Using Eucalyptus for Soil & Water Conservation on the highland Vertisols of Ethiopia

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Chapter 1

Introduction

Introduction

Ethiopia is the third largest country in Africa (about 1 million km^2) and is endowed with a complex variety of agro-ecological conditions ranging from desert to rainforest and from sea level to highlands soaring to over 4,500 meters. This enables Ethiopia to grow a large variety of crops and to keep nearly almost all types of livestock, resulting in integrated crop-livestock systems of land use. The complex topography and wide altitudinal range ensure a variety of temperature and rainfall conditions. For that reason, it is not uncommon to find some parts of the country suffering from too much rain while at the same time other parts suffer from drought. Within Ethiopia, the 1500 meter contour approximates the boundary between settled agriculture in the highlands and nomadic livestock in the lowlands.

Environmental degradation

The area commonly referred to the "highlands" is characterized by a complex configuration of mountains and plateaus and physically constitutes of 44 % of the total land mass. These highlands, which are characterized by favorable environmental conditions, have been settled for millennia and known a similar long-standing agricultural history (McCann, 1995). It is estimated that 88 % of the country's population; 95 % of the cropped areas; about two third of the country's livestock; and 90 % of the country's economic activities are all stationed in these highlands (Constable, 1984). The absence of technological development has created a near total dependence of employment in the agricultural sector and this has created an unbearable burden on land, vegetation and water resources of the highlands (El-Swaify and Hurni, 1996).

With agricultural productivity lagging behind population growth rate (Mulat, 1999), the gap between the availability and the demand for agricultural land continues to grow. This results in severe land-use conflicts between arable farming, animal grazing and forestry. National forests and plantations are encroached upon and cleared for cultivation or grazing. State and community forest interests collide with local grazing interests on hillside land, and grazing and fuel wood interests confront each other in the woodlands. Forestry can play a role in reducing land pressure and land degradation. It is important to note, however, that forestry alone will not be able to solve the problem. Even if the management of existing forest resources is improved and new trees and forests are established, this may well prove futile if the need for crop and grazing land continues to grow due to high population growth rates. Using the land for forestry to improve soil fertility or to rehabilitate and conserve the environment will be viewed as secondary to using the land for cropping and grazing to meet immediate needs of survival. The effects of overgrazing on infiltration, runoff, soil erosion, on site water use and consequent downstream impacts are of great concern (Stroosnijder, 1996), particularly in highland agriculture.

Soil erosion by water is by far the biggest land degradation problem in the Ethiopian highlands (FAO, 1986, Hurni, 1993) and the highest rate occurs from cultivated fields, which is estimated at 42 Mg ha^{-1} y^{-1} (Hurni, 1993). Retention of crop residues in agricultural fields plays an important role in nutrient cycling, erosion control and maintenance of appropriate soil physical and chemical properties (Mando and Stroosnijder, 1999). However, retention of crop residues in the highland farming systems for the purpose of recycling nutrients and the improvement of soil organic matter is unthinkable as long as the current unbalanced demand and supply of livestock fodder persists. It is equally unthinkable to bring dung into the farming system without having a substitute for its domestic fuel use. Hence, attempts to alleviate land degradation in the highlands are critically dependent on efforts to deal with the three main underlying causes of land degradation; population growth, low agricultural productivity and high dependence on fuel wood, dung and crop residue as sources of household energy. The current study explores the compatibility of land intensification that combines an increase in productivity and short-term fuelwood supply through eucalyptus based agroforestry system in seasonally waterlogged highland Vertisols.

According to EHRS (1984), agricultural costs of land degradation in the next 25 years are estimated to 150,000 million birr (the exchange rate in 1984 was 2.7 birr to 1 US dollar). The study further asserted that land degradation could destroy the farmland of some 15 % of the population or 10 million highlanders by the year 2010. If the present trend continues, today's children could see over a third of the highlands become incapable of sustaining cropping while the population triples within their lifetimes. Yet it is here that the Vertisols, the third most common soil in the country after Nitosols and Cambisols (Jutzi and Mesfin, 1986) are found. Currently, out of 8 million ha of highland Vertisols about 2 million ha, which accounts for about one-third of the total national cropland, are under arable crop cultivation (Jutzi and Mesfin, 1986). However, these soils are vastly underutilized due to management difficulties using traditional cultivation practices. In this context, it has long been realized that waterlogging is severe in the highland Vertisols where high rainfall and low evaporative demand prevail (Tesfaye and Dagnachew, 1967; Mesfin, 1981; Mamo et al., 1992). However, with the use of appropriate soil and water management technologies on 25-50 % of Vertisols already in use, these would support about 25 million people, compared with 6 million under the traditional system (Bull, 1988). Thereby reducing exploitative cultivation of marginal lands in highly fragile agro-ecosystems of the highlands.

Distribution and characteristics of Vertisols in Ethiopia

Vertisols occupy 10 % of the geographical area of Ethiopia of which 70 % occur in subhumid climates where the rainfall is 1000-2000 mm y^{-1} (Vermani, 1988). Vertisols in Ethiopia are derived from fine textured basic rocks, volcanic ashes, granitic colluvium, limestone and colluvial-alluvial deposits (Berhanu, 1985). The combination of topographic position, climatic conditions and parent material determines the spatial and temporal linkages of Vertisols with the other soils in the highlands. Vertisols occupy the lower parts of the landscape, comprising level to gently undulating piedmont and bottom valley lands with restricted drainage (Berhanu, 1985). Associated Vertic intergrades (Vertic Calcisols, Luvisols, Cambisols) usually occur in a relatively higher position, comprising gently sloping land to moderately steep plateau. In the central highlands basic rocks under toposequences with Nitosols/ Luvisols on slopes and Vertisols in low-lying positions occur frequently (Mamo et al., 1992).

Vertisols in the highlands generally contain more than 40 % clay in the surface horizons and close to 75 % in the middle part of the profiles. The sand fraction is low, often less than 20 % and is found in the bottom and surface horizons (Asnakew, 1988). The clay mineralogy is dominated by montmorillonite, which belongs to the smectite family of clay minerals (Berhanu, 1985) and is responsible for their Vertic properties. Although Vertisols have above average soil fertility, nitrogen and phosphorus in that order are the two plant growth-limiting nutrients and become more important with improved crop cultivars and cropping systems (Mamo et al., 1992). Vertisols are difficult to work: they are of very hard consistence when dry and very plastic and sticky ("heavy") when wet. Therefore the workability of Vertisols is often limited to very short periods of medium (optimal) water status. However, tillage operations can be performed in the dry season with heavy machinery. Mechanical tillage in the wet season causes compaction.

Current management practices

Moisture conservation during the dry season and removal of excess water during the wet season are crucial management practices for highland Vertisols. Vertisols, due its montmorillontic mineralogy, have a high water holding capacity, a very low hydraulic conductivity and low infiltration rates. Subsequent rains cause ponding, making tillage difficult and initiating erosion. In many highland Vertisol areas farmers follow a strategy of avoiding much of the waterlogging effect by sowing traditional crops and varieties towards the end of the rainy season (September) which then grow mainly on residual soil moisture. Farmers also traditionally use a variety of land layouts to facilitate external drainage such as drainage furrows, ridges and furrows and hand made broadbed systems but none of these are effective enough to utilize the full growing period which is in excess of 150 days (Bull, 1988). Soil burning is practiced extensively at high elevations exceeding 2400 masl, where considerable organic matter (sod) accumulates during an extended fallow period, ranging from 10 to 20 years (Tesfaya and Dagnachew, 1967; Mesfin, 1982). Soil burning enhances in situ drainage through the transformation of clay particles into sand- and gravel-sized particles (Mesfin, 1981). However, it is not only a tedious practice involving woman and children, but introduces inefficient land use when considering the extended fallow period that is needed before land can be brought back into repeated production.

Research based interventions

Cambered beds have shown more than a threefold increase in yields of wheat and barely as compared to the traditional method of land preparation. On the other hand, problems such as power requirements and fragmentation of farmer's holdings have prevented its adoption (Ahmad, 1986). The use of a low cost animal drawn surface drainage implement that forms 20 cm high and 80 cm wide beds has shown remarkable yield advantages over the traditional land preparation methods (Jutzi and Mesfin, 1986). The technology not only minimizes the effect of waterlogging but, not less significant, promotes the advance of the cropping season such that an early sown crop may escape moisture stress later in the season. However, farmers are reluctant to adopt the technology because this practice is not suited to all crops they are growing. Moreover, without a coordinated and integrated approach in watershed management, increased productivity due to surface drainage is not sustainable. The water drained from small fields can cause widespread erosion of agricultural lands down the slopes. Vertisols are susceptible to severe soil erosion under high intensity and high volume storms with a strong seasonal character as in the highlands. Hence, any improved farming system suggested to replace the traditional Vertisol management system must incorporate some elements of soil and water conservation. There seems to be room for farm forestry in rotation with annual crops or for a more integrated agroforestry system, but this has not yet received adequate research attention.

Rationale of the current study

The shrink-swell characteristics of Vertisols, give these soils special attributes that impose constraints to low-input agriculture. The challenge is to develop low-input technologies for Vertisols that will enable resource poor smallholder farmers to achieve sustainable agriculture. Agroforestry has attracted considerable attention because of its potential to maintain or increase productivity where high energy input, large-scale agriculture is impractical (Kidd and Pimentel, 1992). This is particularly so in environments such as in the highland Vertisols where the scope for improving water use efficiency is considerable (Cannell et al., 1996). Young (1987) suggested that trees and shrubs play an essential role in minimizing erosion by reducing runoff, so improving water conservation. Nevertheless, scattered acacia trees among agricultural crops, a common feature of the traditional agroforestry system in the Ethiopian highlands shed their leaves during much of the cropping season and have virtually no ecological interaction in making use of the excess seasonal moisture. Identification and promotion of multi-purpose trees that can be used for soil conservation on Vertisols are difficult. Tree roots of many potential species find it difficult to establish themselves in the subsoil without being damaged by shrinking and swelling phenomena (Van Wambeke, 1991).

Over the recent years as off-farm tree resources decline, *Eucalyptus globulus* trees planted along the borders of cropland has come to dominate the highland Vertisols landscape. *Eucalyptus globulus*, unpalatable to cattle, sheep and goats (Pukkala and Pohjonen, 1989), has a distinct advantage in mixed farming systems where otherwise the protection of trees on farm land is difficult because of dry season free grazing practices. In this environment eucalypt boundaries produce a large biomass within a short period of time (4-5 years) and provides multitudes of benefits to smallholder farmers without inducing a major land use shift. Fast growing eucalyptus species are considered to be voracious consumers of water (Malik and Sharma, 1990) particularly when moisture supply is adequate. *Eucalyptus* that uses the excess water may increase the proportion of rainfall used for biomass production, hence improving the so called green water use efficiency (Stroosnijder, 2003). Thereby mitigating the soil, water and nutrient erosion problems associated with traditional rainy season fallow practices while increasing short-term fuelwood production. However, environmental concerns are frequently taken into concern at policy and planning level, although they are rarely quantified and evaluated from a sustainable resource utilization point of view relevant to Ethiopian climate, soil and land use conditions. Still, at present there are regulations in many areas in Ethiopia that prevent farmers to plant eucalyptus on their farms.

Thus, it is imperative to come up with hard facts and figures that indicate alternative resource utilization in an eucalyptus based agroforestry system under farmer's production circumstances. As this is demand driven and need oriented, its applicability and contribution is expected to be high in the present discussion on issues that revolve around eucalyptus use. It is also expected to enable decision-makers to make informed and unbiased decisions in the area of agricultural and forestry development policies and to give due considerations on farmers' choice of species

Research questions and objectives

The main objective of this study is to evaluate *Eucalyptus globulus* based agroforestry systems as a land use intensification option in seasonally waterlogged highland Vertisols that should raise land productivity and short-term fuelwood supply while maintaining the resource base. Under this apex six research questions were addressed in this thesis:

1. Why do farmers plant competitive eucalyptus trees on their farmland?
2. Is the resource base enough to support intensified tree-crop system on a sustainable basis?
3. Is the allelopathic potential of eucalyptus a real treat to the environment?
4. Does the alternative resource utilization efficiency of eucalyptus justifies its integration into the prevailing agricultural system on highland Vertisols?
5. Are there opportunities to optimise resource use complementary in an eucalyptus based agroforestry system?
6. Can productive and protective functions in an eucalyptus based agroforestry system compliment each other?

In order to answer the above mentioned research equations and to give account of the historical land use / cover dynamics on soil erosion the following specific objectives were formulated:

1.To evaluate the effect of land use/cover change on soil erosion and adoption of water conservation practices.
2. To evaluate the biomass production potential of eucalypt boundaries and their competitive effects on crop productivity on typical Vertisols-Nitosols toposequences in the Ethiopian highlands.
3.To determine the allelopathic potential of eucalypt litterfall across the tree crop interface and litter mulches application.
4. To examine eucalyptus-crop farming practices, factors that affect their adoption and the impact on household income in the smallholder farmer's production environment.
5. To determine the alternative resource utilization efficiency of eucalyptus on highland Vertisols.
6. To determine the soil and water conservation efficiency and seasonal water balance of a short rotational Eucalyptus based agroforestry system.

The study site: Ginchi watershed

The Ginchi watershed lies within 39 ^{o}E and 9 ^{o}N in Dendi woreda (district) Oromya Regional State 80 km west of Addis Ababa and forms part of the central highlands (Figure 1). Ginchi watershed is a sub-watershed of Yubdo Legebatu, named after the small river Legebatu, and is characterized by diverse topographic conditions. The elevation ranges from 2160 m in the south to 2800 m in the north with a mean slope of 8.2 %. Vertisols, Cambisols and Nitosols in that order are the three dominant soil types in the watershed. Vertisols occupy the lower parts in the landscape while Nitosols dominant the upper part of the watershed. Vertic Cambisols occur mid-slope.

The watershed has a subhumid climate with average annual rainfall of 1200 mm of which 30 % occurs before the onset of the main cropping season, between February and April (Figure 2). Runoff, which accounts for 30-50 % of the seasonal rainfall, only occurs between July and

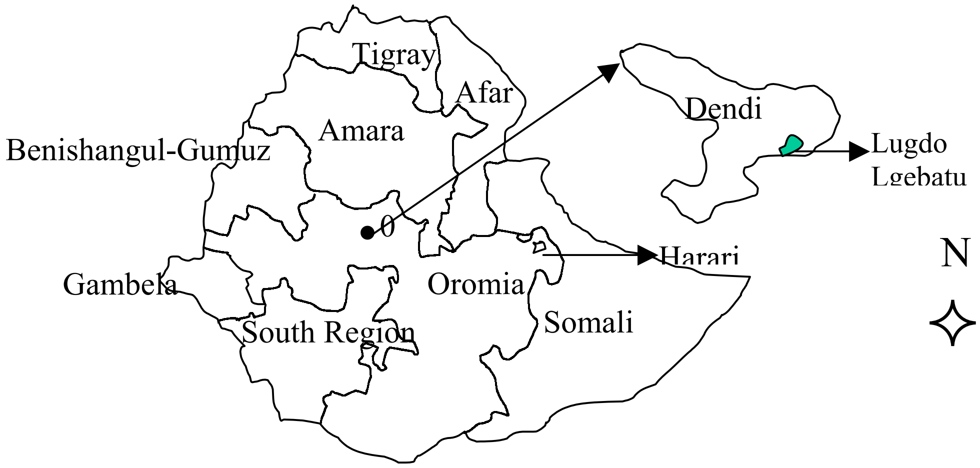

Figure 1. Location map of the study area (0= Addis Ababa).

