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# Adaptation to Climate Change through Sustainable Management and Development of Agroforestry Systems

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## Abstract:

This paper describes the potential role of agroforestry systems in the adaptation to expected changes in climate by smallholder farmers in the tropical regions in general and in sub-Saharan Africa in particular. There is enough scientific evidence to conclude that climate change is happening and to link climate change with the observed changes in the earth's physical systems. Agriculture is one of the high priority sectors where the impacts of climate change exceed tolerance limits with implications for the livelihoods of millions of smallholder farmers dependent on this sector. Agroforestry interventions, because of their ability to provide economic and environmental benefits, are considered to be the best “no regrets” measures in making communities adapt and become resilient to the impacts of climate change. The important elements of agroforestry systems that can play a significant role in the adaptation to climate change include changes in the microclimate, protection through provision of permanent cover, opportunities for diversification of the agricultural systems, improving efficiency of use of soil, water and climatic resources, contribution to soil fertility improvement, reducing carbon emissions and increasing sequestration, and promoting gender equity. These are discussed and limitations are highlighted. While agroforestry systems clearly offer economic and ecological advantages, the development of robust systems compliant with stakeholder needs and requirements is constrained by our limited understanding of the tradeoffs between subsistence requirements, acceptable risks, and the costs involved.

## Introduction:

Over the past two decades climate change has evolved from a debate about whether the planet is really warming to an increased focus on how to mitigate and adapt to its impacts, due mainly from the growing acceptance among scientists, policy makers, and even the general public that climate change is real and happening. This acceptance is based on the overwhelming evidence presented by the scientific community through intensive monitoring of global climatic systems, extensive observations on changes in terrestrial and aquatic systems, and predictive modeling (IPCC, 2007; Stern, 2007; Hansen et al., 2007). From the instrumental records of global temperature since 1850, the Fourth Assessment Report of the

Intergovernmental Panel on Climate Change (IPCC) estimated that the current global mean surface temperature was about 0.42°C to 0.54°C above the 1961-1990 annual average (IPCC, 2007). It also ranks eleven of the last twelve years (1995-2006) among the 12 warmest years. Further evidence of global warming comes from the observations made on the most vulnerable natural systems like glaciers (Hanna et al., 2006), coral reefs and atolls (Hughes et al., 2003), polar and alpine ecosystems (Ackley et al., 2003), and observed increase in the frequency of occurrence of extreme events (Tebaldi et al., 2006). After an extensive review of the available literature on evidence of climate change, the Working Group I to the Fourth Assessment Report of the IPCC concluded that "the warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average temperature". The Stern Review, which has not simply illustrated the science but also the economics of climate change, concluded that "The scientific evidence is now overwhelming; climate change presents very serious global risks, and it demands an urgent global response" (Stern, 2007). The debates and discussions that followed the publication of these reports helped put climate change high on the agenda of a number of Governments across the world and in highlighting the need for initiating timely and appropriate measures by the governments and communities that could mitigate the negative impacts of climate change.

Despite the availability of overwhelming evidence in support of climate change, uncertainty prevails over the exact nature and consequences of climate change especially at local level, making it difficult to plan and develop appropriate adaptation strategies, programs, and technologies. Global level simulations using climate models provide various scenarios with high levels of confidence but these predictions become less clear as to the magnitude and timing of the changes at sub-regional, national and local levels, and according to the IPCC difficulties remain in reliably simulating and attributing observed temperature changes at smaller scales (IPCC, 2007). This is due to the complexity of the interactions involving topography, land use, and water bodies with a strong influence on the local climate variations and the difficulties in modeling the same. However, it is widely recognized that the increased heat stress, shift in monsoons, and drier soils pose much bigger threat to the tropics than the temperate latitudes. With most developing countries located in the tropics and most of them being heavily dependent on agriculture for food and income, the relatively poor countries with limited resources face the costly and formidable task of adapting to climate change (Rosenzweig and Liverman, 1992). Further, much of the agriculture practiced in these countries is already constrained by declining soil fertility, water shortages, widespread degradation of the resource base and poor institutional and policy support and any change in the climate from what the communities are adapted to will have significant adverse impacts on food, nutritional and income securities of millions of those dependent on agriculture and to a large extent on the economies of those countries.

The main objective of this paper is to review briefly the potential risks and probable opportunities that are associated with the expected changes in global and regional climates and present ideas about how agroforestry systems could be used to adapt to, or mitigate, the predicted impacts of climate change on smallholder agriculture. It deals with the widely accepted knowledge of the impacts of climate change; that warmer temperatures will lead to a northward shift in the thermal regimes and domains of various crops, increase water and heat stresses, increase evapotranspiration, and generally reduce average rainfall amounts accompanied by an increase in inter-annual variability. The focus is on tropical agricultural systems in general and on sub-Saharan Africa in particular where many of the world's poorest countries are located.

## Potential impacts of climate change on agriculture

Considering the role of agriculture in the social and economic progress of developing countries, the vulnerability of agricultural systems to the impacts of climate change has received considerable attention from the scientific community (Fisher et al., 2002; IISD, 2003; Kurukulasuriya and Rosenthal, 2003). Much of the available literature suggests that the overall impacts of climate change on agriculture especially in the tropics will be highly negative, although in a few areas there may be minor increases in crop yields in the short term (Maddison et al., 2007). Table 1 presents some of the projected changes in climate and their potential impacts on agriculture as summarised in the IPCC report (Parry et al., 2007).

The major processes of agriculture that are directly influenced by climate change are soil water, carbon and nitrogen cycles, crop growth and development, and incidence of weeds, pests, and diseases. These effects are manifested in terms of increased heat stress, increased evapotranspiration, shortened seasons, and increased photosynthesis and reduced water use due to higher $CO_2$ in the atmosphere. The results of various assessments of impacts of climate change on agriculture (Rosenzweig and Hillel, 1998; Mendelsohn and Neumann, 1999; Reilly et al., 2001; Das, 2003) are generally in agreement and have identified the following as the major challenges that the future agricultural systems will face from climate change.

i. A northward shift in the domain of crops due to the increase in average annual temperature in the northern hemisphere
ii. An increase in crop water requirements to meet the increased evapotranspiration demands
iii. Reduction in the amount of plant available water in most places due to the predicted shortages in water supplies
iv. Spatial and temporal changes in the land available for agriculture with tropical countries being more disadvantaged
v. Increased degradation of land resources from erosion due to the projected increase in extreme events
vi. New management challenges such as dealing with changes in the new pest and disease complexes
vii. Increased cost of inputs due to steep increases in energy and other input costs including taxation
viii. Competition for land by emerging initiatives like biofuel production. This may further lead to an increase of food prices with adverse impacts on accessibility by the poor
ix. Decrease in biodiversity and extinction of some species

x. Erosion of communities' capacity to invest in agriculture due to losses from the increased frequency and intensity of extreme weather (drought, floods, etc.) conditions

