society in general. Today, the idea of incorporating the structure and functions of natural ecosystems into the design of managed ecosystems is gaining wide acceptance.

Fundamental to realization of the promise of agroforestry systems is the multitude of lesser-known woody species that have come to be known as "multipurpose trees" or "multipurpose trees and shrubs" (MPTs). The MPTs are the mainstay of most traditional tropical agroforestry systems. The contributions of MPTs and agroforestry systems in general are usually grouped under two broad categories: production of commodities and ecosystem services. The former refers to enhancement of outputs such as food, animal fodder, fuelwood, timber, and non-timber products, whereas the latter refers to tree-mediated services such as carbon storage, biodiversity conservation, and water-quality enhancement. A large number of indigenous MPTs have been identified[‡] and their multiple roles in providing food and nutritional security, medicines, cash income, and a whole host of other products and benefits have been recognized (e.g., Elevitch, 2006). A vast majority of them, however, have not been domesticated let alone exploited commercially (Akinnifesi et al., 2008). Undoubtedly, a major opportunity as well as challenge in agroforestry lies in domesticating, improving, and exploiting the multitude of these indigenous MPTs.

Thanks to these efforts over the past three decades, agroforestry has now been transformed from "a practice in search of science" into a science-based practice. It has emerged as an integrated applied science that has demonstrated potential for addressing some of the land management and environmental problems the world over. The essence of agroforestry can be expressed by four key "I" words: intentional, intensive, interactive, and integrated. The term "intentional" implies that systems are intentionally designed and managed as whole unit, and "intensive" means that the systems are intensively managed for productive and protective benefits. The biological and physical interactions among the system's components (tree, crop, and animal) implied in the term "interactive," and "integrative" refer to the structural and functional combinations of the components as an integrated management unit. The 1st World Congress of Agroforestry held in Orlando, Florida, USA, June-July 2004 (www.conference.ifas.ufl.edu/wca) signifies this coming of age of agroforestry (Nair, 2007). A Congress Declaration affirmed by the more than 500 delegates from 82 countries states that the adoption of agroforestry over the next decade will "greatly enhance the achievement of the United Nations Millennium Development Goals" by increasing household income, promoting gender equity, improving health and welfare of people, and enhancing environmental sustainability (Nair et al., 2005). The 2nd World Congress of Agroforestry is being organized in Nairobi, Kenya, August 2009 (www.worldagroforestry.org/wca2009).

Ecological Foundations of Agroforestry

Agroforestry is based on the premise that land-use systems that are structurally and functionally more complex than either crop or tree monocultures result in greater efficiency of resource capture and utilization (nutrients, light, and water), and greater structural diversity that entails a tighter coupling of nutrient cycles. Above and below ground diversity of ecosystem processes facilitated by a mixed stand of species provides more system stability and resilience at the site-level (Lefroy et al., 1999). At the landscape and watershed levels, such systems can provide connectivity with forests and other landscape features to achieve desired ecological services such as protection of wildlife habitat and water- and soil quality (Garrett et al., 2000; Nair et al., 2008).

A common thread found in the many historical definitions of agroforestry is the reference to the systems nature of this multi-faceted land-use system. However,

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[‡] Several comprehensive databases of MPTs are available, including the Agroforestree and other databases by ICRAF (www.icraf.cgiar.org/), various tree data bases by FAO (www.fao.org), tropical fruits database http://www.tradewindsfruit.com/fruitscommon.htm,and Forestry Compendium and Forest Products Abstracts database by CABI (http://www.cabi-publishing.org/AbstractDatabases).

the multitude of ways in which trees may be incorporated into agricultural production systems – intercropping as opposed to silvopastoralism, for example – is problematic in terms of conceptualizing all agroforestry systems in one standardized system model. Nonetheless, there is great merit in doing so because it allows comparison with natural forested or agroecosystems as to the relative extent that ecological properties are maintained or relinquished by agroforestry systems. For example, compared with the net primary productivity (NPP) of 2 to 6 Mg dry matter (biomass) ha^{-1} yr^{-1} (depending upon species) for temperate coniferous forest plantations, certain agroforestry systems in the tropics such as the multistrata (vertically stratified) homegardens and shaded perennial systems can produce in excess of 15 Mg ha^{-1} yr^{-1}. Indeed, the ecological indices for species similarity, diversity, and richness (Sorenson's, Shannon-Wiener, and Margalef, respectively) of multispecies homegardens are similar to those of nearby primary forests (Kumar and Nair, 2006; Mohan et al., 2007). These similarities with natural ecosystems are strong indicators of ecological sustainability of agroforestry systems – assuming, of course, that natural ecosystems are ecologically sustainable.