September. Mean monthly maximum and minimum temperatures range between 26 °C and 9 °C and the annual potential evaporation is 1400 mm. The dependable growing period in eight out of ten years exceeds 4.5 months (Bull, 1988). Yubdo Legebatu watershed has a surface area of 41.5 km^2 and is inhabited by some 845 households with an average family size of 6 people (Dendi woreda bureau of agriculture, unpublished data). Thus, the population density is much higher (121 vs. 49 person km^{-2}) than the national average (CSA, 1998). The farming system in the watershed represents the smallholder, subsistence oriented production system, which prevails in the Ethiopian highlands. Cereal crops, with tef being the most important, occupy about 60 % of the cultivated area. Wheat, chickpea, faba bean, noug (*Guiztia abyssinica*) and sorghum in this order of significance, are the major crops in the watershed.

The reasons behind the selection of the Ginchi watershed as a site for this study were: 1) it represents a typical tef based cropping system of the highland Vertisols in terms of climate and socioeconomic environment. 2) the watershed represents a typical Vertisols-Nitosols toposequence in the highlands. 3) since 1994 the watershed has been identified as benchmark site for testing improved Vertisols technology options at watershed scale and hence the results of this study will complement the national efforts to formulate sustainable resource utilization in the highland Vertisols agroecosystem.

Outline of the thesis

This thesis is the result of a multiscale investigation on the extent of soil erosion, feasibility of runoff water harvesting and productive and protective functions of an *Eucalyptus globulus* agroforestry system. Several themes were covered by the study. Temporal changes in land use/cover during three and half decades were evaluated using aerial photographs (Chapter 2). The causes and extent of gully erosion across the three major soil types in the watershed was elucidated and environmental implication and management options are discussed. Widespread gully erosion on hillslopes in response to land use changes enhances the export of sediment produced on the intergully areas by increasing the connectivity in the landscapes, which leads to an increased risk of sediment deposition down slope in addition to a significant drying out effect in the intergully area. To reduce peak flow of ephemeral gullies and thereby reduce off site sedimentation the feasibility of runoff water harvesting in small farm ponds was evaluated, and results are presented in Chapter 3

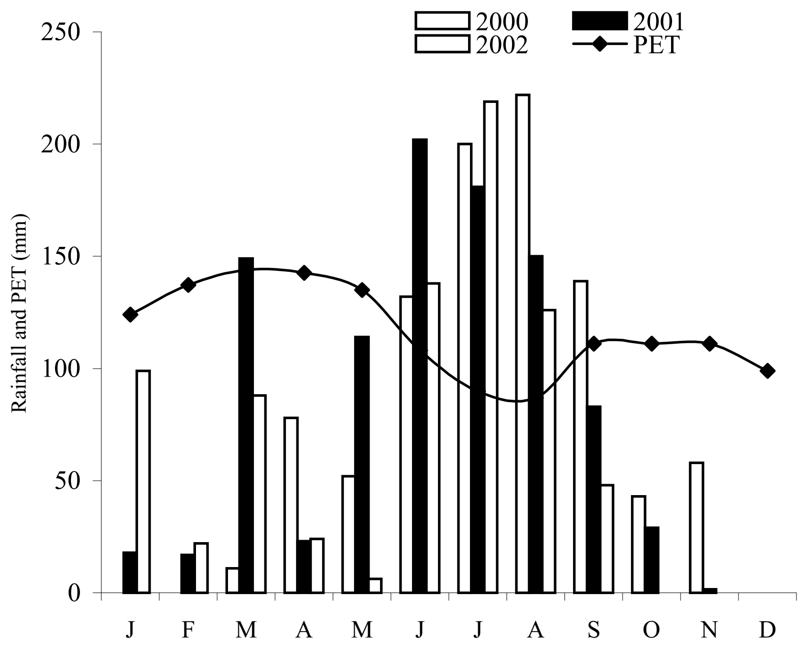

Figure 2. Annual rainfall distribution and mean PET between 2000-2003 at Ginchi, Ethiopia

In Chapter 4, factors that influence the adoption of soil and water conservation measures in two contrasting watersheds namely, Ginchi and Chemoga (northwest Ethiopia) were studied in terms of the extent of soil erosion problems and the policy environment. The results highlight that the issue of land tenure in itself is not enough to motivate the peasants in invest on soil and water conservation measures. It became apparent, however, that awareness, extent and severity of the erosion problem and knowledge on the basic principles of conservation need to be increased amongst both rural people and government decision makers.

Farm practices, economics and factors influencing eucalypt boundary plantings on two major soils of the watershed were studied, and the results are presented in Chapter 5. The alternative resource utilization efficiency of eucalyptus in terms dung fuel replacement is also discussed in this chapter. Allelopathic potential of eucalyptus litter was evaluated both under controlled and field conditions for two years. Main conclusion is that the allelopathic effects demonstrated for litter extract have no ecological relevance in the eucalyptus-crop production system in Ginchi (Chapter 6). In Chapter 7 and 8 the biomass production potential of eucalyptus boundaries and crop productivity on Vertisols and Nitosols, respectively are evaluated. Its implications in reducing pressure on forest resource and the maintenance of biodiversity are discussed as well. Nutrient removal and crop productivity studies under sole and short (three years) rotational eucalyptus based agroforestry indicate that the agroforestry system increases system's productivity without inducing significant nutrient depletion (Chapter 9). Runoff, soil loss and seasonal water use studies under sole and rotational eucalyptus show that eucalyptus trap water and soil that otherwise should have been lost under sole cropping condition. This justifies the integration of eucalyptus in traditional sole cropping systems (Chapter 10). Chapter 11 presents a conclusive summary of the study.

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Chapter 2

Land Use Changes and Erosion on Highland Vertisols of Ethiopia

Selamyihun Kidanu and Tekalign Mamo

Ethiopian Journal of Natural Resources (in press)

Abstract

The study evaluated changes in land use and the associated gully erosion incidence in the past three and half decades at Ginchi watershed in the central highlands of Ethiopia using two panchromatic aerial photo sets (1957 and 1994) as an input to produce GIS-based cover maps and digital elevation models. The results showed that in the watershed area, cropping expanded at a rate of 3 ha per annum into traditional grasslands, and compared to 1957, cropping has risen by 118 %. During the same period the area under woodland and riverine trees declined by 18–20 %. Close examination of the land use change further revealed that 81 % of cropland in the base year was maintained as cropland in 1994, while 17 % was converted back to grassland. Out of the total grassland in the base year only 33 % continued to be under grass in 1994 while 63 % was converted into cropland. Gully formation was a striking phenomenon, and the total length of the gullies in 1994 was about 12 km (3.8 km $km^{-2)}$ as compared to 5.3 km (1.7 km km^{-2}) in 1957. Over the same period, the surface area of the gullies increased from 16.6 ha to 36.2 ha. At a constant rate of expansion this would present an increment of 5 % per year of which 75 % came from new gullies. Over the years, the gullied area under cropland declined by 36 % while those under grassland particularly in upper part of the watershed increased tenfold. This calls for alternative grazing management especially during wet season in order to release pressure on the upper slopes where the risk of environmental degradation and detrimental impact down the slopes remain highest.

Key words: Erosion, Land use, Vertisols, Ethiopia

Introduction

The rapidly increasing population pressure in Ethiopian highlands has led to vast changes in land use pattern mainly caused by increasing agricultural production. In this region, cultivated lands showed slow but continuously increasing trend at the expense of forest and grasslands over the last four decades (Gete Zeleke, 2000; Kebrom Tekele and Hedlund, 2000). Accurate information on land-cover changes and the forces and processes impacting these at local scale is essential for designing sound environmental planning and management interventions, since aggregated effects of local land use changes are recognized to lead the impact at regional and global scale (Ojima et al., 1994).

Land use changes affect the type and quality of the vegetative cover on watershed land which in turn influence the runoff, soil erosion and ultimately the sediment production rate. Vegetation cover retards overland flow and increases surface detention/storage and thereby reduces the peak runoff rates. As a result, the differences in erosion rates caused by different land use practices on the same soil are much greater than the corresponding changes from different soils under the same land use (Morgan, 1995). Farmers' management practices are also quite important in affecting erosion on croplands and may reduce erosion by 50 % or more (Tidaman, 1996).

Considerable potential erosion hazard exists in the Ethiopian highlands (Hurni, 1993). The way in which this potential hazard is turned into actual erosion depends upon factors such as the nature and density of plant cover, erosivity of the eroding agent and erodibility of the soil (Morgan, 1995). The differences in vegetative cover have been mainly responsible for the variation in erosion rates in the Ethiopian highlands (Hurni, 1988). However, the patterns of such a land use change on soil erosion rates have not been supported by quantitative studies in the Ethiopian highlands. This investigation reports the incidence of the advanced stage of soil erosion (gully erosion) associated with land use change over the last three and half decades on a typical Ethiopian highland Vertisol-Nitosol toposequence using panchromatic aerial photographs and a geographical information system (GIS).

Materials and methods

The study area

The study was conducted in the Ginchi watershed in the central highlands of Ethiopia (2200 masl., 38^0 E, 9^0 N), 90 km southwest of Addis Ababa. The Ginchi experimental watershed is a sub watershed of Yubdo Legabatu watershed named after the small river, Batu, which drains towards west of the watershed. The experimental watershed covers 320 ha area and supports 150 households with average family size of five persons per household. The area was delineated in 1994 with the aim of testing improved Vertisol technology option at watershed scale. The altitude ranges from 2100 masl at the outlet to 2600 masl at the highest peak in the north. It has a subhumid climate with an average annual rainfall of 1200 mm, 30 % of which falls before the onset of the main cropping season. About 40–50 % of the annual rainfall is lost as runoff (Teklu Erkossa et al., 1999) between July and September. Vertisols, Nitosols and vertic Cambisols, are the three major soil types in the watershed (Figure 1). They cover 61, 16 and 23 percent of the watershed area respectively. The vertic Cambisols are found between Nitosols and Vertisols, which dominate the upper and lower part of the watershed respectively.

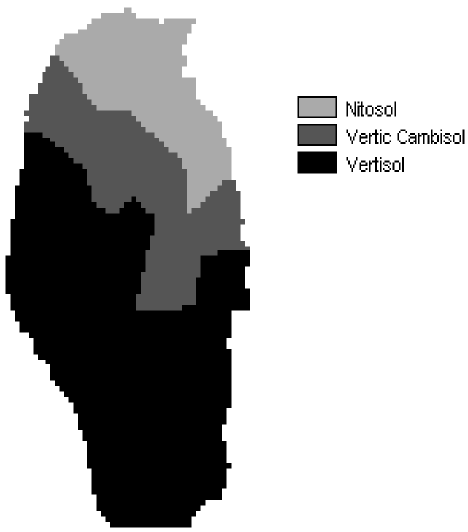

Figure 1. Map showing the major soil types in Ginchi watershed

The area follows monocropping system, predominantly rainfed, and is characterized by a three-year cropping sequence: a grain legume, commonly chickpea (*Cicer arietinum*), in rotation with tef (*Eragrostis tef*) and durum wheat (*Triticum turgidum*) (Gezahegn Ayele and Tekalign Mamo, 1995). In Ginchi watershed, farmers usually apply 30 to 40 kg N and 5 to 10 kg P ha^{-1} to cereal crops (tef, wheat and barley). Fertilizer use on other crops is very rare.

Cattle, the most important livestock, provide income, draught power and manure. Livestock are reared either on communal pasture, private grazing lands or kept in sheds, depending on the season. The grazing lands owned by individuals are quite small in size (0.5 ha) and communal grazing lands are not available to all farmers, and when available, are usually overgrazed. As the low lying Vertisols become waterlogged during the rainy season, all sort of grazing takes place on hill slopes where the land is relatively better drained. Within this system, animal manure is dried for use as cooking fuel, thereby precluding its use as organic fertilizer (manure).

Land use change analysis

A simple classification scheme comprising four land use/cover types was developed for the purpose of this study and a mapping legend was prepared for each of land use type on panchromatic aerial photographs taken in 1957 and 1994 (scale 1:50.000). The aerial photographs covering the watershed site were obtained from Ethiopian Mapping Authority and scanned in Tag File format by a high-resolution scanner at 1200 dots per inch. The TIF files, which gave a resolution of less than 1 meter on the ground, were then imported into MapInfo (MapInfo Corporation, 1995). Retrospective ground trusting was aided by the aerial photographs taken during the same period each year, during informal discussions held with the local people of the area. After interpreting land use cover features gullies and drainage lines were then screen digitized to produce the land cover maps. Each tracing was then registered on the real coordinate system by using Universal Transverse Mercator Projection (UTM) and topographic map of 1: 20, 000 scale prepared. Contour lines from such a topographic map were digitized and a Digital Terrain Model (DTM) of the watershed was then derived at 1-meter grid resolution. The altitude, slope, aspect and digital maps were further produced with the help of IDRISI (IDRISI, 1999). The change in land use types and gully lines between 1957 and 1994 were analyzed using the various models of IDRISI GIS (IDRISI, 1999).

Soil erodibility

Surface and subsurface (at an interval of 30 cm down to a depth of 1.8 m) soil samples were taken from each 1 ha in hilly areas and every 6 ha in nearly flatter areas. The samples were analyzed for particle size distribution by the hydrometer method as described by Day (1965) and soil organic matter content was determined by chromic acid digestion method (Walkey and Black, 1947). Infiltration was measured in 2001 cropping a season using double ring infiltrometers (Bertrand, 1965). Soil erodibility (K) values were determined from the nomograph of Wischmeier et al. (1971).

Results

Physiography of the watershed

About 75 % the Vertisols, which account for 61 % of the experimental watershed have been found in 0-5 % slope range (Figure 2a), and the remaining 25 % occur within the slope range of 5-15 % of which 14 % is within slope range 5-8 %. The other major soil type, vertic Cambisols, most frequently occur in 0-2 % slope range (62 %) followed by 8-15 % slope range (11 %) and 5-8 % range slope (11%), only about 8 % have slope greater than 15%. Unlike the other two soils, substantial amount of Nitosols (35 %) are associated with land units having slope gradient greater than 15 %. Figures 2a and 2b indicate that in spite of differences in slope gradient, the most frequently occurring slope length in the watershed is between 20 to 40 m. Similarly, in Vertisols and Nitosols, the most frequently occurring slope length are 20-40 m, which accounted for 86 and 56 % area of these soil types respectively (Figure 2b). In contrast, the most frequently occurring (48%) slope length in vertic Cambisols has been found to be greater than 80 m.

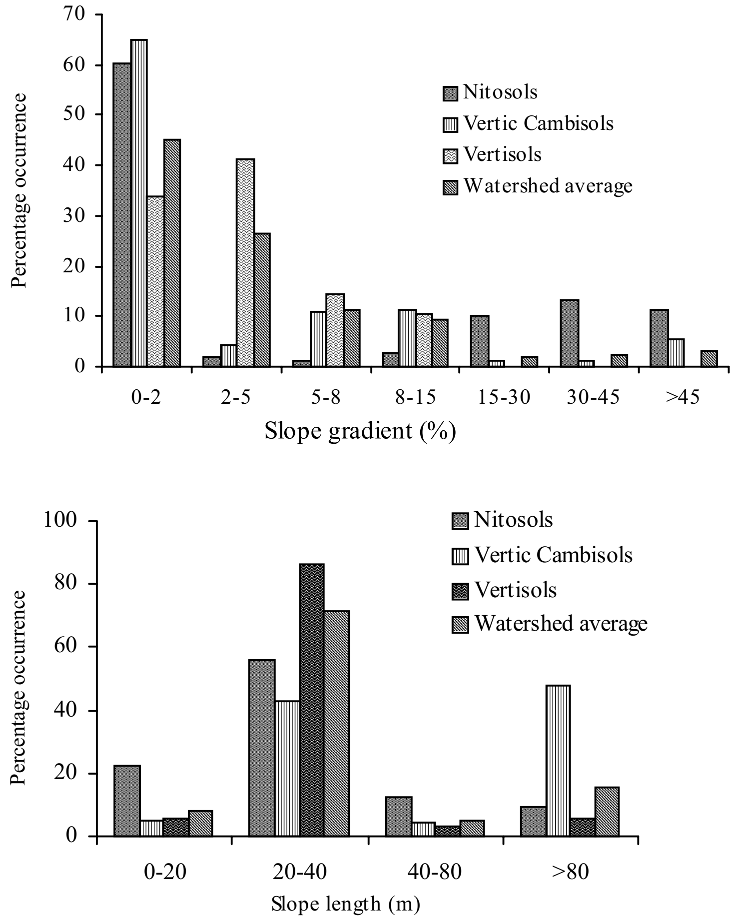

Figure 2. Frequency distribution of slope length (a) and slope gradients (b) in major soil types of Ginchi experimental watershed, Ethiopia.