**Adaptation challenges:**

While communities in the past have shown resilience and capacity to adapt to changes in climate through keen observation, experimentation and practice, adaptation to the rapid changes that are taking place in global climate and other sectors are beyond that of a natural self-correcting process. They require carefully planned interventions including supportive policies and regulations to mitigate the impacts of expected changes in climate while meeting household level requirements for food, fuel and income. Additionally, for rapid and widespread adoption interventions should be subtle, easy to adopt without requiring a complete shift from what communities are currently doing and that build on existing knowledge and practices through which communities have already adapted to the various risks related to variability in the climate. Some of the coping strategies that communities dependent on agriculture have adopted to manage current climate variability include cropping systems with assured returns, use of crops and varieties with less variability, diversification of farm enterprises to increase profitability or reduce risk, involvement in off-farm economic activities, mortgaging and selling of assets, and migrating (Chambers, 1989). As communities are exposed to unexpected or unforeseen changes in weather patterns and increased risk, more robust adaptation plans are required to manage the additional risk. Some of the adaptation challenges include:

1. Managing the heat stress both on crops and animals which requires use of crop varieties and management systems that do well under a broad range of soil and climatic conditions
2. Reversing land degradation through adoption of practices that reduce erosion and loss of organic carbon
3. Effective management of climate related risks through promotion of innovative and sustainable diversification of farm activities and supporting informed decision making on climate information
4. Efficient capture, storage and utilization of rainfall through adoption of appropriate soil and water conservation practices, provision of irrigation and use of systems and practices with high use efficiency
5. Maintaining soil fertility and productivity by arresting nutrient mining and building or sustaining soil fertility
6. Limiting greenhouse gas emissions and encouraging carbon sequestration by promoting management options that reduce tillage and use of fuels
7. Guarding against pest and disease pressure
8. Enhancing the resilience of communities by better targeting investments and improving their use efficiency
9. Ensuring maintenance of food and nutritional security

10. Protection of women and other disadvantaged groups from the adverse impacts of climate change

## Role of Agroforestry in adapting to climate change

Agroforestry, the integration of trees and shrubs with annual crops production, is an age old management system practiced by farmers to provide shade, a steady supply of food and/or income throughout the year, arrest degradation and maintain soil fertility, diversify income sources, increase and stabilize income, enhance use efficiency of soil nutrients, water and radiation, and provide regular employment. Over the past three decades, research by the World Agroforestry Center and its partners has made significant contributions in understanding the various synergies, opportunities and challenges associated with growing crops and trees together and in developing more integrated, robust and science based systems taking advantage of the developments in crop and tree breeding and management. Noteworthy among such practices in tropical environments include incorporation of fast-growing, nitrogen fixing trees and shrubs in agricultural fields to improve soil fertility and minimize erosion, improved management of fallows, domestication of new and underutilized tree species, and intensification of agriculture on smallholder farms through use of appropriate tree and shrub species. A wide range of agroforestry systems now exist with a potential to improve productivity, favorably influence microclimate, prevent soil degradation and restore soil fertility and diversify income generating opportunities, (Table 2).

If supported by appropriate cultivation, processing and marketing methods, agroforestry products can make a major contribution to the economic development of the millions of poor farmers by meeting their needs for food, fuel and income. Combined yields of tree, crop and livestock products from well planned and well managed agroforestry systems tend to be higher than those from sole systems due to increased and efficient use of scarce resources especially moisture. Recognizing the ability of agroforestry systems to address multiple problems and deliver multiple benefits, the IPCC Third Assessment Report on Climate Change (IPCC, 2001) states that "Agroforestry can both sequester carbon and produce a range of economic, environmental, and socioeconomic benefits. For example, trees in agroforestry farms improve soil fertility through control of erosion, maintenance of soil organic matter and physical properties, increased N, extraction of nutrients from deep soil horizons, and promotion of more closed nutrient cycling." We believe that agroforestry interventions provide the best "no regrets" adaptation measures in making communities resilient to the impacts of climate change and do discuss the same in relation to the challenges posed by the changing and variable climate.

### 1. Agroforestry systems play a critical role in moderating the microclimate

The full genetic potential of many crops and varieties can only be realised when environmental conditions are close to optimum. Any change in these conditions, especially during the reproductive stage, will have a direct impact on the production and economic viability of certain crops. While removing the extra energy accumulated and trapped by atmosphere is not feasible, agroforestry systems with appropriate shade trees offer a promising option to moderate the effects of heat stress locally. Trees on farm bring about favourable changes in the microclimatic conditions by influencing radiation flux, air temperature, wind speed, saturation deficit of understorey crops all of which will have a significant impact on modifying the rate and duration of photosynthesis and subsequent plant growth, transpiration, and soil water use (Monteith et al., 1991). Some examples where the beneficial aspects of microclimatic changes are extensively used are shade trees to protect heat sensitive crops like coffee, cacao, ginger and cardamom from high temperatures, wind breaks and shelter belts to slow down the wind speed to reduce evaporation and physical damage to crops, mulches to reduce soil temperature and various crop tree mixes to reduce erosion and maximize resource use efficiency.

In general, shade will create microclimates with lower seasonal means in ambient temperature and solar radiation as well as smaller fluctuations. Beer et al. (1998) while reviewing the literature on shade management in coffee and cacao plantations have observed that shade trees buffer high and low temperature extremes by as much as 5 °C. According to Steffan-Dewenter et al. (2007) the removal of shade trees increased soil surface temperature by about 4 $^0$C and reduced relative air humidity at 2 m above ground by about 12%. Soil temperature under the baobab and *Acacia tortilis* trees in the semi-arid regions of Kenya at 5-10 cm depth were found to be 6 °C lower than those recorded in open areas (Belsky et al., 1993). In the Sahel, where soil temperatures often go beyond 50° to 60 °C, a major constraint to establish a good crop, *Faidherbia* trees lowered soil temperature at 2-cm depth by 5° to 10 °C depending on the movement of shade (Vandenbeldt and Williams, 1992). Shelterbelts, parallel rows of trees over the landscape, is another widely used option to improve microclimates, more specifically to reduce the velocity of the wind by increasing the surface roughness and control wind erosion and evapotranspiration. The effects of properly designed shelterbelts extend from about 10 to 25 times the height of the belt downwind with the greatest effect close to the leeward side.