Nair et al. (2008) have identified four major ecological properties as critical to the understanding of agroforestry system design, development, management, and evaluation. These are: spatial and temporal heterogeneity (considerable variations of system components in size, lifespan and phenology), disturbance in ecosystem succession of components (some components such as crops being repeated in short life cycles while others such as trees developing much longer life-spans), perennialism (perennial nature of some components contributing to efficient nutrient cycling), and structural and functional diversity (providing niches for a multitude of organisms that are not normally associated with single-species agricultural systems). An important consideration in exploiting these characteristics of agroforestry systems is the proper design of systems such that the interplay and magnitude of ecological, economic, and social benefits can be maximized. As illustrated schematically in Fig. 3 (after Nair et al., 2008), enhanced and sustained production of many typical 'services' normally associated with food or timber production systems is possible largely as a result of forced integration of trees, crops and/or animals in such a way that interactions are created both above and belowground. The resultant 'production system' feedbacks at a number of scales to extra and intra-system components provide a number of ecosystem services typical of those found in natural, undisturbed systems.

Ecosystem Services of Agroforestry

Arising from the above ecological foundations, agroforestry systems have shown to provide several ecosystem services and benefits. In discussing these, it needs to be emphasized that the effects of many of these services and benefits cannot be measured in quantitative terms in relatively short time periods that are common for agricultural production systems. Furthermore, available methods that have been developed for single-commodity-oriented production systems are not sensitive enough to measure the interactive benefits of mixed species, multiple-benefit-oriented, integrated agroforestry systems.

Soil Productivity and Protection

One of the tree-mediated benefits of considerable advantage in the tropics is that trees and other vegetation improve the productivity of the soil beneath them. Research results during the past two decades show that three main tree-mediated processes determine the extent and rate of soil improvement in agroforestry systems. These are: 1) increased nitrogen (N) input by N_2-fixing trees (NFTs), 2) enhanced availability of nutrients resulting from production and decomposition of tree biomass, and 3) greater uptake and utilization of nutrients from deeper layers of soils by deep-rooted trees. Furthermore, presence of deep-rooted trees in the system can contribute to improved soil physical conditions and higher soil microbiological activities under agroforestry.

A major opportunity for capitalizing on the soil improvement attributes of agroforestry systems is in the reclamation of degraded lands. As discussed before (see the Introduction section), soil and land degradation