Soil erodibility and infiltration

Soil erodibility (K) values calculated for 150 sites in the experimental watershed ranged from 0.24 to 0.68. About 48 % of the watershed had erodibility values greater than 0.4 (Figure. 3) and of these, only 6 % had values $\geq$ 0.6. The northwestern and central parts of the watershed, which largely overlap with the area under Nitosols and vertic Cambisols, were more erodible ($K \geq 0.4$). As a result, at some scattered spots Nitosols have 30-40 % stones by weight from the surface to a depth of 40-60 cm.

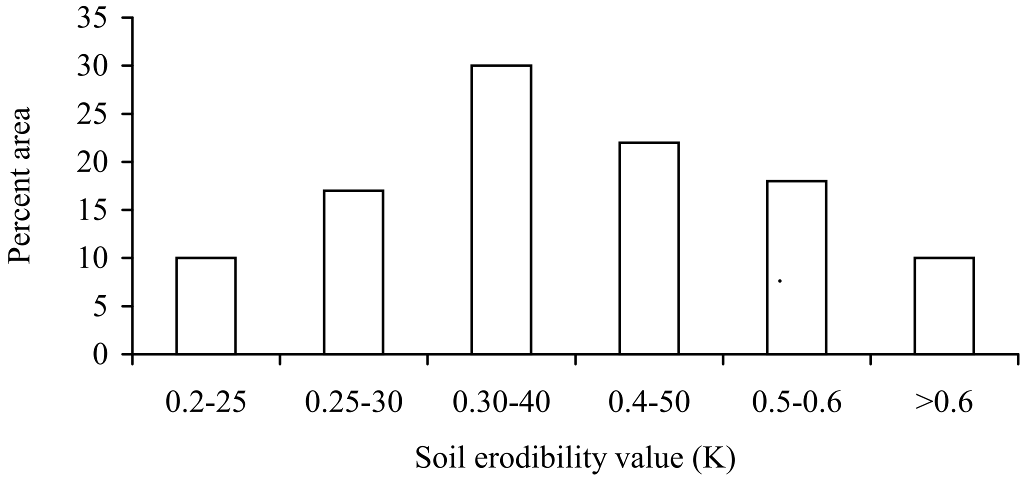

Figure 3. Distribution of erodability values at Ginchi experimental watershed, Ethiopia

During early part of the rainy season, Vertisols had relatively high infiltration rate (> 60 mm/hr) followed by vertic Cambisols and Nitosols (Figure 4). Consequently, high runoff rates during this period would be expected from Nitosols and vertic Cambisols as compared to low lying Vertisols. However, with the advance of the season infiltration rates declined (< 10 mm h^{-1}) subsequently due to swelling and surface crusting respectively

Land use dynamics

Figure 6 shows the land use maps of the watershed for the years 1957 and 1994, and statistical summaries of different land uses are given in Table 1. In 1994, 63 % of the land within the watershed was under crop cultivation while 28 % was under natural pasture. The remaining land of about 9 % was almost equally shared between woodland and riverine trees. On the other hand, in 1957, 60 % of the watershed was covered by natural pasture and only 29 % was under crop cultivation. Thus, over the years, cropping has expanded by 119 % into grassland, which declined by about 53 %. In contrast woodland and riverine trees' area declined by 18-20% during the same period.

A close examination of the land use change further revealed that the 81 % land under arable cropping in 1957 was still under arable cropping in 1994 whereas the remaining 19 % was converted back to grassland (17 %) and to riverine trees (2 %). Similarly, 33 % of the grassland in 1957 continued to be under grass in 1994 while 63 % and 4 % were converted to cropland and riverine trees respectively. Of the total land under the riverine trees in 1957, 66 and 20 % were converted to grassland and cropland over the years respectively. Unlike the other three-land use types, only 20 % the woodland was converted to other land use types in 1994.

Further, the land use dynamics also varied with soil types of the watershed (Table 1). On Nitosols, the cropland was expanded at the expense of the grassland and woodland more than any other soil type. Nevertheless, woodland and grassland, which accounted for 49 % and 25 % of the land under Nitosols respectively, were the dominant land use types on these soils. On the sloping intermediate part of the toposequence, grassland was the dominant land use, which covered 70 % of vertic Cambisols in the base year as opposed to 45 % in 1994. Unlike on Nitosols, cropland, which expanded at the expense of grassland over the years, became equally important land use with grasslands on vertic Cambisols. On Vertisols, the original grass and riverine tree cover was shrunk by 72 % and 39 % respectively while the area under cropland increased by 106 %. In 1994, the grasslands, which accounted for about 16 % of the land under Vertisols, were totally engulfed into wide gully floors, where annual crops couldn't be grown.

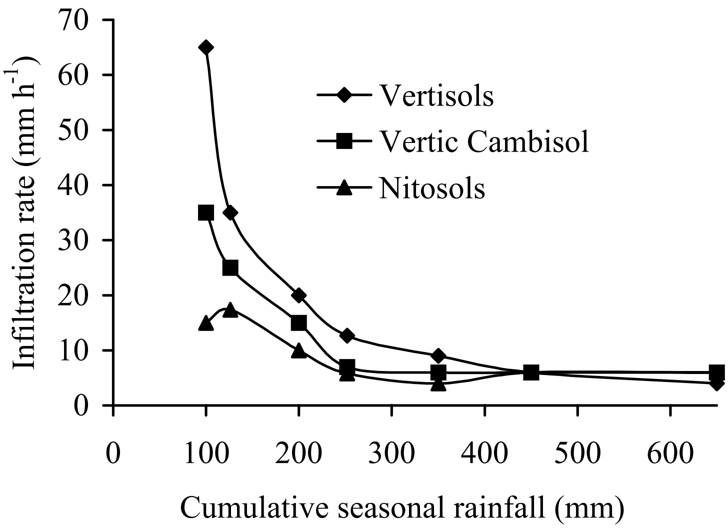

Figure 4. Change in infiltration rate measurements versus cumulative seasonal rainfall in 2001 cropping season in Ginchi watershed.

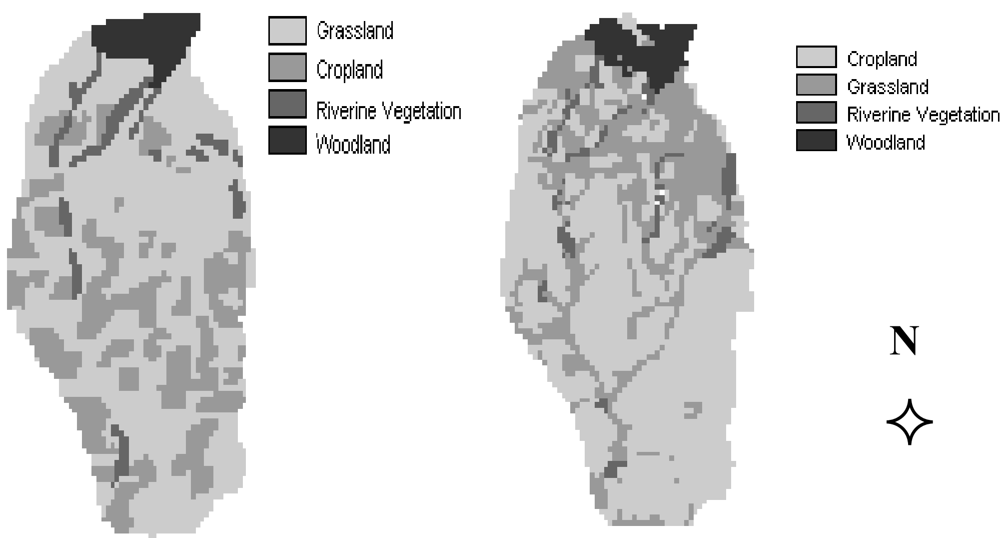

Figure 6. Land use types in Ginchi watershed in 1957 (left) and 1994 (right)

Incidence of gully erosion

In Ginchi watershed, gully formation was a striking phenomenon, and the total length of the gullies in 1994 was about 12.0 km (8 km km^{-2}) as compared to 5 km (1.7 km km^{-2}) in 1957 (Tables 2 and 3; Figure 6). Likewise, the surface area of the gullies increased from 16.6 ha in 1957 to 36.2 ha over thirty seven years period in 1994 (Figure 7). Assuming that the gully erosion proceeded at a constant rate, the head ward gully erosion rate was 26.8 m y^{-1}, 95 m y^{-1} and 122 m y^{-1} on Nitosols, vertic Cambisols and Vertisols respectively (Table 3).

However, when the rate was expressed per unit area of the respective soil types in the watershed, gully erosion was most severe on vertic Cambisols than on any other soil types (Table 3). Here the gully length per ha^{-1} (47.1 m ha^{-1}) was about two to three times higher than the gully length encountered on Vertisols (23 m ha^{-1}) and Nitosols (17 m ha^{-1}) respectively.

The total gullied area in 1994 was 6.6 %, 18 % and 10 % of the area observed under Nitosols, vertic Cambisols and Vertisols respectively, in contrast to 1.4 %, 7.9 % and 5.2 % in base year. In the base year (Table 3), the highest incidence of gully erosion (61.9 %) was associated with croplands followed by riverine trees (22.3 %) and grasslands (15.8 %). In contrast in 1994, 65.9 % gullied area was under the grasslands followed by cropland (18.4 %) and riverine trees (15.7 %).

Table 3. Incidence of gully erosion associated with land use types in Ginchi watershed between 1957 and 1994 (Ethiopia)

Land use	Gully in 1957		Gully in 1994	
	Length (km)	Area (ha)	Length (km)	Area (ha)
Crop land	3.4	10.3	2.2	6.7
Grassland	0.9	2.6	7.9	23.8
Riverine Tree	1.2	3.7	2.0	5.6
Woodlands	-	-	-	-
Total	5.50	16.6	12.0	36.2

Discussion

In 1957, there was relatively little incidence of gully erosion probably due to protection given by the native grasses, which occupied more than 60 % the watershed. However, when the native grasses were disturbed and the land was used to produce crops, erosion became a serious problem as judge from gullies developed over the years. The conversion of grassland into cropland was obviously promoted by the need to produce more food and fiber required to support the ever-increasing population of the tropical highlands (Hurni, 1993; Mohamed Saleem, 1995).

The gully erosion incidence was severe on vertic Cambisols as compared to Nitosols and Vertisols probably because in this part of the watershed the potential erosion hazard has the greatest chance of being converted into real erosion. Although steeper slopes are usually shorter, they are generally longer on vertic Cambisols which occupied medium phase on the local landscape (Figure 2). Zingg (1940) reported that the average soil loss per unit area increases in proportion to 0.6 power of the slope length. According to Morgan (1995) long, steep slopes are potentially hazardous from an erosion point of view. Compared to Vertisols, land units with steep slopes were more frequent on Nitosols and vertic Cambisols (Figure 2). When these land units were put under crop production by removing vegetation for a major part of the year, they had marked effect on increasing the erosive action of the rainfall and surface runoff.

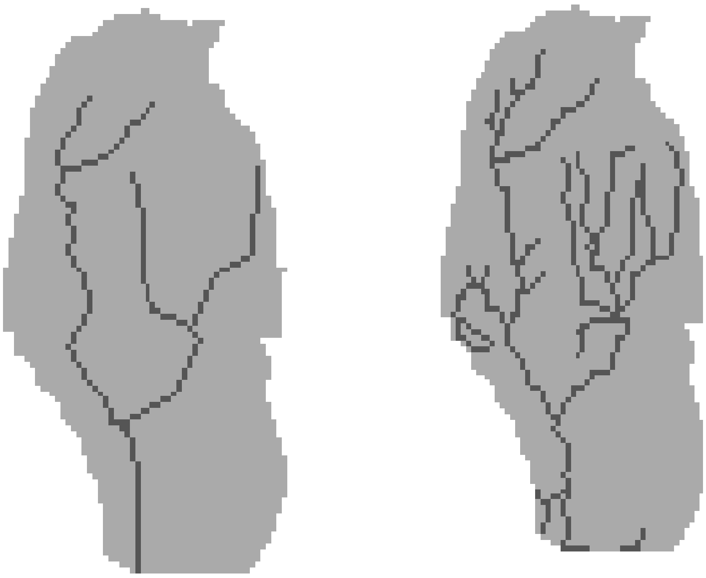

Figure 7. The incidence of gully erosion in Ginchi watershed in 1957 (left) and 1994 (right)

The rate of gully erosion depends primarily on runoff producing characteristics of a watershed. In spite of low terminal infiltration rate (< 10 mm h^{-1}), the water intake capacity of Vertisols was quite high (> 60 mm h^{-1}) during early part of the season. The initial high infiltration rates of Vertisols during early parts of the season may be ascribed to surface cracks that extend deep into the subsoil as well as to high depression storage capacity due to surface roughness. Further formation of microcracks in Vertisols between two rainfall events may also provide high infiltration rate and surface storage for the next storms. Their contribution in reducing runoff and associated risk of soil erosion would be quite significant in such swell-shrink soils.

In contrast, initially high infiltration rates of Nitosols and vertic Cambisols might have been greatly reduced during early rainstorms by surface sealing/crusting caused by raindrop impact and translocating fine particles into the subsoil. Runoff during the early part of the rainy season from cropped Nitosols and vertic Cambisols, would thus be much greater than on the cropped Vertisols. This highlights that early vegetative cover establishment appears more important for vertic Cambisols and Nitosols, which may not be so crucial for Vertisols.

Table 1. Changes in land use (ha) on three major soil types and total land use in Ginchi watershed between 1957 and 1994

Land Use	Major soil types						Total area (ha)		Change (%)
	Nitosols		Vertic Cambisols		Vertisols				
	1957	1994	1957	1994	1957	1994	1957	1994	
Cropland	0.5	9.9	14.5	32.2	77.5	159.8	92.5	201.9	+118
Grassland	30.9	25.4	51.3	33.8	111.6	31.6	193.8	90.9	-53
Riverine tree	5.1	4.1	7.3	7.0	6.0	3.7	18.4	14.8	-20
Woodland	15.8	12.9	-	-	-	-	15.8	12.9	-18
Total (ha)	52.3	52.3	73.1	73.1	195.1	195.1	320.5	320.5	

Table 2. Incidence of gullies for three major soils at Ginchi experimental watershed 1957 and 1994 (Ethiopia)

Soil types	Gullies in 1957		Gullies stabilized since 1957		New gullies since 1957		Gullies in 1994	
	Length (km)	Area (ha)	Length (km)	Area (ha)	Length (km)	Area (ha)	Length (km)	Area (ha)
Nitosols	0.2	0.7	0.1	0.3	1.0	3.0	1.1	3.4
Vertic Cambisols	1.9	5.7	1.0	2.9	3.4	10.2	4.3	13.0
Vertisols	3.4	10.2	1.3	4.0	4.5	13.6	6.6	19.8
Total	5.5	16.6	2.4	7.2	8.9	26.8	12.0	36.2

The problem of soil erosion associated with grassland, however, needs to be viewed in the context of the whole watershed. Farmers in the watershed seasonally change strategies for grazing their livestock. During the main rainy season (June to September) farmers tend to keep their livestock further away from the waterlogged bottomlands and graze the upper part of the watershed. With increasing grazing intensity, the vegetation cover gets reduced below critical levels; consequently, the impact of raindrops increases, soil organic matter and soil aggregates decrease, surface crust formation and soil bulk density increase and water infiltration deceases (Johnston, 1962; Bari et al., 1995 and Mwendera and Mohamed saleem, 1996). The end result is increased runoff and soil erosion, which trigger events ultimately leading to large-scale land degradation (Gifford and Hawkins, 1978). Moreover, the runoff from the upper slopes can also cause wide spread soil erosion down the slopes.