While there is a general consensus on the beneficial effects of trees in moderating and ameliorating the microclimatic conditions, there is still considerable uncertainty on the productivity and economic benefits of these systems (Beer et al., 1998; Kho, 2000; Rao, et al.1998). This is partly due to the complex interactions common with agroforestry systems. The major biophysical factors influencing the performance mixed systems are crop and tree type, number and distribution of trees, age of the tree, management of crop and tree and climate during the season. Based on the response of crops to shade, Brenner (1996) has classified leafy horticultural crops (e.g., alfalfa, cliver) as the most responsive crops and cereals as moderately responsive (e.g., barley and millet) or less responsive (e.g., maize, and wheat). The net shade effect was reported to be more positive when the annual crop is a C3 plant which is normally light saturated in the open (Ong, 1996). Among the climatic regimes, higher crop yields were noted mostly in inherently fertile soils in humid and subhumid tropics where benefits from fertility improvement are much larger relative to the effects of competition (Rao et al., 1998). In the semi-arid tropics, the competition for water and nutrients severely reduced maize yields when grown with *Grevillea robusta* (Ong et al., 2000).

## 2. Agroforestry systems are highly effective in soil and water conservation through provision of permanent cover.

With nearly two thirds of the continent occupied by deserts and drylands, Africa faces the biggest threat of desertification and degradation. Since climate exerts a strong influence over various soil processes that contribute to degradation, the expected changes in climate will have the potential to alter these processes and thereby soil conditions. A recent assessment by IIASA predicted that the arid and semi-arid areas in Africa will increase by 5-8% by 2080 (Fischer et al., 2005). There are several ways by which climate change manifests soil degradation. Higher temperatures and drier conditions lead to lower organic matter accumulation in the soil resulting in poor soil structure, reduction in infiltration of rain water and increase in runoff and erosion (Rao et al., 1998) while the expected increase in the occurrence of extreme rainfall events will adversely impact on the severity, frequency, and extent of erosion (WMO, 2005). These changes will further exacerbate an already serious problem the continent is facing.

Arresting degradation and restoring the productive potential of soil calls for improvement in the physical, chemical and biological conditions. The advantage with agroforestry systems is in their ability to bring favourable changes in all the three conditions. Agroforestry systems like improved fallows, contour hedgerows and other systems involving permanent cover play an important role in arresting and reversing land degradation via their ability to provide permanent cover, improve organic carbon content improve soil structure, increase infiltration, enhance fertility, and biological activity. In western Kenya, the World Agroforestry Centre, in collaboration with the Institut de Recherche pour le Développement (IRD) and Kenyan national agricultural research services, has tested the potential of improved fallow for controlling soil erosion, using fast growing shrubs such as *Crotalaria grahamiana* and *Tephrosia spp*. These species showed great promise in reducing soil losses (Figure 1). Soil protection through improved fallow is a process that starts right from the fallow period when tree cover reduces soil battering by raindrops, but continues way after fallow clearance due to the improvement of soil structure and biological activity.

Very few studies have quantified soil faunal activity under planted fallows, compared with natural fallows or continuous cropping. Observations made at Muguga, Kenya under natural forest, continuously cropped maize, one-year-old sesbania fallow, and grass fallow indicated that sesbania fallows restored the soil biological activity to the same level as in natural forest (Table 3) and was several-fold higher than in the cropped fields or grass fallows.

In a parallel development aimed at improving the diagnosis and monitoring of soil quality, World Agroforestry Centre has made substantial progress in the application of infrared spectroscopy for rapid analysis of soils and various other organic resources (Shepherd et al. 2003). The technique not only provides a better understanding of the complexity and diversity of local soils, but also serves a tool for monitoring soil quality for environmental protection. Infrared spectroscopy allows for large numbers of geo-referenced soil samples to be rapidly characterized. It can therefore be used in conjunction with satellite imagery to interpolate ground measurements over large areas. There is potential for use of IR spectroscopy to increase efficiencies and reduce costs in both large-area applications (soil survey, watershed management, pedo-transfer functions, soil quality indicators) and site-specific management problems (precision agriculture, farm advisory services, process studies). In particular, the ability to rapidly characterize large numbers of samples opens up new possibilities for risk-based approaches to soil evaluations that explicitly consider uncertainty in predictions and interpretations of soil properties.

## 3. Agroforestry systems offer a major pathway for sustainable diversification of agricultural systems and incomes

Diversification of agricultural enterprises is one of the oldest practices adopted by the farmers to reduce/spread the risks and capitalise on the opportunities associated with variable climate through better exploitation of potential synergies and complementarities among different farm enterprises. Diversification is an adjustment of the farm enterprise pattern in order to increase farm income or reduce income variability by reducing risk, exploiting new market opportunities and existing market niches, diversifying not only production, but also on-farm processing and other farm-based, income-generating activities (Dixon et al., 2001). At the farm level it is the adoption of multiple production activities that are complementary in economic and/or ecological dimensions involving crops, trees, livestock and post harvest processing. Integrated agroforestry systems are a suitable pathway for sustainable diversification of agricultural systems. Examples of such systems are abound. The fast growing poplar has become a major tree component on many farms in South Asia. Across Africa, home gardens with a diverse range of vegetable and fruit yielding trees are quite popular (Mendez et al., 2001; Vogl et al., 2002; Wezel and Bender, 2003) and contribute significantly to food security by providing products year round. A global review on the contribution of home gardens to food and nutrition of households found that up to 44% of calorie and 32% of protein uptake are met by the products from home gardens (Torquebiau, 1992). Besides meeting the subsistence needs of households, the role of home gardens in generating additional cash income cannot also be overlooked (Christanty, 1990; Torquebiau, 1992; Dury et al., 1996; Mendez et al., 2001).

It is now being recognized that expanding market opportunities for smallholders particularly in niche markets and high value products is critical to the success of agroforestry innovations (Russell and Franzel, 2004). The major constraints to the growth of the small holder tree product sector in Africa are forest policies, physical and social barriers to smallholder participation in markets, the overall lack of information at all levels on markets for agroforestry products, and the challenges to outgrowing schemes and contract farming. Notwithstanding these constraints, there are promising developments including contract fuelwood schemes, small-scale nursery enterprises, charcoal policy reform, novel market information systems, facilitating and capacity building of farmer and farm forest associations, and collaboration between the private sector, research and extension (Russell and Franzel, 2004). The possibilities for integrating farms with traditional and non-traditional trees that provide fruits, nuts and other food products, medicinal plants (Rao et al., 2004), short rotation woody crops (Rockwood et al., 2004), and biomass energy plantations (Hall and House, 1993) are plenty, if suitable market structures are put in place.