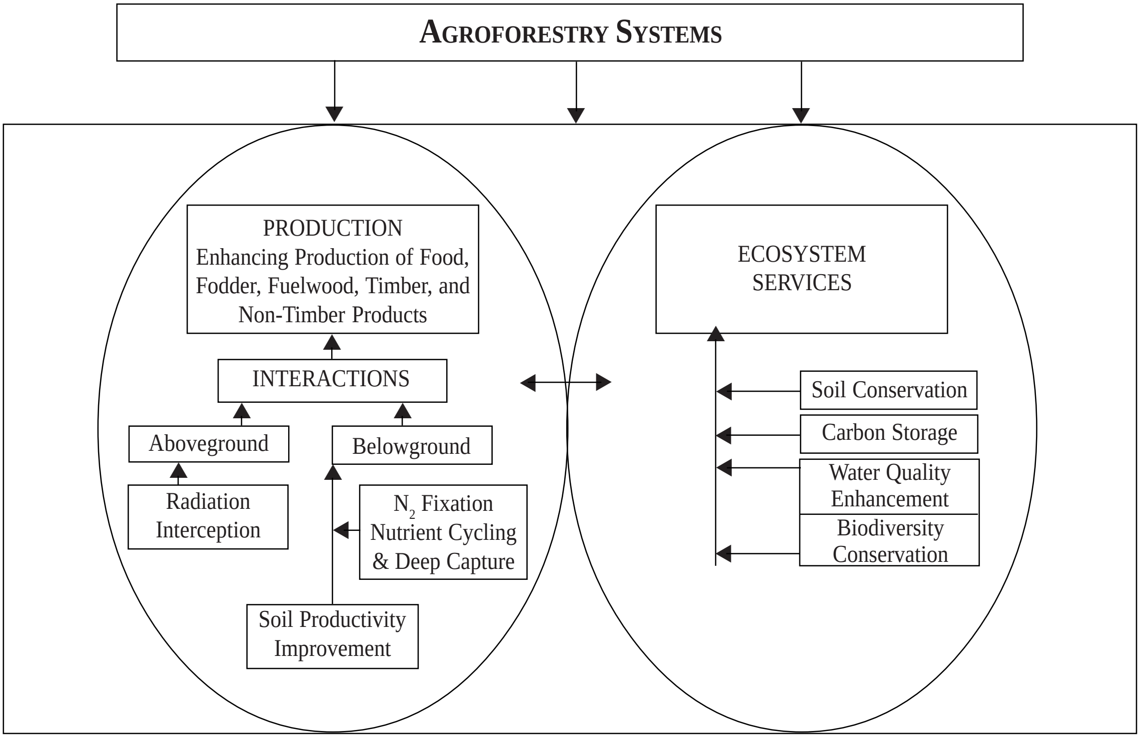

Figure 3. A schematic presentation of the major mechanisms and processes involved in production- and service attributes of sustainable agroforestry systems (Source: Nair et al., 2008).

is a major problem in many parts of the tropics. About 1.9 billion ha of land, a third of total farmland, in developing nations are estimated to be degraded through erosion, salinity, and fertility depletion. The potential of agroforestry to reduce the hazards of erosion and desertification as well as to rehabilitate such degraded land and to conserve soil and water has been well recognized. Lal and Bruce (1999) estimated that, out of the 250 million ha of land that is degraded by erosion worldwide, about 100 million ha constituted the ‘most strongly degraded cropland area’ that is not suitable for agriculture, and that with proper planning and management, these lands could be grown to appropriate shrubs and tree species including biofuels. Furthermore, salt-affected soils cover about one-tenth of the earth’s land (Szabolcs, 1998), and one-third of the arid and semiarid regions (Rengasamy, 1998) constituting 930 million ha worldwide (Sumner et al., 1998). One of the successful land reclamation techniques recommended for these salt-affected soils is planting of salt tolerant species using the agroforestry approach (Gupta and Abrol, 1990; Singh et al., 1994 and Singh et al., 1997).

The soil ameliorative potential of agroforestry has been demonstrated and is being exploited in the temperate regions too. For example, research results show that the agroforestry designs of grass-shrub-tree buffers (riparian buffer) are superior to grass buffers in reducing sediment losses, and trees used as windbreaks around agricultural fields reduce soil erosion caused by wind and water (Garrett et al., 2000; Rigueiro-Rodríguez et al., 2008).

Biological Diversity in Working Landscapes

As much as 90% of the biodiversity resources in the tropics are located in human-dominated or working landscapes. When landscapes are increasingly being fragmented and remaining patches of natural vegetation are reduced to isolated habitat islands consequent to population pressure and human activities, mixed species agroforestry systems could play a significant role in maintaining a higher level of biodiversity and provide greater landscape connectivity. Agroforestry impinges on biodiversity in working landscapes in at least three ways. First, the intensification of agroforestry systems can reduce exploitation of nearby or even distant protected areas. Second, the expansion of agroforestry systems into traditional farmlands can increase biodiversity in working landscapes. Third, agroforestry development may increase the species and within-species diversity of trees in farming systems (Nair et al., 2008). Another promising aspect of agroforestry in the context of biodiversity conservation is in growing commercial crops such as coffee (*Coffea* sp.) and cacao (*Theobroma cacao*), known as shaded-perennial systems in the agroforestry literature. This is projected to start a trend of combining environmental research with consumer products, which could then have a large impact on global conservation (Schroth et al., 2004; Schroth and McNeely, 2006).

In the temperate regions too, agroforestry can augment the supply of forest habitat and provide greater landscape connectivity. Where croplands occupy most of the landscape, riparian forest buffers and field shelterbelts can be essential for maintaining plant and animal biodiversity, especially under a changing climate scenario. A comprehensive assessment of shelterbelt agroforestry systems in the northern Great Plains of the USA has clearly demonstrated their importance on enhancing bird species richness and community composition at both the farm- and landscape levels (McNeely, 2004).