The runoff magnitude was quite high on vertic Cambisols where concave slopes favor flow convergence towards the base of the slopes, leading to wide spread gully erosion compared to any other soil type in the watershed. This therefore calls for alternative grazing management during the rainy season and release of pressure on the upper slopes where the risk of environmental degradation and detrimental impact down the slopes appears to be highest. Although gullies can remove vast quantities of soil, according to Zachar (1982) (as quoted by Morgan, 1995) gully densities are not usually greater than 10 km km^{-2} and the surface area covered by the gullies is rarely more than 15 % of the total watershed. In the present study both gully densities and percent gullied area were lower than reported by Zachar (1982).

As gullies work upstream, the most active portion lies near the upper end (the gully head) whereas the most stable section of the gully generally rest in the lower part of the watershed. Thus one would normally expect the highest rate of gully headward advancement on Nitosols and vertic Cambisols rather than on Vertisols. However, gullies once initiated can develop very rapidly on Vertisols due to the slumping nature of wet Vertisols. In addition, gully incision destabilize a wide belt along the gully channel as the runoff water at a distance of tens of meters from the gully finds its way through side cracks deep in the profile causing piping and tunneling which further promote new gully development.

Gullies on Vertisols, which occurred in the lower reaches of the gully system were generally unsuitable for agriculture even where they had wide beds and were easily accessible for reclamation. During the main rainy season they were too wet for grazing either. As a result, a gradual succession of plant species eventually protects the gullied area with grasses, vines, shrubs or acacia trees, which are native to the area. Once stabilized these wide gully floors then are usually put under natural pasture for hay production to supplement dry season feed shortage. Usually, the hay is harvested a month or two after the end of the main rainy season. Livestock trampling and extreme grazing down to the root during critical period of the season is thus excluded in this system. Thus, unlike the grasslands on Nitosols and vertic Cambisols, which are grazed throughout the year this system allows an excellent recovery of vegetation and maximum soil protection. Vertisols may be used as natural pasture because they allow better recovery of vegetation as well as a maximum soil protection. In this way, active gully associated with cropland may be gradually stabilized and converted into grassland and riverine trees land use on the long time basis.

Conclusion

Over the last three and half decades the area of cultivated land has increased significantly, at the expense of grassland in Ginchi experimental watershed. Though less dramatic, woodland and riverine trees have also declined by about 18-20 %. The driving force behind the land use change was obviously the need to produce more food and fiber to support the ever-increasing population. When the native grasses were disturbed out and the land was used to produce crops, erosion became a serious problem as judge from gullies, which developed over the years particularly, in the upper part of the watershed. The erosion problem was more critical on grasslands than on croplands. This, therefore, calls for alternative grazing management during the wet season in order to release the pressure on upper slopes where the risks of environmental degradation and detrimental impact down the slope remain highest.

Obviously, if the grasslands are to retain a cover to protect the soil and continue to produce abundant vegetation, they must be cared for and managed properly. Cut and carry system may allow an excellent recovery of vegetation and an ideal way of soil protection. This will lead to realization of the potential productivity of Vertisols on moderate slopes and would also contribute towards stabilization of the Ethiopian highland ecosystems.

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Chapter 3

Water Harvesting Prediction for Small Farm Ponds in Ethiopian Highland Vertisol

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Ethiopian Journal of Natural Resources (in press)

Abstract

In the Ethiopian highland Vertisols efficient management of rainwater for increasing water availability to the crops during the growing seasons, and collection of the excess rainwater by water harvesting with the view to develop water resources in the region on a long-term basis, is essential. Studies have revealed that runoff occurs in July, August and September. Under the traditional tef (*Eragrostis tef (Zucc*) Trotter) based cropping system of the highland Vertisols, it is observed that about 30 % of the seasonal rainfall of 700 mm can be harvested into dugout ponds for using as supplemental irrigation. Runoff prediction with curve number method was precise for most runoff prediction purposes provided that the input parameters were calibrated for local conditions. Calibrated curve number method predicted the total runoff volume with relative error of less than 5 % in the three most runoff sensitive months of the year while un calibrated curve number underestimated runoff by 30 %.

Introduction

Water is a basic requirement for agricultural production as well as for the survival of human and animal life. In the Ethiopian highlands (1500 masl.), the predominant source of water is rainfall, which, on the average, is about 983 mm per annum (NMSA, 1996). However, due to temporal and spatial variation in the occurrence of the rainfall, about one–fourth of the country is subject to drought of various intensities every year (NMSA, 1996). It is estimated that even after developing all the available water resources for irrigation, about 85 percent of the cultivated area will remain as rainfed (MWR, 1998). Nevertheless, it is reported that 112,450-million m^3 runoff water is lost from twelve Ethiopian highland watersheds alone into rivers and sea annually (MWR, 1998).

Vertisols cover 8 million ha in the Ethiopian highlands and of these two million hectares are under annual crop production which in turn accounts for about one-third of the total national cropland under arable crop cultivation (Jutiz and Mesfin Abebe, 1986). Vertisols have high water holding capacity and low intrinsic hydraulic conductivity due to the smectitic mineralogy. Thus, seasonal waterlogging poses a serious limitation on the traditional use of these soils to the extent that crops grow and mature on residual moisture. As a result, crop production levels are low, apart from being unstable due to inefficient management of the rainwater received, coupled with adverse physical properties of the soils (Berhanu Debele, 1985). It is therefore essential to develop appropriate strategies for efficient rainwater management on a long-term basis to ensure uniform availability of moisture for crop growth and water for human and animal life by collecting the inevitable runoff water into farm ponds at field and watershed levels. The small-scale nature of farm ponds would make it amendable to management on a private household level. In addition, a network of small ponds could reduce the sediment loads and improve the timing of water delivery to large–scale reservoirs found in this region.

Runoff records of sufficiently long time series are needed for quantitative runoff assessment. For most agricultural watersheds however, installation of runoff monitoring systems are not economical and in those that have been installed concurrently measured runoff and rainfall data are scanty to make prognosis for the future based on statistical methods. Alternatively process based hydrologic models are precise for most runoff prediction purposes but extensive input data requirement often limit their application. Given the small size and relatively homogeneous soil of the small agricultural watersheds, the curve number method (SCS, 1972) can be used to estimate direct runoff, as a function of daily rainfall, and a potential maximum retention, S, which is a function of the chosen curve number (CN).

The curve number method is widely used as a simple watershed model and as a runoff-estimating component in more complex watershed models (Williams et al., 1985; Young et al., 1989). However as any empirical model its application in new area needs input parameter calibration. In this method the basic assumption is that, for a single storm, the ratio of actual retention after runoff begins (Ia) to potential maximum retention (S) is equal to the ratio of direct runoff to available rainfall. Ia term represent water losses such as plant interception, infiltration, and surface storage which occur prior to runoff and are thus subtracted from the total rainfall available for either soil retention or runoff (SCS, 1972). The standard assumption is that Ia = 0.2S (SCS, 1972). The "0.2S" was based on watershed measurements with a large degree of variability and other researchers have reported using values ranging from 0.0 to 0.3 (SCS, 1985); Ponce and Hawkins, 1996). In Vertisol watersheds in addition to several sources of error associated with theses estimates in normal soils (SCS, 1985) Ia value is likely to change within the growing season because of the swelling and shrinking nature of these soils which in turn influences the rate of infiltration at the soil surface as well as the rate of profile water transmission. In the original method the CN values used to estimate potential maximum soil retention values were developed from annual rainfall-runoff data from the literature of a variety of watersheds generally less than 2.16 km^{-2} in area (SCS-1985). CN value is adjusted to estimate less runoff under dry conditions and more runoff under wet conditions based on antecedent moisture condition (AMC) that is the amount of rainfall over the previous five days (SCS, 1972). The appropriateness of this adjustment is likely to depend on location and size of the watershed (Ponce and Hawkins, 1996). Because of these variability Schulze (1982) found a 30-day antecedent period to yield better simulation of direct runoff in the humid areas of the U.S.A., but a 5- day to be applicable in the arid zones. Hope and Schulze (1982) used a 15-day antecedent period in an application of the SCS procedure in the humid east of South Africa.

Keeping the above in view, in this study, CN, AMC and S were investigated based on measured rainfall and runoff data. The capability of the curve number method to assess the quantity of runoff that could be harvested and stored for subsequent use in traditional tef based cropping system in the Ethiopian highland Vertisols was evaluated.

Materials and methods

Study area

The study was conducted from 1994 to 2000 at Ginchi experimental watershed in the central highlands of Ethiopia (2200 m a.s.l., 38^0 E, 9^0 N), 90 km southwest of Addis Ababa. The watershed has a subhumid climate with an average annual rainfall of 1200 mm, 30 % of which falls before the onset of the main cropping season. For this study, at the bottom part of Ginchi watershed a 45 ha (WS-3) land area with average slope of 0.4 to 3.5 % was selected. Within in WS-3 again two sub watersheds with area of 7 ha (WS-1) and 7.8 ha (WS-2) were selected Figure 1. These watersheds were installed with H flumes, F type Stevenson stage recorders and sediment samplers for measuring runoff and soil loss.

The soils of the area represent the deep black soils (pellic Vertisols) of the central highlands of Ethiopia. Under dry conditions cracks as deep as 80-125 cm and as wide 4-8 cm at the surface were developed in a polygonal pattern. Some of the physical and chemical properties of the soils are given in Table 1. The clay content varied from 44 to 64 percent. Clay minerals are mainly of the smectite type. The soils were well supplied with cations, poor in humus and nitrogen and extremely deficient in phosphorus. The available water capacity (AWC) calculated as soil moisture difference that retained at field capacity and permanent wilting point was varied from 1.79 mm cm^{-1} at surface to 1.20 mm cm^{-1} at bottom horizons.

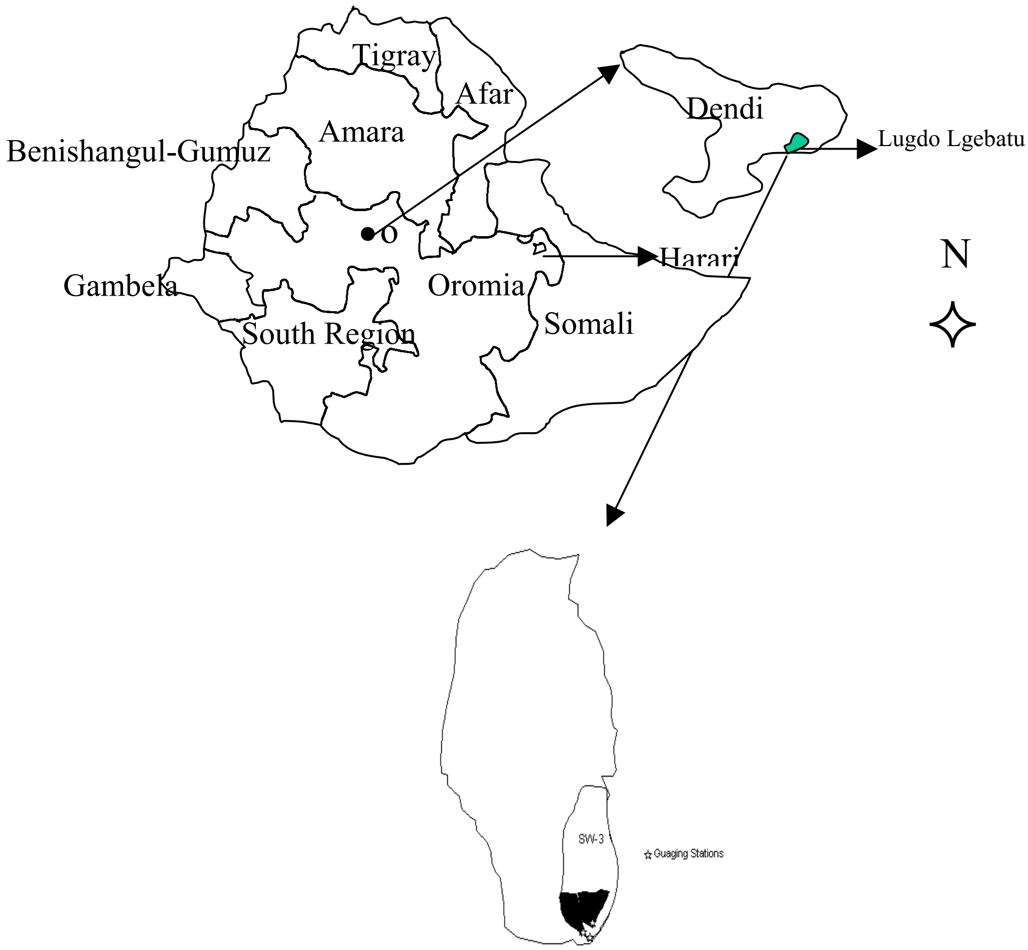


Figure 1. Map showing the administrative regions of Ethiopia and the study watersheds.

Cropping system

Ginchi Vertisol represents a typical tef (*Eragrostis tef (Zucc*) Trotter) based cropping system of the highlands with grain legumes, commonly chickpea (*Cicer arietinum*) followed by two years of tef production (Gezahegn Ayele and Tekalign Mamo, 1995). Tef is an indigenous cereal crop in Ethiopia, ranking first in terms of national cereal grain production (Tareke Berehe, 1981). It accounts for about two-third of the daily protein intake in the diet of the population (Ethiopian Nutrition Survey, 1959).

Table 1. Physical and chemical properties of the pellic Vertisols in the study watershed, Ginchi, Ethiopia

Depth (cm)	Texture (%)			PH (H_2O)	P (Olsen)	OM	TN	CEC	AWC (mm cm^{-1})
	Clay	Silt	Sand			-----%-----			
0-15	52	23	25	6.5	7.0	3.0	0.12	55	1.76
15-30	62	22	16	6.5	6.3	2.8	0.10	67	1.96
30-100	64	20	17	7.2	6.0	1.8	0.09	68	2.31
100-200	44	21	35	7.9	5.0	1.6	0.06	50	1.20

* TN and AWC stands for total nitrogen and available water capacity respectively
** the value of CEC is given in Meq/ 100 g soil

Tef is sown on more than 2 million ha annually, and is produced extensively by peasant farmers within a labour-intensive system based on oxen traction (National Research Council, 1996). Tef culture requires a long period of frequent plowing during peak rains to prepare a fine seedbed on which tef seeds are broadcast as late as mid August. Thus unprotected fields remain vulnerable to rill and interrill erosion during the major part of the rainy season. Waterlogging sensitive grain legumes are sown towards the end of the rainy season (September) and hence grow and mature entirely on residual soil moisture. Seedbed preparation for grain legumes is not as intensive as that of tef and usually two passes using a local plough, *maresha*, is considered optimal. In the first plowing the soil is manipulated just when it is plastic with the intention of maintaining a rough surface that can trap the excess water that otherwise is lost as surface runoff during major part of the rainy season. During the experimental period, on the average 80-85 % of the total area of each watershed was under tef while grain legumes account about 10-15 %. Other cereals (wheat, barely and sorghum) and grassland occupied less than 2 and 1 percent respectively.