## 4. Agroforestry systems have the capacity to enhance the use efficiency of rain water

Water is already a scarce resource and climate change is expected to make the situation worse. Climate change has both direct and indirect impacts on water availability. The direct impacts include changes in precipitation patterns while the indirect ones are increases in losses through runoff and evapotranspiration. Based on the results from extensive studies conducted under the Comprehensive Assessment of Water Management in Agriculture, CA warns that today’s food production and environmental trends, if continued, will lead to crises in many parts of the world (CA, 2007). Hence with or without climate change, improving agricultural productivity of water is extremely important in managing the acute water shortages that the humankind is expected to face over the next 50-100 years.

There are several mechanisms whereby agroforestry may use available water more effectively than the annual crops. Firstly, unlike in annual systems where the land lies bare for extended periods, agroforestry systems with a perennial tree component can make use of the water remaining in the soil after harvest and the rainfall received outside the crop season. Secondly, agroforests increase the productivity of rain water by capturing a larger proportion of the annual rainfall by reducing the runoff and by using the water stored in deep layers. Thirdly, the changes in microclimate (lower air temperature, windspeed and saturation deficit of crops) reduce the evaporative demand and make more water available for transpiration.

Despite its importance, the knowledge and understanding of the competition for resources between the tree and crop components remains imperfect due to the complex nature of the interactions and difficulties associated with quantification. Much of the evidence is based on the interpretation of the observations made on above ground components of the system which have mostly reported negative effects of trees on crop yields. This negative effect is commonly attributed to the competition for nutrients in case of humid areas where moisture is unlimiting and to moisture in case of semi-arid tropics primarily to water. Soil water measurements made over three consecutive seasons under hedgerow intercropping with contrasting Senna species (*S. siamea* and *S. spectabilis*) and a maize–cowpea (*Vigna unguiculata*) annual crop system at

Machakos, Kenya (av. rainfall 760 mm $yr^{-1}$ in two rainy seasons), highlighted the importance of competition of hedgerows for water in semiarid environments (Figure 2). Soil water under both hedgerow systems was lower than in the annual crop system throughout the study period and the differences were greater in periods of water stress. Soil water depletion was greater under the fast-growing and high-biomass-producing *S. spectabilis* than under the slower growing and less-biomass-producing *S. siamea*. The soil profile was never fully recharged, even when rainfall was 547 mm (50% higher than normal) during the ‘short rainy’ season of 1994–95, because of severe water depletion in the previous season (Rao et al., 1998). Interception of rain by canopy can also play a significant role in reducing the amount of water reaching the soil and losses as high as 50%, depending on the tree density and the amount and distribution, of the rainfall were reported (Ong et al. 1996).

Vertical root complementarity is considered as one of the advantages of agroforestry systems. Studies on root growth indicate that all trees used in agroforestry systems do not always have deep pivotal roots, and that mixed and superficial tree root architectures are common (vanNoordwijk et al., 1996). Similarly, trees tend to develop or redirect their roots to the upper soil layers, if water recharge below the root zone is infrequent as it happens in low rainfall years and in the absence of plant available nutrients (Rao et al., 2004). Only a few species have the root systems that can reach relatively deep water tables. Consequently, there seems to be less scope for vertical root complementarity than originally thought (Sanchez, 1995; Ong and Swallow, 2004) highlighting the need for management approaches to reduce the competition. Side-pruning of trees to reduce above ground competition and periodic root pruning to reduce below ground competition were tried, although the feasibility for managing root competition is questionable on many tropical farms.

## 5. Agroforestry systems provide economically viable and environmentally friendly means to improve soil fertility

Nutrient mining from continuous cropping without adequately fertilizing or fallowing the land is often cited as the main constraint to increase in productivity in most countries across Africa. It is estimated that on average African soils have been depleted by about 22 kg nitrogen, 2.5 kg phosphorus, and 15 kg potassium per hectare of cultivated land over the past 30 years in 37 African countries – an annual loss equivalent to $4 billion worth of fertilizers (Sanchez, 2002). While fertilisers offer an easy way to replenish the soil fertility, at the current prices it is very unlikely that there will be any change in the investments made by African farmers in fertilisers. In this context, Agroforestry systems have attracted considerable attention as an attractive and sustainable pathway to improve soil fertility. World Agroforestry Center made substantial progress in the identification and promoting of agroforestry systems aimed at improving soil fertility.

According to Sanchez et al. (1997), there are four ways through which trees can contribute to the improved nutrient supply -increase nutrient inputs to the soil, enhance internal cycling, decrease nutrient losses from the soil, and provide environmental benefits. After extensive experimentation with a wide range of soil fertility replenishment practices, the World Agroforestry Center has developed a system with three components that can be used in combination or separately: (i) nitrogen-fixing leguminous tree fallows, (ii) indigenous rock phosphates in phosphorusdeficient soils, and (iii) biomass transfer of leaves of nutrient-accumulating shrubs (Sanchez, 2002). The Leguminous trees of the genera Sesbania, Tephrosia, Crotalaria, Glyricidia, and Cajanus are interplanted into a young maize crop and allowed to grow as fallows during dry seasons, accumulating 100 to 200 kg N ha$^{-1}$ over the period from 6 months to 2 years in subhumid tropical regions of East and Southern Africa. The quantities of nitrogen captured are similar to those applied as fertilizers by commercial farmers to grow maize in developed countries. The other options tried include mixed intercropping with gliricidia (*Gliricida sepium*) and biomass transfer with wild sunflower (*Tithonia diversifolia*) or gliricidia (Place et al. 2002). These systems were found to provide 50 to 200 kg N ha$^{-1}$ to the associated cereal crops. Yield increases are typically two to three times that with current farmers' practices. These approaches, although attractive, are not useful in all the agro-ecologies. Improved fallows have yet to prove their worth in the semiarid tropics of Africa where the much longer dry season limits their growth and nitrogen fixation potential, in shallow soils, poorly drained soils, and frost-prone areas (Sanchez, 2002).