Carbon Storage and Mitigation of Greenhouse Gases

Agroforestry systems have been recognized as a greenhouse-gas mitigation strategy under the Afforestation and Reforestation (A & R) activities of the Clean Development Mechanism (CDM) of the Kyoto Protocol primarily as a strategy for biological carbon (C) sequestration (Nair et al., 2009a). In addition to sequestering C in biomass and soil, these systems can contribute to both carbon conservation (conservation of carbon stocks in forests by alleviating the pressure) and carbon substitution (reducing fossil fuel burning by producing fuel wood). Recent studies on the magnitude of soil C sequestration under different agroforestry systems in different regions of the tropics have clearly illustrated the significant GHG-mitigation benefits of agroforestry systems that have hitherto been unrecognized (Nair et al., 2009b). In the tropics, agroforestry systems are estimated to have helped to regain 35% of the original C stock of the cleared forest, compared to only 12% by croplands and pastures. It has been estimated that an increase of one tonne (Mg) of soil carbon pool of degraded cropland soils may increase crop yields by 20 to 40 kg ha^{-1} (Lal, 2004). A projection of C stocks for smallholder agroforestry systems indicates C sequestration rates ranging from 1.5 to 3.5 Mg C ha^{-1} yr^{-1} and a tripling of C stocks in a 20-year period, to 70 Mg C ha^{-1}. In temperate regions, agroforestry practices have been estimated to have the potential to store C in the range of 15 to 198 Mg C ha^{-1} (mode: 34 Mg C ha^{-1}; Pandey, 2002). Recent research evidence that biofuels derived from low-input high-density (LIHD) mixture of native grassland can provide more usable energy, greater GHG reductions, and less agrichemical pollution per ha than can corn (maize) grain ethanol or soybean bio-diesel (Tilman et al., 2006) has brought in new perspectives on mixed-stand plant-communities the world over. For example, in a study on multispecies systems in Thrissur, India, Saha (2008) found that soil C stock (an indicator of C sequestration) was higher in land-use systems with higher plant species diversity and tree intensity than under monocultural stands of trees and crops. Thus, scientific evidence is accumulating pointing to the enormous environmental benefits of mixed-species systems.

Available estimates of C sequestration potential of agroforestry systems are derived by combining information on the aboveground, time-averaged C stocks, and the soil C values; but they are generally not rigorous. The extent of C sequestered in any agroforestry system will depend on a number of site-specific biological, climatic, soil, and management factors. Furthermore, the profitability of C sequestration projects will depend on the price of C in the international market, additional income from the sale of products such as timber, and the cost related to C monitoring. Our knowledge on these issues is unfortunately rudimentary. Until such difficulties are surmounted, the low-cost environmental benefit of agroforestry will continue to be underappreciated and underexploited.

Global warming is now accepted as a real issue the world over. Ways of reducing CO_2 in the atmosphere will undoubtedly be receiving increasing attention in the future. More than twice as much carbon is held in soils as in vegetation or the atmosphere; changes in soil carbon can have a large effect on the global carbon budget. Assuming that one hectare of agroforestry could save five hectares from deforestation, carbon emission caused by deforestation could be reduced substantially by establishing agroforestry systems. Along with these efforts, carbon markets will become stronger and more active. The opportunity offered by agroforestry systems to sequester carbon and market it for real money is real, even in poor countries (Montagnini and Nair, 2004; Takimoto et al., 2008).

Water Quality and Environmental Amelioration

Agricultural non-point source pollution is a significant cause of stream- and lake contamination in many regions of industrialized world. A major causative source of this pollution is nutrients such as phosphorus (P) and nitrogen (N) that are lost from soils of fertilized agricultural and forestry operations, particularly in coarse-textured, poorly drained soils where drainage water ultimately mixes with surface water. Recent studies have shown that agroforestry practices such as silvopasture and riparian buffer could be a means of addressing the problem of environmental impact of non-point source pollution. The deeper and more extensive tree roots will invariably be able to take up more nutrients from the soil compared to crops with shallower root systems – the so-called "safety-net" effect that has been affirmed in various agroforestry situations. Consequently, nutrient-leaching rates from soils under agroforestry systems where trees are a major component can be lower than those from treeless systems (Schultz et al., 2004; Michel et al., 2007; Nair et al., 2007).

The water-quality enhancement resulting from the reduction of nutrient loading could be a substantial environmental benefit of agroforestry in heavily fertilized agricultural landscapes. With increasing realization of the adverse impacts of chemical agriculture and climate change on availability and quality of water in many parts of the world, water is now a critical issue in natural resource management. Time-tested integrated land-use practices such as agroforestry could be appropriate approaches to addressing the problem. But the science of this is non-existent and needs to be explored and established.