SCS-CN parameter estimation

The basic assumption of the SCS curve number method is that, for a single storm, the ratio of actual retention after runoff begins to potential maximum retention is equal to the ratio of direct runoff to available rainfall. This relationship, after algebraic manipulations written as (SCS, 1972):

$$Q = \frac{(P - Ia)^2}{(P - Ia) + S} \qquad (1)$$

where Q = total direct runoff volume, P = precipitation; S= potential maximum watershed retention; Ia = initial abstraction. All variables are in millimeter units. This equation is further developed (SCS, 1972) by assuming that the initial watershed abstraction of precipitation is a linear function of S as:

$$Ia = kS \qquad (2)$$

Combining equation (1) and (2) and taking k= 0.2 (SCS, 1972) results into:

$$Q = \frac{(P - 0.2S)^2}{(P + 0.8S)}, P > 0.2S \tag{3a}$$

$$Q = 0, P \leq 0.2S \tag{3b}$$

The variable S, is converted to CN through the relation

$$CN = \frac{25400}{254 + S} \tag{4}$$

S can be solved from equation 3 (Hawkins, 1993)

$$S = 5\left[P + 2Q - (4Q + 5PQ)^{1/2}\right] \tag{5}$$

CN is a dimensionless parameter related to land use, land treatment, hydrological soil group, and antecedent soil moisture condition in the drainage basin. In the curve number method, AMC is classified into three classes based on a 5-day antecedent rainfall (Table 2).

Table 2. Five-day antecedent rainfall divisions as presented in SCS (1985).

Antecedent Moisture condition	5 day cumulative rainfall (mm)
I (dry)	<36
II (normal)	36-53
III (wet)	>53

The two input parameters k and CN were calibrated using three years (1995-1997) concurrently measured runoff-rainfall data from WS-2. CN value was estimated using derived distribution method (James and Bonta, 1997). In this method the inverse function of Eq. 3 was used to calculate P from measured runoff data as:

$$P = B + \left\{Q\left[Q + \frac{1016}{CN}(100 - CN)\right]\right\}^{1/2} \tag{6a}$$

$$B = \frac{Q}{2} + \frac{50.8}{CN}(100 - CN) \tag{6b}$$

and then the CN value in Eq. 6 was adjusted until the cumulative frequency distribution of predicted rainfall was reasonably close to cumulative frequency distribution of measured rainfall. The CN value (selected by trial and error), at which the maximum error between the P and inverse distribution is a minimum, is a basis for CN estimation using derived distribution. All runoff producing rainfall such that $P/S \geq 0.465$ when S is estimated from Eq. 5 were included in the analysis as suggested by Hawkins et al., (1985).

A CN value estimated from the inverse function was then substituted in Eq. 3 to calibrate the k parameter and antecedent soil moisture condition (AMC). Calibrations were done until the predicted runoff values were reasonably close to the observed values. The statistical measures used to compare observed and predicted data included regression analysis, comparisons between the means of observed and predicted daily runoff values and Nash and Sutcliffe's model efficiency analysis before and after calibration (Nash and Sutcliffe, 1970). The model efficiency is expressed as:

$$ME = 1 - \left[\frac{\sum \left(Y_{obs} - Y_{pred} \right)^2}{\sum \left(Y_{obs} - Y_{mean} \right)^2} \right] \qquad (7)$$

where Y_{obs} (mm) is measured runoff, Y_{pred} (mm) is predicted runoff, Y_{mean} is mean measured runoff per event and ME is model efficiency. The model efficiency can range from -∞ to 1, and the closer the value is to one, the better are the individual daily predictions.

The model was validated using 5 years (1995 to 1999) concurrently measured runoff rainfall data from watershed SW-1 and SW-3. Daily rainfall in three most sensitive months: July, August and September were used in the analysis provided that the total rainfall in a given day is greater than the value of initial abstraction. Three types of analysis were made on the results of the study, and they were based on (1) total runoff (2) event by event comparison; and (3) cumulative frequency distribution for daily runoff prediction. Expected total runoff volumes are important in assessing the potential of harvestable water and in designing proper water harvesting systems. Event- by- event comparison is important in designing soil and water conservation structures.

Frequency analysis

Daily rainfall and daily runoff data were subjected to analysis to arrive at the extreme value using the double exponential Gumbel distribution method (Gumbel, 1958) and to determine the maximum expected rainfall and runoff amounts for different return period using equation:

$$X_T = \overline{X} - 0.45_S + 0.78_S \left[-\log_e \log \frac{T}{T-1} \right] \qquad (8)$$

where $\overline{X}$ is the mean of the series for extreme values,
S is the standard deviation of the series,
T is any return period and
X_T is the rainfall and runoff amount for any return period

Since measured runoff and rainfall data at WS-3 were only available for 5 years curve number predicted data were also included in the analysis. Daily runoff values were predicted with calibrated curve number method using nineteen years rainfall data (1982-2000) taken from Ginchi research farm 6 km west of the experimental watershed.

Results

Monthly rainfall and runoff data observed from July 1995 to September 1999 for the three watersheds are given in Table 3. The variability of rainfall between years is not large though the first two years had lower rainfall than the last three years. However the amount of runoff produced in first two years was comparable or higher than the amount runoff produced in the last three years particularly in WS-1 and WS-2. The total seasonal rainfall is a crude indicator of runoff production since only runoff–producing rainfall is relevant and the occurrence of dry spells between such events is of vital importance in runoff generation. The rainfall peaks in August and levels off towards September. Among the major runoff–producing months August has the highest probability, followed by July and September. The runoff coefficients in these three runoff producing months were 23, 51 and 38 %, respectively, which is equivalent to 102 to 258 mm runoff water per annum. Though the month of June had some occasional runoff producing rainstorms in 1995 and 1998 the larger proportion of the seasonal runoff was generated between mid July and end of August due to high moisture deficit of surface horizons at the beginning of the rainy season. During this period the threshold rainfall at which runoff starts ranged between 3 to 4 mm per day. Daily average runoff ranged from 3.45 mm after mid July to 8.2 mm in August.

Table 3. Measured rainfall and runoff (mm) at Ginchi experimental watershed, Ethiopia. (1995-1999).

	WS-1									
	1995		1996		1997		1998		1999	
	RF	RO	RF	FO	RF	FO	RF	RO	RF	RO
June	121	3.8	120	0.0	109	0.0	204	6	86.0	0.0
July	179	72	235	85	229	1.8	228	97	222	86.0
August	228	108	160	44	200	98	273	130	229	105
September	135	75	148	44	157	67	89	65	71.4	4.8
October	0.8	0.0	8	0.0	57	0.0	22	0.0	137	6
Total	**663**	**258**	**671**	**173**	**752**	**167**	**816**	**298**	**745**	**201**
	WS-2									
June	120	0.0	105	0.0	109	0.0	204	4	86	0.0
July	154	41	223	102	229	9	228	101	222	0.0
August	192	108	152	83	200	99	273	162	229	170
September	130	73	134	47	157	62	89	40	71.4	1.7
October	0.0	0.0	12	0.0	57	0.0	34	0.0	137	3.1
Total	**596**	**222**	**626**	**232**	**752**	**170**	**828**	**307**	**745**	**174**
	WS-3									
June	121	0.00	86	0.0	109	0.0	204	2	86	0.0
July	179	45.0	200	41	200	3.0	228	78	222	0.0
August	228	149	173	38	200	88	273	121	229	170
September	135	51.0	124	23	162	47	89	71	71.4	5
October	0.8	0.00	8	0.0	57	0.0	34	0.0	137	3
Total	**682**	**245**	**591**	**102**	**728**	**138**	**828**	**272**	**745**	**178**

* RF and RO stands for rainfall and runoff respectively

To investigate the effect of watershed size on runoff volume, daily runoff versus daily runoff producing rainfall is plotted in Figure 2. The runoff producing rainfall with multiple events were summed over twenty-four hours with the assumption that large runoff and storm events last less than 24 hours, and that there is only one large event per day for small watersheds. Linear relationships were found to provide the best fit between rainfall and runoff. The difference between the two regression lines reflects less time of concentration and less trap efficiency of watershed WS-1 compared to watershed WS-3. As a result, the water yield per unit area was increased by 5-8 % in WS-1 than what it was in WS-3.

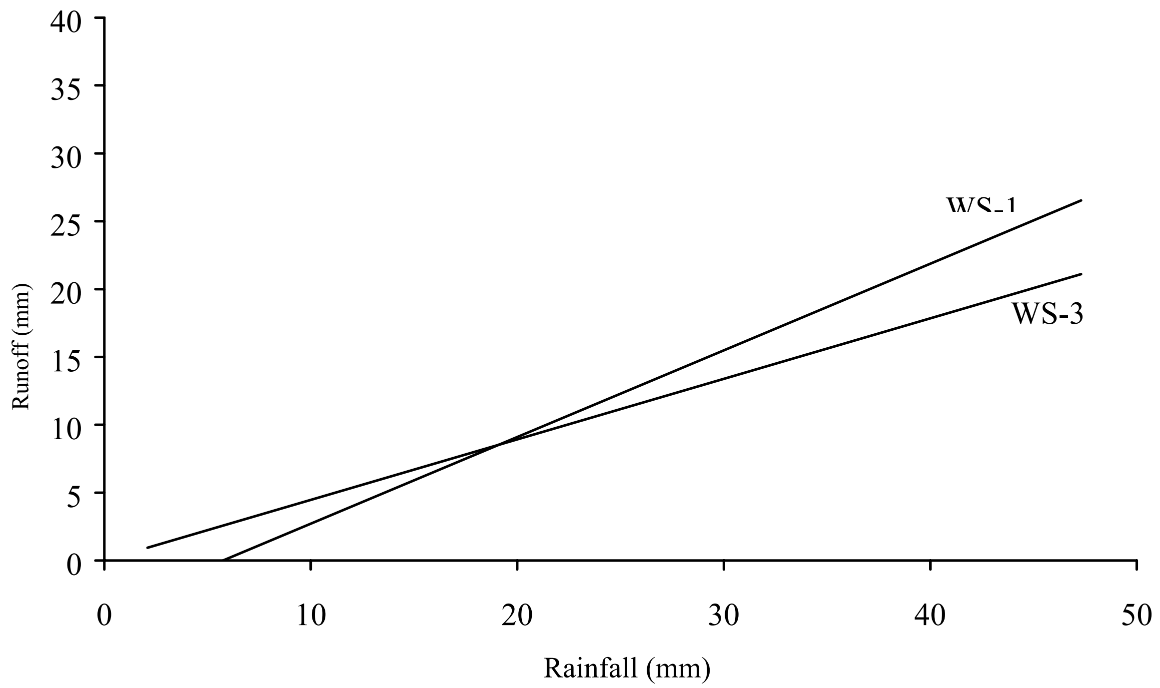


Figure 2. The influence of watershed size on runoff at Ginchi experimental watershed. (WS-1 =7 ha, WS-3 = 45 ha).

Model calibration

Frequency distribution of P versus derived distribution for watershed WS-2 is plotted in Figure 3. The maximum error between the P and inverse distribution was minimum at CN value of 95.2 and hence taken as the optimal CN value for tef based cropping system of highland Vertisols at AMC III. The good fit of P to derived frequency distribution demonstrates the capability of the curve number method to predict direct runoff from measured rainfall data. Further predicted rainfall (Rp) was validated by cross comparison with measured P. Linear regression was: Rp=0.9922 P + 0.09 (r^2 = 0.97; no= 57). The high r^2, slope near one and intercept value not significantly different from zero indicate that the inverse function provides a good correspondence with measured rainfall data that produced the runoff. Under this specific condition (P/S>0.465) the inverse function explained 97 % of the rainfall variability that produced runoff. This implies that the curve number method, from which the inverse function was derived could explain about 97 % runoff variability measured at the outlet of WS-2.

Tables 4 and 5 show predicted and observed runoff data, ME values and simple linear regression statistics (intercept, slope and coefficient of determination, r^2) before and after curve number calibration. Before calibration the curve number method on the average underpredicted the total runoff volume by about 30 % in contrast to a relative error of less than 5 % after calibration. The best linear fit between measured and predicted runoff was obtained when Ia was set at 0.1S for AMC I & II and 0.2S for AMC III respectively. The curve number runoff prediction was better when AMC was calculated at 10-day antecedent rainfall period than at 5-day or 15 day antecedent rainfall period. Calibration of the two input parameters improved the precision of the curve number runoff predictions as measured by model efficiency. The ME increased from 57 % to 88 % following the model parameters calibration.

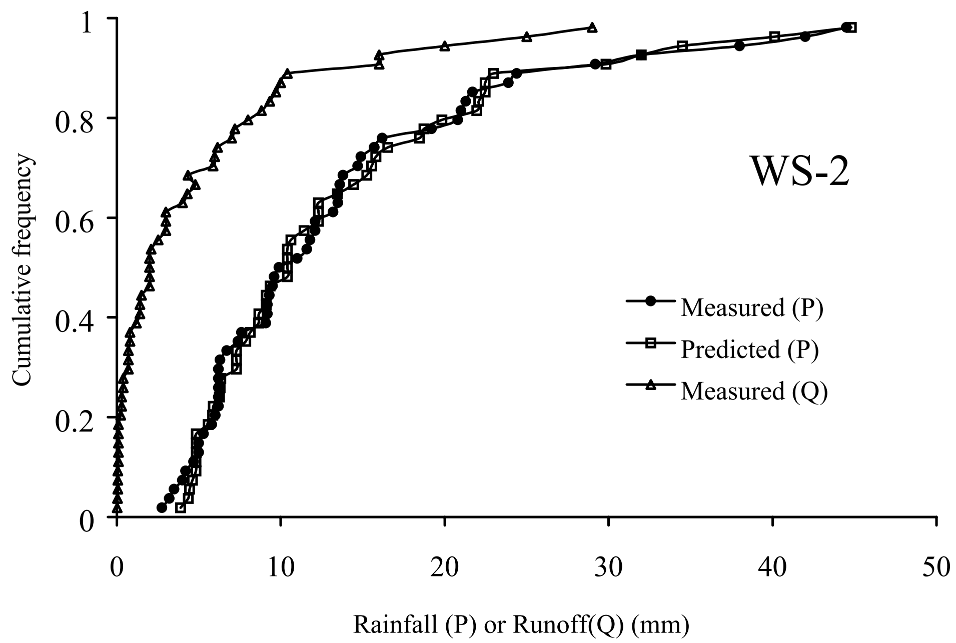


Figure 3. Cumulative frequency of measured runoff (Q) and measured rainfall (P) and predicted rainfall from derived distribution at optimal CN value of 95.2 for WS-2

Table 4. Results of regression analysis between measured and predicted runoff before model calibration (CN= 88 at AMC II; k=0.1S at AMC I and II and k= 0.2S at AMC III).

Month	Total runoff volume (mm)		No. of	Slope	r^2	Intercept	ME
	Observed	Simulated	Events				
July	173	130	32	0.66	0.62	1.3	50
August	228	190	38	0.78	0.72	-2.0	60
September	201	165	28	0.75	0.91	3.6	60

Table 5 Results of regression analysis between measured and predicted runoff after model calibration (CN= 88 at AMC II; k=0.1S at AMC I and II and k= 0.2S at AMC III).