## 6. Agroforestry systems have the potential to limit carbon emissions and sequester carbon

The greatest role of agroforestry in relation to climate change is perhaps in mitigating the emissions of $CO_2$ by productively sequestering carbon from the atmosphere (Figure 3). The tree component of the agroforestry systems can be a significant sink for carbon in lands devoted to agriculture. The three major paths through which tree can help reduce atmospheric carbon are: conservation of existing carbon pools through practices such as avoided deforestation and alternatives to slash and burn; sequestration through improved fallows and integration with trees, and substitution through biofuel and bioenergy plantations to replace fossil fuel use (Montagnini and Nair, 2004).

A number of studies have estimated the potential of agroforestry systems to act as effective carbon sinks (IPCC, 2000; Albrecht and Kandji, 2003; Montagnini and Nair, 2004, Palm et al., 2005). Assuming mean carbon content of above ground biomass of 50%, average carbon storage by agroforestry practices has been estimated to be 9, 21, 50, and 63 Mg C ha$^{-1}$ in semiarid, subhumid, humid, and temperate regions respectively (Schroeder, 1994). The quantitative importance of agroforestry as carbon sink derives from its wide applicability in existing agricultural systems. Worldwide it is estimated that 630 x $10^6$ hectares are suitable for agroforestry. Improved fallows aimed at improving nutrient depleted soils is undoubtedly one of the most promising agroforestry technologies in the sub-humid tropics and has, in recent years, shown great potential for adoption in southern and eastern Africa. Even in drier areas such as the Sudan- Sahel zone of West Africa, recent field experiments have shown that the technology could significantly contribute to curbing land degradation and improving farm productivity. Unlike the more perennial systems in the humid tropics, improved fallows are mostly short-rotation and as such sequester much less carbon aboveground. Nevertheless, if the time-averaged aboveground carbon is considered, they store substantial quantities of carbon compared to degraded land, croplands or pastures (Albrecht and Kandji, 2003).

While the potential of agroforestry systems to store additional carbon is well established and widely recognised, possible tradeoffs between carbon storage and profitability in agroforestry systems have to be taken into account while promoting these systems (Gockowski et al., 2001). It is estimated than an increase of 1 tonne of soil carbon of degraded cropland soils may increase crop yield by 20 to 40 kg ha$^{-1}$ for wheat, 10 to 20 kg ha$^{-1}$ for maize, and 0.5 to 1 kg ha$^{-1}$ for cowpeas. Carbon sequestration is a secondary product but it is unclear how smallholders can benefit from carbon sequestration projects and CDM (Montagnini and Nair, 2004). Better quantification of carbon sequestered is required to establish how much carbon is sequestered and how much is added to the soil carbon pool before any of this can figure in carbon audits and provide incentives to smallholder farmers.

Nevertheless, the potential of agroforestry as a strategy for carbon sequestration has not yet been fully recognized, let alone exploited. A major difficulty is that empirical evidence is still lacking on most of the mechanisms that have been suggested to explain how agroforestry systems could bring about reductions in the buildup of atmospheric $CO_2$.

## Adoption of agroforestry systems:

During the past two decades, research has demonstrated that agroforestry systems can generate substantial environmental benefits while meeting the immediate requirements of food and income, when implemented with carefully selected species that meet end user requirements and when the competition for growth resources between the tree and the crop component is adequately managed. Past research also indicates that the added value of trees when integrated with crops occurs more commonly in sequential, as opposed to simultaneous, agroforestry systems, because the competition for water, nutrients and light between the crop and tree component is separated over time (Sanchez 1995). It is for this reason that the sequential agroforestry systems, such as improved fallows, found widespread acceptance and adoption by smallholder farmers in Southern Africa (Figure 4).

Agroforestry systems provide the unique opportunity to utilise the resources to achieve maximum return from a unit of available soil, water, nutrient, and sunlight in an economically and ecologically sustainable manner. As highlighted earlier, the environmental benefits from these systems substantially outweigh the economic gains. At present the trade-offs between crop productivity and environmental functions are not well quantified. During the past decade, environmental services such as carbon sequestration, watershed protection and biodiversity conservation have been recognised as global environmental services and to some extent are being financed. Chaco et al. (2002) and Tomich et al. (2002) using the data from the Alternatives to Slash and Burn (ASB) programme in Indonesia predicted how carbon sequestration payments would change the relative returns to alternative land use systems. Their results indicate that carbon payments could be sufficient to increase returns to smallholder agroforestry systems to levels comparable to those generated by oil palm plantations. This makes agroforestry attractive to CDM since projects must be shown to add value to the existing situation. Pilot carbon sequestration schemes with smallholder farmers are currently in progress in several developing countries, with the most experience accumulated in Latin America.

Observations on farmer fields indicate that, farmer do accept yield losses provided the new intervention results in a clear return on investment. For example, *Panicum maximum* grass strips are widely adopted in the Machakos area despite greater trade-offs between erosion control and crop productivity even though it is twice as competitive as *S. siamea* hedgerows because of the direct benefit from the grass which provides fodder for dairy production (Kinama et al., 2000). In central Kenya, farmers use highly competitive species such as Napier grass (*Pennisetum purpureum*) and *Calliandra calothyrsus* trees for soil conservation on hillslopes, where they produce 3–5 t ha$^{-1}$ per year of high quality fodder (Angima, 2000). In the traditional parklands of West Africa, dense shading by shea butter trees (*Vitellaria paradoxa*) and nere (*Parkia biglobosa*) which reduces millet yield by 50–80% are used because of the high economic yields from marketable tree products (Kater et al., 1992).

The available literature suggests that there are opportunities to make the agroforestry systems more attractive and profitable. There is a need to survey existing agroforestry systems to determine the interaction between component species, to classify the trees used, and then to refine the systems in view of soil, climate, and socio-economic limitations. Detailed studies on the competition and complementarity between trees and understorey agricultural crops for solar radiation, space, and soil factors are needed. Future systems should integrate trees that are tolerant to strong light and high evaporative demand and crops that are adapted to shade and relatively high humidity. It is disappointing that so few tree species with limited competitive effects on crop plants and high economic value to the farmers have been identified to date. The role of agroforestry systems in moderating the pest and disease incidence and allelopathic influences has been rarely studied. Finally there is a need to study the various socio-economic constraints and design appropriate strategies to convince the farmer that the short- and long-term payoff in adopting agroforestry will be considerable.

### *Conclusions:*

The growing and compelling evidence about global warming and its impact on global climatic systems has firmly established that climate change is real and that its consequences will be serious especially for Africa more than any other continent. The agricultural impacts of climate change are of the greatest concern to most developing countries, particularly in the tropics, because of higher dependence on agriculture, subsistence level of operations, low adaptive capacity and limited institutional support.