Food and Nutritional Security

The MPTs play a major role in food production in two ways: directly by providing edible products such as fruits, and indirectly by supporting food production through enhancing the soil's ability to support agriculture. A large number of fruit-producing trees are integral parts of traditional homestead and other agroforestry farming systems with their characteristic multistrata canopies in many developing countries (Kumar and Nair, 2006). Although several of these fruit trees have not been studied scientifically and are thus underexploited and little-known outside their habitat, they make significant contributions to food- and nutritional security.

Another group of underexploited species of immense cultural and economic value are the natural medicinal plants ("medicinals"; Rao et al., 2004). In Africa, more than 80% of the population depends on medicinal plants to meet their medical needs, and about two-thirds of the species from which such medicines are derived are trees. While the majority of these tree products are obtained by extraction from natural forests, some 'well-known' agroforestry tree species grown on farms for other uses (such as fodder, food, or fuelwood) are also used for their medicinal values. Examples include *Acacia nilotica* used in India and Africa; *Azadirachta indica*, the neem tree, used throughout Asia and Africa; *Parkia biglobosa* (*neré* or the locust bean tree) used in Africa; and *Tamarindus indica,* the tamarind tree, used in India and Africa. There is also increasing interest in such traditional, plant-derived medicines in the developed world, creating new or expanded markets for these products. This puts further extraction pressure on the natural forests. Many of the medicinal tree species are already overexploited. Some species are so depleted that their gene pools are greatly eroded (e.g., *Prunus africana*), and some are in danger of extinction.

Outlook

The time has arrived for a rethinking on the way agricultural development programs are planned and implemented around the world. "Business as usual" is not an option; we need a paradigm shift. We need to encourage the "remarriage of trees and crops" on our agricultural landscape and exploit the time-tested benefits of such practices to address some of the major threats facing the world today, such as food- and nutritional security, eroding soils, and expanding deserts. Too often, we treat agriculture and forestry separately, yet these two sectors are often interwoven on the landscape and share many common goals; this artificial dichotomy has to be eschewed.

If we are to meet society's needs and aspirations for forest-derived goods and services, we must find ways of augmenting conventional forestry by utilizing agricultural lands where agroforestry can be practiced. Indeed, in many places the only opportunity to provide increased forest-based benefits, such as wildlife habitat or forested riparian systems, is through the increased use of agroforestry (and such integrated systems that may be known by other names) on agricultural lands. Current interest in ecosystem management in industrialized countries strongly suggests that there is a need to embrace and apply agroforestry principles to help mitigate non-point source pollution and other environmental problems and better meet the current and future needs for the products and services of the land.

While it is creditable that considerable progress has been achieved during the past three decades in transferring the age-old agroforestry practices into a science-based activity, several knowledge gaps exist even in areas that have received research attention in the past. There are also several potentially promising areas that have not yet been explored. For example, substantial efforts are needed to domesticate indigenous fruit and medicinal trees and promote their cultivation on farms. Research partnerships between agroforestry and the medical and nutritional sciences and the food products industry will be crucial to ensure that the key tree species for such uses are developed for farm cultivation. In our obsession with "grain crops" in modern agriculture, we have ignored them. The exploitation of these species, and the agroforestry practices involving their use, has wide implications in food security and environmental protection, as well as conservation and use of genetic resources. A new "tree crops revolution" is needed that broadens the array of tree products that are produced, processed, and delivered by developing countries to regional and global markets.

While agroforestry cannot provide a solitary cure for all land management problems, it can play an important role in improving land management in specific situations. Despite this advantage, though, the full potential is yet to be realized by a wider community. In addition, agroforestry suffers from a perceived negative "image" that is a hindrance to the acceptance of and confidence in its methods. Agroforestry and such other integrated systems are sometimes viewed narrowly and vaguely as synonymous with a specific practice that may have some drawbacks such as a higher labor demand or reduced possibilities for commercial production, without acknowledging the existence of a broad spectrum of such options under varied conditions. A systems perspective that accounts for the sum of all benefits in the long term, tangible and intangible, is required in order to appreciate the full value of potential benefits, as opposed to being solely concerned with the performance of a single crop,

Thirty years ago, agroforestry began to attract the attention of the international development and scientific community, primarily as a means for sustaining agricultural production in marginal lands and remote areas of the tropics that were not benefited by the Green Revolution. Today, thanks to input from modest research, agroforestry has been recognized as having the potential to offer much more toward ensuring not only food security in poor countries, but also environmental integrity in poor and rich nations alike. As the global community continues to realize these potential benefits, we will witness the coming of age of a valuable and sustainable land management tool.

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