Month	Total runoff (mm)		No. of				
	Observed	Simulated	Events	Slope	r^2	Intercept	ME
July	173	172	45	0.97	0.87	0.09	84
August	228	221	43	1.00	0.84	-0. 04	87
September	201	183	35	0.99	0.91	-0.21	93

Model validation

The calibrated model parameters were validated using 5 years (1995-1999) measured runoff and rainfall data from two small agricultural watersheds. Regression results for the analyses of predicted versus measured runoff are presented in Table 6. There was a good fit between measured and curve number predicted runoff. For all data combined, the slope and the intercept of the regression lines were 0.96 and 0.02 for WS-1 and 1.00 and 0.18 for WS-3 and were not significantly different from 1.0 and 0.0 respectively, at the 95 percent confidence level. Similarly, when the predictions were made on monthly bases r^2 values, which range between 0.89 and 96, were large enough to demonstrate the suitability of the curve number method to predict runoff in the most runoff sensitive months of the year. The differences between observed and predicted total runoff were not significant at $P \leq 0.05$. Likewise the differences in normalized runoff per runoff producing rainfall were not significant ($P \leq 0.05$) either. The model efficiency values were also quite high and ranged from 0.87 to 0.95.

Measured runoff data from SW-1 and SW-3 was plotted against measured rainfall in Figure 4. The CN derived from inverse function was adjusted for average (CN, AMC II) dry soil condition (AMC I) following the procedures outlined in SCS (1972). Predicted runoff volumes using these three curve numbers are shown as solid curves in Figure 4. What is particularly interesting about Figure 4 is that nearly all observed events fall within the bounds of the plotted curves which once again indicate the accuracy of the calibrated curve number runoff prediction.

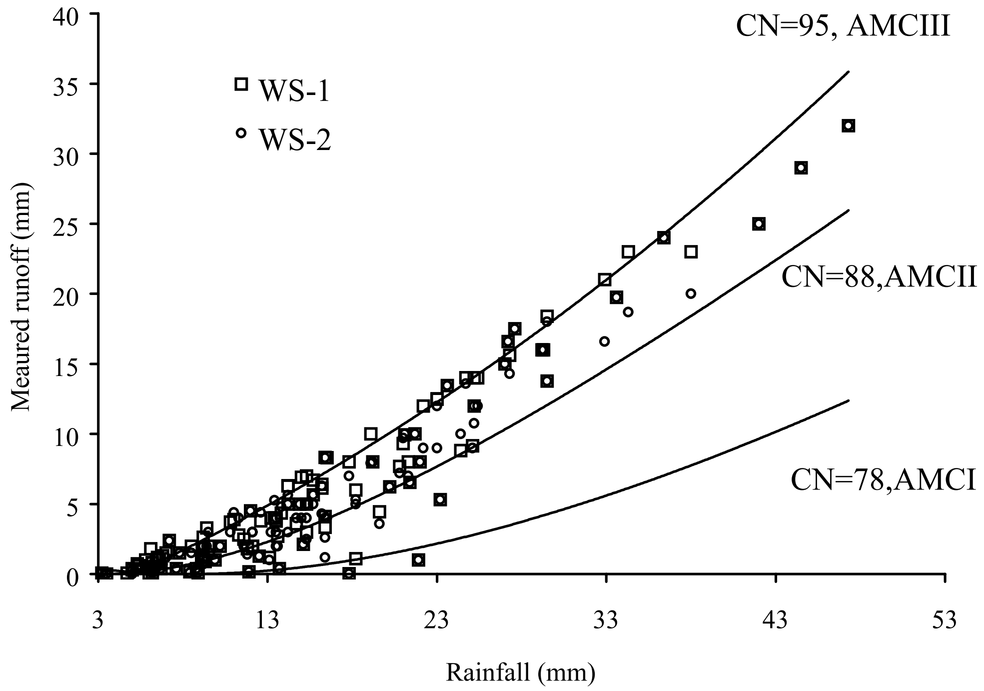
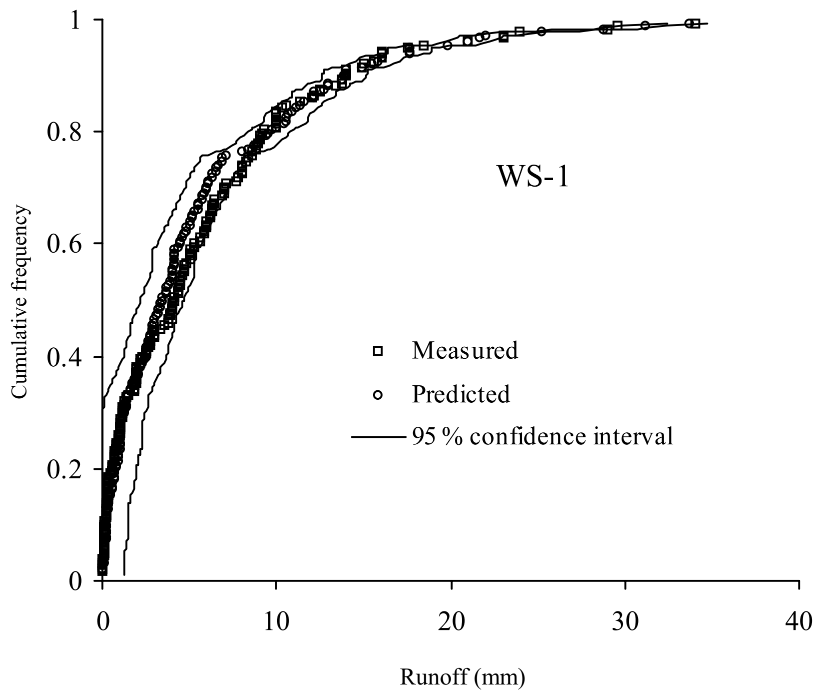


Figure 4. Measured runoff and rainfall at WS-1 and ws-3 watersheds between 1995-1999 at Ginchi, Ethiopia.

Runoff cumulative distribution curves for watershed SW-1 and SW-3 are plotted in Figure 5. In both cases predicted runoff values were within 95 % confidence interval of measured runoff distribution. Based on the comparison of measured and predicted runoff data and derived frequency distribution analysis, it was concluded that the curve number method is a suitable model for predicting daily runoff volume from measured rainfall data under Ginchi conditions.



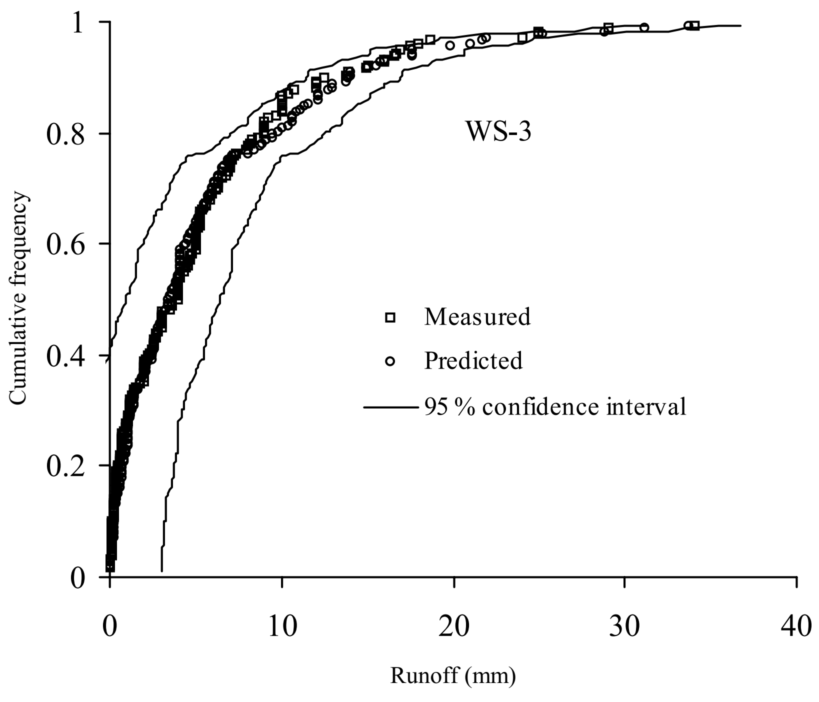


Figure 5. Cumulative frequency distribution of measured and predicted runoff volumes for WS-1 and WS-3.

Table 6. Results of regression analysis and model efficiency during model validation period (1995-1999), Ginchi, Ethiopia.

Months	Runoff (mm)				Slope	Intercept	r^2	ME
	Measured		Predicted					
	total	mean*	total	mean				
				WS-1				
July	213	3.94	198	3.9	0.98	-0.2187	0.96	0.95
August	482	7.19	471	7.03	0.99	-0.0853	0.90	0.88
September	307	6.86	293	6.18	0.96	0.0261	0.92	0.89
Combined	1002	5.68	963	5.47	0.96	0.0261	0.92	0.91
				WS-3				
July	194	3.67	198	3.91	1.033	-0.0295	0.95	0.95
August	463	6.91	471	7.03	1.029	-0.0871	0.91	0.90
September	290	6.57	293	6.18	1.030	-0.0416	0.89	0.87
Combined	923	5.28	963	4.47	1.007	0.1884	0.92	0.90

*total runoff divided by total number of runoff producing rainfall events.

Table 7. Return period analysis of daily rainfall (mm) and measured daily runoff (mm) in months of July, August and September of WS-3 at Ginchi Ethiopia (1995-1999)

Return period	Daily rainfall (mm)				Daily runoff (mm)			
(years)	July	Aug.	Sept.	Combined	July	Aug	Sept.	combined
2	25	32	28	28.3	12.3	19.2	19.7	14.4
5	30	41	37	38.4	17.1	27.4	26.3	24.0
10	33	47	43	45.3	21.2	31.0	31.8	30.0
20	36	53	48	51.9	22.4	36.2	35.6	36.3

Table 8. Return period analysis based on curve number runoff prediction in months of July, August and September at Ginchi research farm, Ethiopia (1982-2000).

Return period	Daily rainfall (mm)				Daily runoff (mm)			
(years)	July	Aug.	Sept.	combined	July	Aug	Sept.	combined
2	30	29	30	30	15.3	21.3	19.7	16.7
5	39	43	40	40	21.4	33.4	26.3	26.1
10	45	52	46	48	25.6	41.4	31.8	32.3
20	50	62	53	55	29.6	48.2	35.6	38.2

Discussions

When surface runoff is to be stored in ponds or reservoirs, the total runoff volume for a period of several months is of more interest than runoff from design storm. In this regard, the present study clearly demonstrates the feasibility of harvesting rainwater into dugout ponds even from small watersheds of one-hectare size for developing water resources in Ginchi Vertisols. An important parameter for runoff collection is the rainfall depth at which runoff starts. With the calibrated curve number method, runoff is generated only when the daily rainfall exceeds a threshold of 0.2S and 0.1S at wet and dry soil condition respectively. This threshold depends on the curve number and varies between 2.7 mm for wet condition (CN = 95) to 8 mm in dry soils (CN = 78) just after the surface cracks are closed. The narrow ranges between these thresholds demonstrate the ability of Vertisols watershed to produce runoff even during light rainfall once the surface cracks are closed.

The traditional tef based cropping system of highland Vertisols transformed 23-40 % of the seasonal rainfall (July, August and September) into runoff, which is equivalent to 102 to 307 mm runoff water ha^{-1} $annum^{-1}$. Thus, the water yield from one hectare of land would be more than enough to raise a second crop on a hectare of land in the post rainy season (Kamara and Haque, 1988). At the end of the rainy season, there is plenty of available soil moisture in the deeper soil layers of the highland Vertisol, but the surface is frequently quite dry (Abiye Astatke and Mohamed Saleem, 1998). This seriously impairs the possibility of crop planting in the post rainy season; where crops are planted, the plant stands are quite poor (Abiye Astatke et al., 1995). Thus supplemental irrigation with harvested rainwater would not only improve stand establishment but also increase the overall use efficiency of rainwater stored in the soil.

Farm pond with a size of 35 m by 35 m and 10 m deep would be enough to trap the runoff from a hectare of land. However, for supplementary irrigation it is not necessary to store the whole runoff water. In addition, in the face of land constrained smallholder farmer with limited household labor a pond size that could accommodate one-third of runoff water seems more practical. The small-scale nature of the system would make it amendable to management on a private household level. This limits the risk of unclear management responsibilities and subsequent free riding behavior, which often prevails in large-scale irrigation systems. Small farm ponds are efficient means to control runoff and regulate stream flow from uplands and hence could provide a base flow to the permanent streams for a considerably longer period than would be likely in the case of unregulated gullies and seasonal streams. In addition, a network of small ponds could reduce the sediment loads and improve the timing of water delivery to large–scale reservoirs found in this region. On the other hand, the storage of a reasonable amount of water in the ponds might reduce the amount of water available for the major reservoirs in periods of low rainfall. This aspect deserves further consideration though the probability of drought in the study area is estimated at 2 out of 10 years.

The rainfall and runoff frequency analysis values are necessary for crop planning, for determining the feasibility of water harvesting and for developing design criteria for farm ponds. Further, the analysis will also indicate the necessity for structures either at a higher density or wider spatial pattern, apart from identifying the potential areas of soil erosion. Direct runoff estimated with the curve number method was precise for most runoff prediction purposes provided that the CN, k and AMC parameters are calibrated for the local conditions. CN value determined by derived distribution method agreed closely with standard CN values given by SCS (1972) indicating that the inverse function can be used as objective function to calculate runoff producing rainfall from runoff data. In contrast, AMC and k parameter values were different from those used in the original curve number method.

A 10-day antecedent rainfall period was found to yield better prediction of direct runoff from traditional tef based cropping system of the highland Vertisols. The use of relatively longer antecedent period probably ascribed to slow drainage and slow drying rates of these soils once recharged to their maximum seasonal moisture content. Schulze (1982) found a 30-day antecedent period to yield better simulation of direct runoff in the humid areas of the U.S.A., but a 5- day to be applicable in the arid zones. Hope and Schulze (1982) used a 15-day antecedent period in an application of the SCS procedure in the humid east of South Africa.

In this study the precision of curve number method runoff prediction improved when Ia value of 0.1S was used for AMC II & I as opposed to the standard value of Ia = 0.2S (SCS, 1972). Various authors have been reported that the initial abstraction is less than 20 % of the potential maximum retention; percentages of 15, 10 and even lower have been reported (Aron et al., 1977 and Tidaman, 1996).

In the traditional tef based cropping system of highland Vertisols the calibrated curve number method predicted daily runoff with a relative error of less than 5 % in the three most runoff producing months of the year. However, these runoff-rainfall relationships may not be extrapolated to off-season rains, which contribute 30 % of annual rainfall as the curve number parameters were derived under moist soil conditions where at least surface cracks were essentially closed. Nevertheless, this may not be a problem to predict direct runoff in most runoff producing months of July, August and September as soils during this period are at their maximum seasonal moisture recharge and these are months that contribute almost 100 % the total runoff per annum.

Conclusion

Information on rainfall, runoff and frequency analysis showed that the highland Vertisols have a high potential for water harvesting. The seasonal runoff coefficient varies from 23-51 % in the three most runoff producing months of the year, which is equivalent to 102 to 258 mm ha^{-1} $annum^{-1}$. It is also observed that the smaller the watershed the higher is the runoff. Calibrated curve number runoff predictions are precise for runoff assessment purpose. From the frequency analysis, it is observed that a minimum of 300 m^3 runoff can be expected per ha watershed for a 10-year return period, while it is 140 m^3 for a two year return period. The results of this study clearly establish that it is feasible to harvest the inevitable runoff amounting to 140 m^3 for a two-year return period and using the same for supplemental irrigation and developing water resources on a long-term basis in the region.