Agroforestry systems offer a win-win opportunity by acting as sinks for atmospheric carbon while helping to attain food security, increase farm income, improve soil health and discourage deforestation. While agroforestry systems clearly offer economic and ecological advantages, the management of these systems is complicated by the tradeoffs between subsistence requirements, acceptable risks, and costs involved. A critical and scientific assessment of these trade offs requires quantitative data and tools to make a realistic assessment of the complex interactions involved in natural resource use and economic and environmental benefits. Because of the long lead time required to study agroforestry systems thorough complete rotations and high research costs associated with such studies, much of the current assessment is based on incomplete data. Well calibrated and validated system simulation models have the potential to contribute significantly to the understanding and quantify the benefits. Though not much progress has been made in simulating agroforestry systems, the progress made in simulating the annual crop production suggests that it can be done.

In addition to an in depth understanding of the benefits from the systems and farmer requirements, mainstreaming of agroforestry requires better market linkages for the goods and services produced. An analysis of consumer needs, local and regional markets including the opportunities for linking carbon sequestration benefits to the CDM, and promotion of market intelligence systems and farmer associations are some of the areas where interventions are required to link smallholder farmers with markets.

Most research, to date, has focused on the impacts of climate change on major annual crops and very little on trees and perennial crop systems. The long duration of the perennials and difficulties in changing varieties over short periods pose special challenges and more research is required to address the same. A thorough understanding of how well the perennial trees overcome the impacts of climate change is an essential requirement before promoting their use.

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**Figure 1. Effect of improved fallow on soil erosion in the long rains (March-July) of 2003, Luero, western Kenya (data from Boye, unpublished) The total rainfall for the season was 871mm (Legend: Cm = continuous maize; Cg = *Crotalaria grahamiana*; Tc = *Tephrosia candida*)**

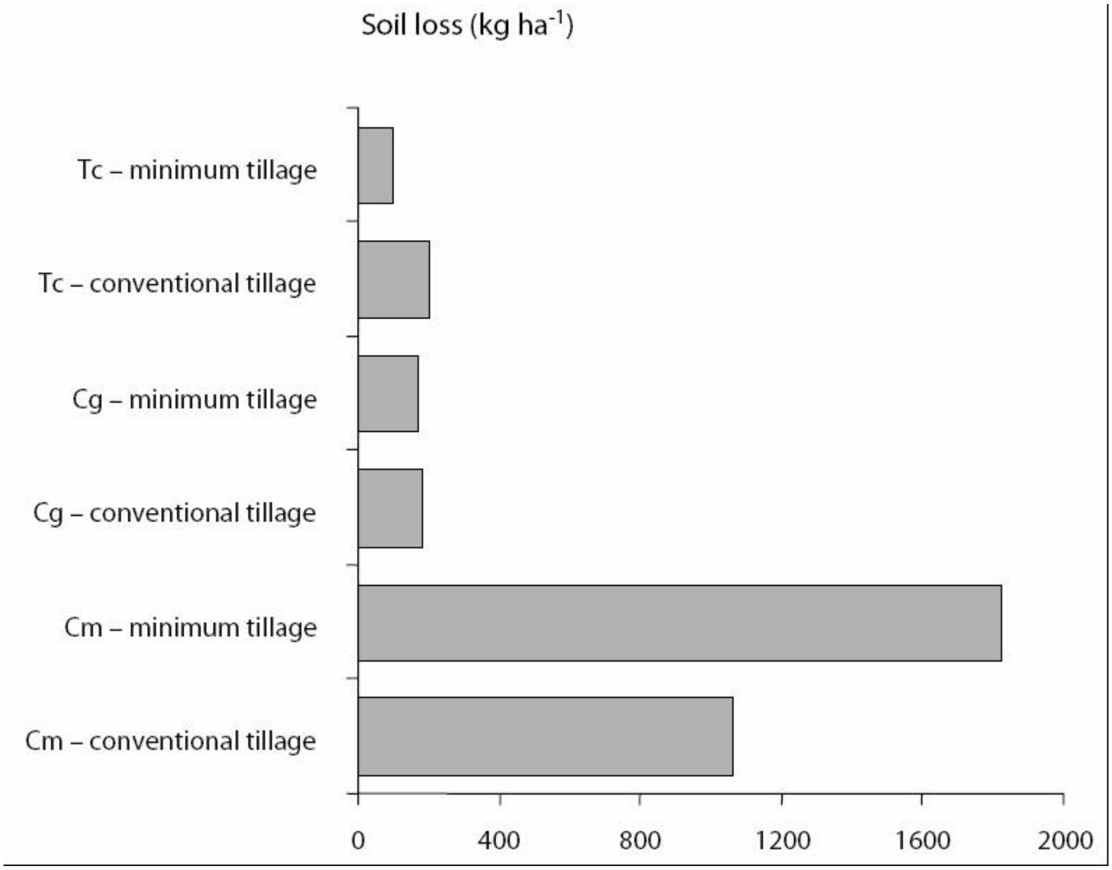
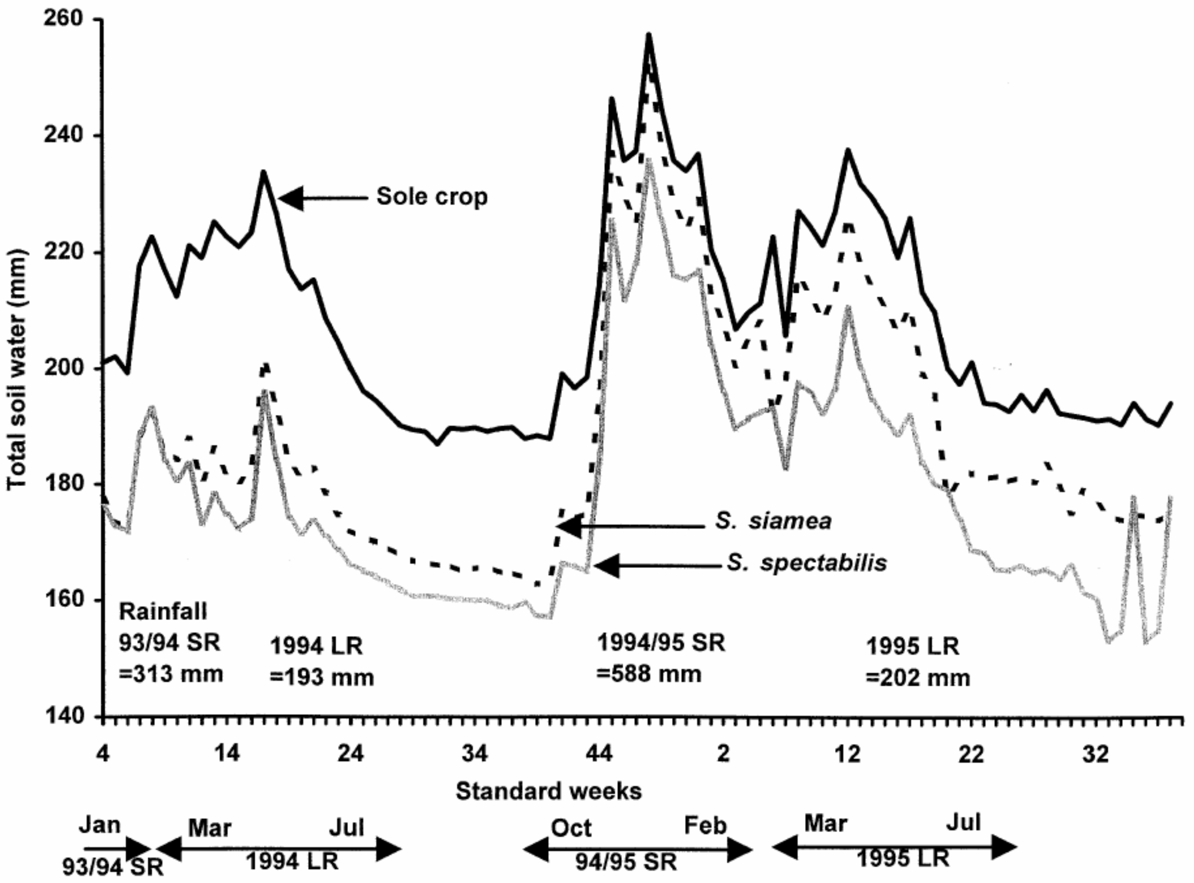