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Chapter 4

Land tenure and soil & water conservation adoption in Ethiopia

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Land use policy (submitted)

Abstract

In Ethiopia, land is owned by the state. Farmers are granted the right to use land, but at any time the government can redistribute the land to accommodate young, landless farmers. Although farmers are aware of erosion, and can pinpoint erosion indicators, their adoption of soil and water conservation (SWC) practices is low. It is often thought that more secure land rights would improve farmers' willingness to invest in SWC. However, the outcome of this research shows that factors like farmers' experience, the source of the land, and severity of erosion are of greater influence on the adoption of SWC measures. In this light, policies to improve the adoption of SWC are discussed.

Keywords: Ethiopia, land tenure, land security, land use policy, privatisation, land titling, erosion, soil and water conservation.

Introduction

Soil erosion is a natural process of loosening soil particles and transporting it by water, wind or ice until the point at which the transportation capacity is reduced and so sedimentation takes place. Often enhanced by human activities, soil erosion is a multidimensional problem in which not only biophysical factors, but also social, economic, cultural and political factors are influential. As a consequence, no simple explanation for the causes and effects of soil erosion can be given. Instead, an area-specific study must be done to ascertain the factors influencing the extent of soil erosion and the adoption and use of conservation measures, as these might differ spatially.

The study we describe here approaches erosion from a sociological point of view. It looks at the existing land tenure system(s) and farmers' feeling of security about their rights to use the land (henceforth referred to as land security) as a possible influence on the adoption and use of SWC measures by farmers in the Ethiopian highlands.

It is important to understand why farmers are reluctant to use conservation measures, because erosion is a severe problem in Ethiopia, especially in the highlands where more and more sloping land is being put under cultivation. It has been estimated that the annual soil loss from cropped land in the Ethiopian highlands is 100 tonnes per hectare (Beshah, 2003: 21). If erosion continues at this rate, the soil of the present cropland will disappear within 100-150 years (ibid: 21).

The research, which was performed in 2001, took place in two watersheds, Ginchi (Oromiya Region) and Chemoga (Amhara Region), both situated in the highlands of Ethiopia. Ethiopia has undergone many political changes in the past, which have influenced the land tenure. Since the Ethiopian revolution of 1974, all land has been state owned. It has been stated that farmers do not feel secure about their land: “In Ethiopia, land tenure, or rather the insecurity of tenure, is often seen as an important factor in land degradation and the lack of investment by farmers in SWC” (Sutcliffe, 1995: 64).

Approach and methods

To meet the aim of the research it was important to look into the present-day and historical land tenure system(s) in Ethiopia and into how farmers[1] can get access to land. This also reveals how the political system of the Federal Democratic Republic of Ethiopia is organised from federal to local level. It was also important to know farmers' feeling about the security of the existing land tenure system. Finally, it was important to know what motivated farmers to adopt or ignore SWC measures, whether the government encourages such measures and, if so, how.

This research does not elaborate on different types of conservation measures (whether indigenous or introduced), or their effectiveness. In this study, the SWC practices comprise both those that farmers are already familiar with and those that have recently been introduced.

The data were collected in the field using quantitative (baseline questionnaire) and qualitative research techniques (group discussions and in-depth interviews). For the baseline questionnaire, the total sample was 60 farmers' households out of a total of 2,128. Because we expected farmers to differ in opinion depending on whether they lived high or low in the watershed and on whether their right to use the land dated from before or since the most recent redistribution, we stratified the sample according to these two variables.

Both regional governments have the autonomy to modify federal legislation, like the legislation on land redistribution, and to implement such legislation at different times. The most recent redistribution in Chemoga was in 1997, while in Ginchi it was in 1974. Because of this, the Ginchi farmers in the sample were, on average, older.

In both areas, two group discussions were held with farmers. In each area there was one group of farmers without land and one group of farmers who had been allocated land by the state. We expected that landless farmers would react differently to the research questions compared with farmers with land use rights. Eight farmers were interviewed in depth: three were landless and five had been allocated land. Local stakeholders (people from the regional Ministry of Agriculture and several development agents[2] were also interviewed, because of their local knowledge of farmers' practices and of government policies and their implementation.

Trends in policy

National land tenure policy before 1974

In order to understand the insecurity that farmers may feel in the current land tenure system, it is important to put the land tenure policies of Ethiopia in a historical perspective. Until 1974, when the *Derg*[3] took over, most farmers did not own the land they cultivated. Prior to 1941 there were two main landowners: the king and the church. The power of the Ethiopian kings to allocate land was not great, since in practice the people who cultivated the land, had the right to till it and to leave it to their children. The farmers paid a part of the crop as tax (Akalu, 1982: 23-24). Between 1941 and 1974, under the rule of Emperor Haile Selassie, there were land reforms. People who served the government were given the right to own land (ibid: 39).

In general, it can be stated that prior to the reforms of 1974 there were three land tenure

[1] The inhabitants of both research areas are mainly depending on agricultural activities for their living, even though they might have no use rights over land, and are therefore referred to as farmers.
[2] Extension workers, working with farmers on a local level.
[3] The military regime that ruled Ethiopia from 1974 until 1991.

systems in Ethiopia:
Communal land tenure, which was mainly found in the northern parts of Ethiopia, in the area that had been the heartland of the old kingdom of Ethiopia (Woube, 1986: 45). The communal land was redistributed every seven years. (van Beurden, 1994: 43);
Private land tenure[4], which was especially common in the south. It was introduced at the end of the 19th century and continued until the end of Haile Selassie's reign. Members of the ruling classes were given land to be able to control the peasant population. Traditional land tenure systems were also converted in these landlord–tenant relationships (ibid: 45);
Government land tenure, which was mainly found in the lowland areas. These remote parts of Ethiopia were populated by pastoralists. The government used the area for commercial, export-oriented agriculture (Woube, 1986: 46).

National land tenure policy between 1974 and 1991
Between 1974 and 1991, the socialist *Derg* governed Ethiopia. They made some important changes to the land use policy that had been in existence until then. One change was the prohibition of hired labour, because it was seen as exploitation. Landlordism was abolished, the land was proclaimed to be collective property of the Ethiopian people, and farmers were given rights of possession over the land they were cultivating at that time. The church was not allowed to own land. It became impossible to rent, sell or exchange land; it was to be distributed as equitably as possible, with a limit of ten hectares per household (Woube, 1986: 50).

For the establishment of state farms, the government started to organise farmers into Peasant Associations (PA's). Many farmers initially supported these changes (van Beurden, 1994: 43-44). When they were first introduced, the leaders of the PA's were genuinely committed to socialist ideals. One of their tasks was to redistribute land, but after some time the leaders started to abuse its power and appropriated large and fertile pieces of land for their own use and for friends and relatives (Wolde-Giorgis, 1999: 294). It soon became clear that the newly introduced policies were not a success.

A major problem with the land policy of the *Derg* was that land was continuously being redistributed to accommodate the young and landless generation. This led to land holdings becoming smaller, and to land eviction, and insecure land rights. It also adversely affected the sustainability of land use (Adal, 1999: 6-7).

National land tenure policy since 1991
Since the Ethiopian Revolution in 1991 land ownership has not changed in essence. The Federal Democratic Republic of Ethiopia, established in 1995, has maintained state ownership of land. Land is the property of the state and is not to be sold (Adal, 1999: 12). Farmers pay tax for the land they have use rights over[5]. There have been some changes, though, which should improve people's feelings of land security (Lemma, 1999: 1). Unlike the *Derg*, the present government allows land to be leased and labour to be hired (Adal, 1999: 12). Peasants and pastoralists have the right to procure land without payment, to use it for cultivation or grazing purposes, and they have protection from eviction and displacement from it. However, in practice the peasants and pastoralists are no more protected from eviction and displacement than during the period of the *Derg*; they can still lose land

[4] Land tenure in both fieldwork areas was organised according to this private system prior to 1974
[5] In this article, the term land use right refers to the right that is given by the state to a farm household to cultivate a certain piece of land and to yield its produce.

through land redistribution (Lemma, 1999: 10-11). Land redistribution is still organised at PA level. In the constitution it is stated that in the case of a redistribution, farmers will be compensated for the permanent improvements made on it (Adal, 1999: 11).

The farmers' livestock needs to be fed. For this purpose the government provides communal grazing lands. Chemoga in particular has a considerable area of communal grazing land, mainly in the floodplains. There is almost no private grazing land, in contrast to Ginchi, where almost all the farmers graze their animals on some of the land they have use rights over. In Ginchi, only a small amount of land has been designated by the government as communal grazing land. On these communal grazing lands, overgrazing is a serious problem. In addition to using these grazing lands, farmers let their animals roam freely over all cropland during the period after harvest and before planting.

Regional land tenure policy since 1991

Since 1991 regional governments have had the power to decide on the when and how of a possible land redistribution. In the current constitution it is stated that holdings are redistributed when the community decides this is necessary. In Ginchi, though farmers have wanted a redistribution for some years, none is yet planned. In Chemoga there has been a redistribution in 1997, but farmers are requesting another one, as the use of political criteria has led to inequity in land holdings. In the rest of this section we will discuss the regional land tenure policy of Amhara and Oromiya Regions. Since 1991, there has been one land redistribution in Amhara Region, in 1997. Land is the main source of income for most people, so it was very important for more people to be given access to it (Adal, 1997: 63). The motive for the redistribution was the inequitable pattern of rural land tenure that arose during the *Derg*, because at that time the PA took land from poor farmers who could not meet the grain quota[6] that was introduced by this military regime. The PA gave that land to farmers who were able to sell the necessary amount of grain (information gained through personal conversation with Selamyihun Kidanu, soil and water conservation specialist, on June 12 2003).

Four committees, whose members had been elected, were set up to enforce the redistribution. One, to verify land possession, registered all the land possessed by each PA member. Another, to verify family size, registered the household sizes and the number of landless people in the PA. The third, to allocate land, redistributed the land (ibid: 63). The fourth, the grievance hearing committee, heard complaints from people unsatisfied with the redistribution (Wolde-Giorgis, 1999: 298).

In addition to the criterion of family size, land was redistributed according to which of the four categories a farmer had been assigned to (Wolde-Giorgis, 1999: 297):

Bureaucrats who were involved in politics or had served in the army during the *Derg*. They were bound to lose land;

Feudal remnants, from families that had been important landowners during the imperial rule of Haile Selassie. The descendants of these people were also assigned to this class. Bureaucrats and feudal remnants were allowed to have only one hectare of land regardless of their family size at the time of this 1997 redistribution. They were allowed to select this from the land they had possessed before;

Rich farmers, who had more than 3 ha at the time of the redistribution. Their landholding was cut down to three hectares;

[6] By means of this grain quota system, farmers were forced to sell part of their produce at very low pr ice. The amount of grain to be sold was proportional to the area of land that a farmer had use rights over.

Poor farmers, who were considered to be the victims of the *Derg* rule. In general, they are those farmers who belong to none of the previous three categories. They were the major beneficiaries in this redistribution of 1997. For poor farmers there was only one criterion: family size. The minimum size of land holding was set at a quarter of a hectare.

After this redistribution in 1997, the government stated that it had been executed successfully. Its goals had been achieved, it was democratic and participatory. This made the redistribution fair and just. It was also stated that land security was assured by this redistribution (Adal: 1997: 65).

To date, Oromiya Region has not undertaken any redistribution, but is considering one, since in some areas the problem of landlessness is very serious. Estimates show that in some areas about 50 % of the people are landless (Tefera et al., 2000: 24). In Ginchi the interviewed farmers said that in their area as many as two-thirds of farmers had no land.

Land is a scarce resource in Oromiya Region, especially in the highlands. Land that is not suitable for agriculture is still being cultivated, because of the high population pressure. There is no maximum or minimum norm for the size of land holdings, and there is great fragmentation of land, because all farmers were previously given several small plots of land of different quality (ibid: 25).

National soil and water conservation policy between 1974 and 1991

National and international SWC and forestation efforts were induced in response to the 1972/73 drought and its consequences. This required intensive labour input. Many aid agencies started food-for-work (FFW) programmes in order to involve the local people, and the Ministry of Agriculture mobilised the necessary labour via the PA's (Admassie, 2000: xxii). The physical results of this effort were very impressive: between 1976 and 1985, 600,000 km of soil and stone bunds and about 470,000 km of hillside terraces were constructed. Also, 80,000 ha of steep slopes were no longer to be used for agricultural purposes (Admassie, 2000: xxiii). However, the local communities were not consulted about the installation of these conservation structures (Tessama, 2000: 8).

There were some problems that raised doubts about the sustainability of the conservation works. One problem was that some works depended so heavily on food incentives that it was difficult to further expand them without incentives. Furthermore, during the programmes doubts arose about the technical durability of certain structures. Neither was it clear how the programmes would benefit the farmers (Admassie, 2000: xxvii).

National soil and water conservation policy since 1991

After the overthrow of the *Derg* in 1991, the SWC and afforestation programme was terminated. The innovations had not been taken up by the farmers: many conservation structures had been destroyed or badly neglected, and hillside plantations had been cut down (Admassie, 2000: 71-73). After being in use for almost 20 years, the programme had few lasting results (ibid: 86) because the local farmers felt no sense of responsibility for what they had constructed or planted during it (Tessama, 2000: 8); they associated the programme with an unwanted regime.

In 1997, the Federal Democratic Republic of Ethiopia adopted a conservation strategy that has sustainable development as one of its main aims. Regional governments have based their environmental policies on it (Tessama, 2000: 9). It is now recognised that for the sustainable conservation of natural resources, land security is an urgent priority. Therefore customary rights of access are protected, provided they are constitutionally acceptable and socially equitable. It is also recognised that traditional community institutions should be empowered to manage natural resources, as long as these institutions are preferred by the communities and are not in conflict with state and federal constitutions (Lemma, 1999: 12). Soil conservation activities have largely been taken over by NGOs, which means less government involvement (Tessama, 2000: 7).

Regional soil and water conservation policy since 1991

In Chemoga area, the development agent gives farmers some SWC training and there is a demonstration plot to show farmers the different conservation measures. The farmers are obliged to participate in conservation activities. Together with the development agent, who supervises this group work, the farmers construct soil bunds on each other's fields. Most of them do not see the benefits of this conservation measure and do not like having bunds on their plots, but the development agent fines them if they refuse to cooperate or to maintain the bunds on their fields. The development agent thinks that as soon as farmers realise the long-term benefits of the bunds, they will maintain them voluntarily. Meanwhile, farmers who are using conservation measures on their own initiative are rewarded by the local government; they are given extra training and are made model farmers whom other farmers are taken to visit.

In Ginchi, no such initiatives are taken by the development agent and the local government. The only efforts made to improve adoption of SWC are some training by the development agent and a demonstration plot set up by a foreign NGO. Farmers in Ginchi are gradually and illegally cutting down more and more forest on the hills so they can cultivate the land. This increases the amount and severity of erosion, especially since the farmers have no experience in cultivating sloping land.

Results and Discussion

Land tenure and the adoption of soil and water conservation

There is a clear difference between the two research areas regarding the amount of land that farm households have use rights over (table 1). In Chemoga the land holdings are smaller due to the recent redistribution of 1997, but the amount of landless farmers is lower compared to Ginchi.

Table 1: Percentage of farm households in Ginchi and Chemoga watershed, classed according to their family size at the time of the last redistribution and the amount of land they have use rights over (data for 2001).