**Figure 2. Weekly changes in the total soil water content in 165-cm profile under hedgerow intercropping with Senna siamea and S. spectabilis, and sole annual crop (maize–cowpea (Vigna unguiculata) sequential) system during three cropping seasons (January 1994 to November 1995)**



LR = long rainy season; SR = short rainy season

(Source: unpublished data of H. Odhiambo and C. K. Ong, taken from Rao et al., 1998).

**Figure 3. Carbon sequestration potential of different management options (adopted from IPCC, 2000)**

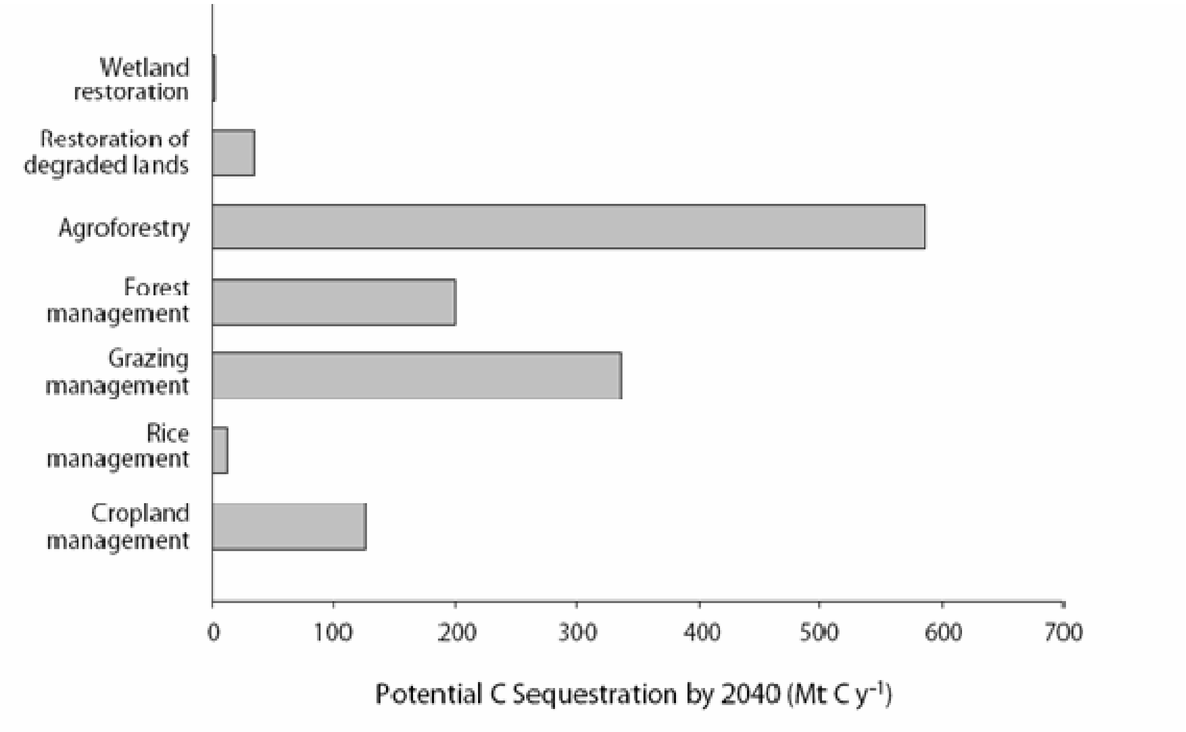


**Figure 4. Number of farmers planting improved tree fallows in Eastern Zambia (From Zambia ICRAF annual report, 2005)**

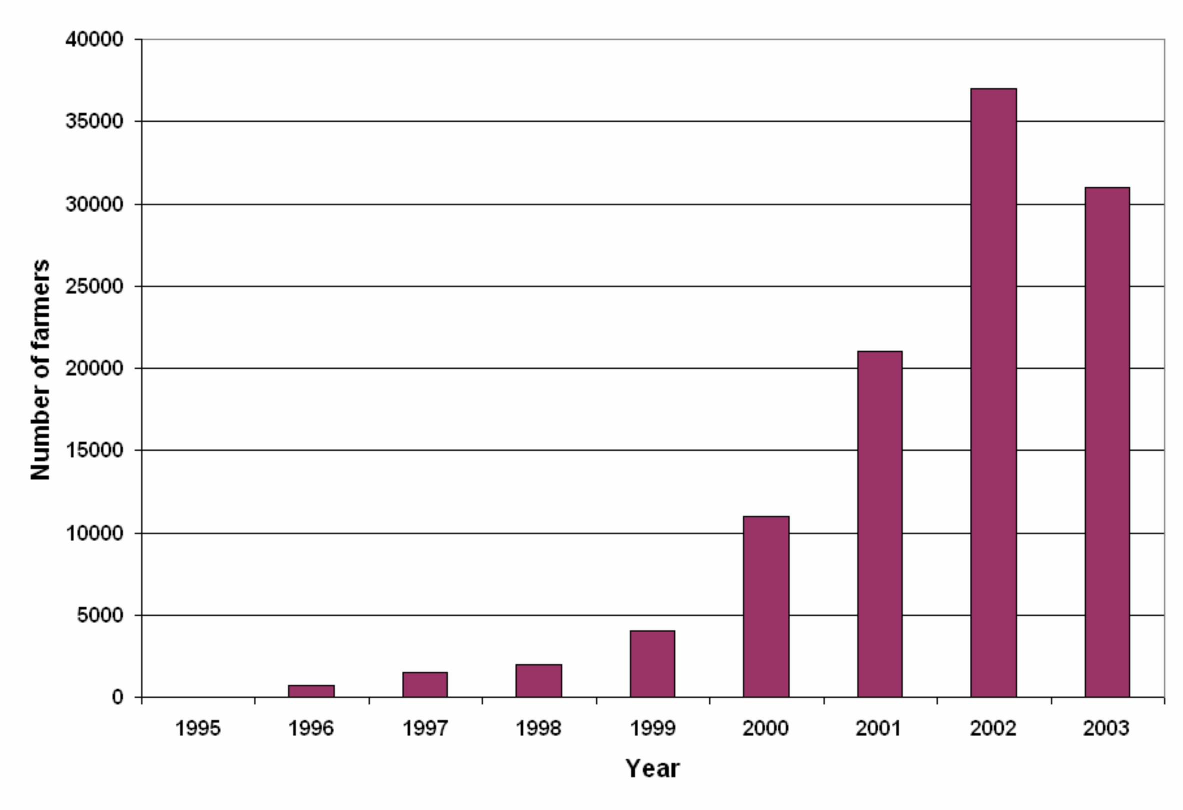


**Table 1. Projected changes in climate and their impact on agriculture**

| ***Phenomena and direction of change*** | ***Likelihood of occurrence*** | ***Major projected impacts on agriculture*** |
|---|---|---|
| Warmer and fewer cold days and nights; warmer/more frequent hot days and nights over most land areas | Virtually certain (>99% chance) | Increased yields in colder environments<br>decreased yields in warmer environments<br>increased insect outbreaks |
| Warm spells/heat waves: frequency increases over most land areas | Very likely (90-99% chance) | Reduced yields in warmer regions due to heat stress; wild fire danger increase |
| Heavy precipitation events: frequency increases over most areas | Very likely | Damage to crops; soil erosion, inability to cultivate land due to water logging of soils |
| Area affected by drought: increases | Likely (66-90% chance) | Land degradation, lower yields/crop damage and failure; increased livestock deaths; increased risk of wildfire |
| Intense tropical cyclone activity increases | Likely | Damage to crops; windthrow (uprooting) of trees; damage to coral reefs |
| Increased incidence of extreme high sea level (excludes tsunamis) | Likely | Salinisation of irrigation water, estuaries and freshwater systems |

**Table 2. Some agroforestry systems and practices (Schoene et al., 2007)**

| System | Practice | Combination | Components |
|---|---|---|---|
| Agro-silvicultural systems | 1.Improved fallow | trees planted during non-forest phase, if land not expected to revert to forest | t: fast growing<br>h: agricultural crop |
| | 2.Taungya | crops during tree seedling stage | w: plantation species<br>h: agricultural crops |
| | 3. Alley cropping | trees in hedges, crops in alleys | w: coppice trees<br>h: crops |
| | 4. Tree gardens | multispecies, dense, mixed | w: vertical structure, fruit trees<br>h: shade tolerant |
| | 5. Multipurpose trees on cropland | trees scattered, boundaries | w: multipurpose trees<br>h: crops |
| | 6. Estate crop combinations | | w: coffee, coconut, fruit trees<br>h: shade tolerant |
| | 7.Homegardens | multistorey combinations around homes | w: fruit trees<br>h: crops |
| | 8. Trees in soil conservation, reclamation | | w: multipurpose fruit trees<br>h:crops |
| | 9. Shelterbelts, windbreaks, live hedges | around farmland plots | w: trees<br>h:crops |
| | 10. Fuelwood production | firewood species around cropland plots | w: firewood species<br>h: crops |
| Agro-silvipastoral; systems | 14.Homegardens with animals | around homes | w: fruit trees<br>a : present |
| | 15.Multipurpose woody hedgerows | trees for browse, mulch, soil protection | w: coppicing fodder trees<br>a, h: present |
| | 16. Aquaforestry | trees lining ponds | w: leaves forage for fish |
| Silvipastoral systems | 11.Trees on rangelands | scattered trees | w: multipurpose, fodder<br>f: present<br>a: present |
| | 12. Protein banks | trees for protein-rich cut fodder | w: leguminous trees<br>h: present<br>a: present |
| | 13. Estate crops with pasture | Example cattle under coconut palms | w: estate crops<br>F: present<br>a: present |

W: woody species, a: animals, h: herbaceous (crop) species

**Table 3. Biomass of macrofaunal groups under different land-use systems at Muguga, Kenya**

| Group | Natural forest | Sesbania fallow | Grass fallow | Maize monocrop |
|---|---|---|---|---|
| | Macrofauna biomass (g m–2 of 0–30 cm soil depth) | | | |
| Earthworms | 3.54 | 09.58 | 3.34 | 0.92 |
| Woodlice | 0.37 | 0 | 0.01 | 0 |
| Millipedes | 15.42 | 00 | 02.19 | 0.53 |
| Centipedes | 0.05 | 0.03 | 0.22 | 0 |
| Termites | 0.06 | 3.77 | 2.41 | 0.14 |
| Cockroaches | 0.11 | 0 | 0.05 | 0 |
| Crickets | 0.08 | 0 | 0 | 0 |
| Beetle larvae | 0.66 | 3.91 | 3.04 | 2.44 |
| Beetle adults | 0.78 | 0.17 | 0.53 | 0.12 |
| Ants | 0.11 | 0.05 | 0.25 | 0.05 |
| Spiders | 0.02 | 0.10 | 0.02 | 0 |
| Others | 0.05 | 2.20 | 0.02 | 0.01 |
| Total | 21.25 | 19.81 | 12.08 | 4.21 |