	Use right over land in Ginchi (ha) (N=40)						Use right over land in Chemoga (ha) (N=20)					
fam. size	0-1	1-2	2-3	3-4	4-5	fam. size	0-0.25	0.25-0.5	0.5-0.75	0.75-1	1-1.25	>1.25
1-4 (N=9)	11	22	56	11	0	1-3 (N=6)	33	17	33	0	0	17
5-8 (N=17)	12	35	41	6	6	4-6 (N=9)	0	0	11	33	45	11
9-12 (N=10)	0	30	50	20	0	7-9 (N=5)	0	0	20	40	0	40
>12 (N=4)	0	0	50	25	25	>9 (N=0)	0	0	0	0	0	0

Concerning the size of land holdings can be said that there is no relation between the amount of land a farmer was granted by the state and the use of SWC. In Chemoga all farmers apply conservation measures on their land, while in Ginchi half of the farmers use SWC practices, no matter the amount of land they have use rights over.

A land market exists in both research areas to enable farmers to optimise the use of their inputs labour and draft animals. There are four sources for acquiring or disposing of land:

- Redistribution by the government;
- Gifting: relatives can transfer part of their land to each other. Usually, land is given by parents to children;
- Renting from other farmers;
- Sharecropping: the farmers involved share their resources and the produce. Usually, one farmer has one or more oxen and the other has land but not enough oxen to plough it.

In both areas, landless farmers and farmers with only a small amount of land rent land, sharecrop, or are given the right to use land by their parents. Most of the Chemoga farmers, who already had land before the 1997 redistribution, had to relinquish land and decided not to give land to related beneficiaries of that redistribution, because they feel that their land has already been redistributed to their children.

In Table 2 the farmers' plots have been classified according to how they were obtained. The table shows the percentage of farmers who have adopted SWC measures on their plots. It is striking that conservation measures are taken more often on rented and sharecropped land than on gifted land. Land is becoming scarce, making it more difficult to get a rent or sharecropping contract. Farmers do their best on rented and sharecropped land, to increase their chances of renewing their contract. It can be concluded that adoption of SWC depends not only on tenure, but also on other factors. One such factor is the feeling of security about the rights to the land.

Table 2: Percentage of farmers in Ginchi and Chemoga (Ethiopia) who have adopted SWC measures, classed according to how they obtained individual plots of land (data for 2001). N = 251

Source of land	% of farmers who have adopted SWC
Redistribution (N =176)	63
Gift (N =24)	33
Rent (N =46)	67
Sharecropping (N =4)	75

Land security and adoption of soil and water conservation

Recall that one important question we set out to answer was whether the farmers feel secure about their land and how this sense of security could be improved. Half of the farmers in Chemoga feel secure, compared to only a third of the farmers in Ginchi. From this we infer that the difference in the timing of the last organised redistribution in the two areas has affected their feeling of security. In general, young farmers who have recently been allocated land feel secure, as they now have land and pay tax for it. Farmers who have no rights to use land also feel reasonably secure: they will get land in the future, and they have access to land through gifts, rent or sharecrop arrangements. They see this as a kind of ownership. Their sense of security might increase, though, if they are allocated land to use through a redistribution.

The young Chemoga farmers who participated in the in-depth interview and the group discussion said that land tenure is more secure if more farmers have land that they are entitled to use. From this we infer that security has increased since the most recent redistribution, but that it could be better. The land tenure is not yet equitable, since some farmers have three hectares, while others are landless. All the interviewed farmers who had had land before the 1997 redistribution felt insecure. In that redistribution one of them was deemed to be a feudal remnant and was allowed to keep only one hectare, even though he had seven dependants at that time.

Ginchi farmers seem to fear a future redistribution more than the Chemoga farmers. Of the four interviewed Ginchi farmers with land, two had been tenant farmers during the reign of Haile Selassie. They agreed with the young farmers that land tenure is secure: the government protects their land holding. Two other farmers used to be landlords, and they feel insecure. They have more land than other farmers and are bound to lose a considerable amount of it in the next redistribution.

In both areas the local Ministry of Agriculture employees think that land tenure is secure and that the farmers are assured of land use rights. The development agents, however, see two groups of farmers in their areas: the richer farmers with more land who feel insecure because they will lose land in the next redistribution, and poor farmers with little or no land, who feel secure because in that redistribution they will gain land. They all mentioned that in this system it is impossible to have full security, even though it is the fairest system, allowing all farmers to get access to land.

In Table 3 the farmers have been classified according to their feeling of land security. The table shows the percentage of each class who have adopted SWC measures. From this Table we conclude that for the adoption of SWC, security is more important than tenure status (see Table 2), but it must be remembered that young farmers often use SWC measures because their access to land is insecure. They hope to increase their chance of future rent and sharecrop arrangements by applying SWC practices on the land they use. In this case it is insecurity that leads to a higher adoption rate of SWC. This suggests that there are other factors that influence the adoption of SWC.

Table 3: Percentage of farmers in Ginchi and Chemoga (Ethiopia) who have adopted SWC measures, classed according to their feeling of land security (data for 2001). (N = 60)

Feeling of security	% of farmers who have adopted SWC
Yes (N =25)	80
No (N =35)	57

Severity of erosion and adoption of soil and water conservation

The severity of erosion appears to be an important factor in deciding how to manage the land (Table 4). Erosion is more severe in Chemoga compared to Ginchi, where the erosion is less visible sheet erosion. As mentioned before, all farmers use conservation measures in Chemoga compared to half of the farmers in Ginchi. Farmers living higher up in both watersheds, where erosion is more severe, are better able to recognise erosion indicators. Farmers in both areas tend to use fewer inputs like fertiliser and herbicide on plots with a higher erosion rate, but on these plots they use SWC measures more often.

Table 4: Percentage of farmers in Ginchi and Chemoga (Ethiopia) who have adopted SWC measures, classed according to their perception of the severity of erosion on individual plots of land (data for 2001). (N = 251)

Perception of erosion	% of farmers who have adopted SWC
No erosion (N =94)	32
Little erosion (N =88)	73
Considerable erosion (N =40)	73
Severe erosion (N =29)	100

Farmers' experience and adoption of soil and water conservation
More experienced farmers use SWC measures more often, although less experienced farmers stated that they are very interested in such measures (Table 5). Farmers do not recognise erosion in an early stage . In both areas the farmers said they felt they did not know enough about SWC measures to be able to sufficiently protect their land from erosion, and to see the benefit of conservation works. Responding to the baseline questionnaire, about a quarter of the Ginchi farmers mentioned that they might use SWC if they knew more about it. The interviewed farmers said they needed and wanted more training. Though the development agents in both areas do train farmers, they feel that both farmers and development agents need to learn more about SWC.

Table 5: Percentage of farmers in Ginchi and Chemoga (Ethiopia) who have adopted SWC measures, classed according to their experience in farming (data from 2001). (N =60)

Duration of farming experience (in years)	% of farmers who have adopted SWC
5-10 (N =15)	53
11-20 (N =12)	67
21-30 (N =10)	60
31-40 (N =12)	75
> 40 (N =11)	82

Policies to improve the adoption of SWC

The farmers' feelings as revealed by the data collected can be compared with the official viewpoint on SWC. This gives an idea of the likelihood that certain policies will work.

Improving land security
According to the interviewed local Ministry of Agriculture employees, there are two alternatives to the current system of land redistribution: land privatisation and a pre-defined use time (redistribution at set times). In the privatised system, the government is unable to accommodate poor and landless farmers. The disadvantage of the second system is that towards the end of their term of use rights, farmers might act destructively.

In general, the farmers and local stakeholders said they did not prefer a privatised land tenure system, and only suggested slight changes to the current system. They mainly called for equality through redistribution. Some farmers felt secure with the existing land tenure system and others did not. Most of those who felt insecure had been landlords during Haile Selassie's reign, or beneficiaries of the *Derg* regime and had lost land during the 1997 redistribution, or were afraid they would lose land in a future redistribution. Young farmers and former tenants in particular felt secure as long as they paid rent or tax for the land they had use rights over. Even landless farmers felt secure, because they would be the beneficiaries of a future land redistribution.

Given this situation, an improvement of land security must be sought within the existing land tenure system. To improve security, farmers should be issued with an official document that confirms their user rights. To give this document value, the government should state that if the land is subsequently taken from farmers, they will be compensated for improvements they have made to it, such as the installation of SWC structures. This would stimulate farmers to invest more, and it would make a pre-defined term of land use rights more useful.

The government must not delay a new redistribution until two thirds of farmers are landless, or use political criteria in a redistribution. Having said that the system intended to be equitable, it is important that the government can guarantee this equality. This can be achieved by involving local people and independent outsiders from other areas in the redistribution committees. The latter will have no local interest, and should therefore be able to minimise nepotism and corruption. Appointing the *yagershimagile*[7], known to be honest people, as local committee members, is one way of giving farmers trust, as they trust indigenous institutions. If no political criteria had been used in the 1997 land redistribution in Amhara Region, that redistribution would have been better organised.

Creating rules for land use

From interviews with the local stakeholders it appeared that the federal government has suggested a land use policy in which plots of land are given a designated use that farmers must adhere to. This suggested policy also specifies on which plots SWC measures must be used. Nearly all farmers interviewed would not like that idea, as they feel that they know their land better than the government does. Some of these farmers would try it on their plots, but only if they agree with the assigned destination of it.

A land use policy may seem to be a good system to force farmers to use SWC measures, but it is not a good base to build upon. A similar approach was followed during the *Derg*, but after that regime fell there was large-scale destruction of the conservation works. For security of tenure it is important for farmers to be able to use the land without such strong interference from outside. The introduction of a land use policy can be expected to make farmers feel less secure. Another possibility to motivate farmers to apply SWC would be to assign them a small plot of land near the house that will never be redistributed. This might also improve their feeling of security. In areas where conservation measures are indispensable, the first plots on which SWC practices are applied are usually those around the homestead, as farmers believe that this land will not be taken from them. On these plots, farmers will see the results of their conservation works in due time.

Improving farmers' experience

Education, training, and the giving of incentives are useful methods through which farmers are better able to judge the severity of erosion on their fields and take the necessary precautions. From

[7] *Yagershimagile* is a chosen group of elders that has an important function in the local community. Elders are respected for their wisdom. People go to the *yagershimagile* to solve disputes, ask advice, make rent and sharecrop arrangements, and to get married.

the interviews and discussions it is clear that the farmers do not want to be told what to do. As long as they do not see why they should be taking measures, farmers will not be very willing to use them on their land, regardless of the land tenure system.

SWC measures do not have an instant effect: the results become apparent after several years. But as implementing such measures is labour intensive and takes up land, which is already a scarce resource, farmers want to see immediate benefits. Demonstration plots are a good way of showing what the benefits of the measures are and which measures are most suitable for the farmers. These plots are also very useful for educating farmers. The state should actively promote conservation, since it remains the owner of the land. Farmers therefore feel that the government should also make investments in the land.

Conclusion

The improvement in land security needed to improve adoption of SWC adoption can be achieved by guaranteeing that:

- farmers will be compensated for any improvements made if the land is taken from the farmer;
- land will be redistributed within a reasonable time interval;
- a small plot around the homestead will not be redistributed.

However, other factors reviewed earlier, such as experience in farming, the observed severity of erosion, and the source of the land, seem to have a stronger influence on the adoption of SWC measures than land security. The results presented here suggest that increasing farmers' knowledge on erosion and conservation practices will improve the adoption of SWC more than focussing on the existing tenure system. This might be achieved through the development of a good education and training system with incentives for farmers. By so doing, farmers will learn to see the severity of erosion, the necessity of conservation measures, and the benefits of these measures for the land they have use rights over.

Finally, more research is needed on the negative effect of the land fragmentation produced by recurrent land redistribution. As land holdings become smaller, farmers will be less interested in applying SWC practices, as these take up part of the land. A solution for this problem might be to create better work opportunities for farmers outside agriculture. This would reduce the pressure on the land, as fewer people will depend on land for their income.

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Chapter 5

Farm practices and economics of Eucalyptus globules boundary plantings on highland Vertisols in Ethiopia

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Agriculture and Human values (submitted)

Abstract

Population pressure led to changes in land use and livelihood strategies in the highlands of Ethiopia. Among others, fast growing exotic trees species are integrated into tree-crop production systems in spite of a perception that this practice adversely affects crop productivity. This study has investigated tree crop farming practices with special reference to *Eucalyptus globulus* boundary planting, its economic implication and factors affecting adoption of the practices, based on a case study from Ginchi watershed in the central highlands of Ethiopia.

E. globulus trees are planted along farm boundaries in a row aligned in east-west or north-south direction with one meter inter row spacing. Farmers use different levels of management for this tree planting. In the Ethiopian highlands *E. globulus* produce a harvestable tree within four to five years although farmers on Vertisols prefer a longer rotation period (8-12 years) to maximize wood production. The annual wood production rates range between 168 to 2900 kg ha^{-1} y^{-1} depending on soil type, stand age and rotation cycle.

Farming experience, educational background, farm size, soil type and the position of farmland in the landscape are the most important factors, which influence the adoption of boundary planting. Most households plant trees along boundaries for fuelwood and timber production. It also considered a cash crop. Most farms prefer to plant one tree specie at a time, although there are more than 10 suitable species available. Its fast growth and coppicing ability makes *E. globulus* the most preferred tree specie in the Ethiopian highlands. The economic advantages override the reduction in crop yield. In spite of low stand density and long pay off period, the *Eucalyptus*-wheat system achieved returns to land 1.3–1.7 times, and returns to labor 1.2-1.5 times greater than sole wheat cropping. In addition, for the smallholder farmer the role of *Eucalyptus globulus* boundary planting is far reaching when it is evaluated in its potential contribution to the farming system through its substitution of dung fuel.

Introduction

Population pressure in the Ethiopian highlands has lead to a change in land use/land cover. Projections based on the estimated deforestation rate of 150 000 to 200 000 $ha^{-1}y^{-1}$ combined with per capita biomass requirements (0.75 m^3) suggest that Ethiopia's indigenous woodland would completely be exhausted by 2015 (Stiles et al., 1991). Establishment of woodlots and plantations with exotic tree species (Pinus and Eucalyptus) has long been advocated as a strategy for relieving pressure on indigenous forest and woodland in the Ethiopian highlands. In many situations, exotic trees have proved to be growing faster than the native species this and has been utilized for quick results. Nevertheless, tree planting at the scale that satisfies the biomass energy demand alone would occupy 6 % of the total utilizable land area in Ethiopia by 2014, requiring a major land use shift (Bojo and Cassells, 1995). Given the urgency of food security in the country, plantations with exotic trees underscore the importance of integrating trees into more intensive tree-crop production systems whenever the environment is conducive.

Traditional agroforestry practices in Ethiopia involve the planting of trees in various spatial patterns to meet wood, fuel and fodder requirements. In recent years, however, single rows of *E. globulus* trees planted along crop field borders have come a dominant feature of the central highland landscape. *E. globulus* trees, unpalatable to cattle, sheep and goats (Pohjonen and Pukkala, 1990), have a distinct advantage as boundary planting where otherwise communal dry season free grazing rights limit the success of privately planted trees on farmland. *Eucalyptus* trees planted along farm boundaries provide versatile use: fuelwood from the early stages of their establishment to harvest, cash income, construction of farm implements and houses. In the Ethiopian highlands, four to eight year old *Eucalyptus globulus* boundary plantings on a hectare of land have a potential to satisfy 50 to 75 % of the annual biomass energy requirement of a rural household with a family size of five people for four to eight consecutive years (Selamyihun et al., 2001). The greater availability of fuelwood may displace the dung fuel, which currently accounts for more than 81 % of the biomass energy consumption of rural household in favour of its use as fertilizer. In addition, preservation of indigenous woodland and biodiversity may be achieved when substitutes for indigenous forest products are established. Currently about 95 % of the total demand for wood and woody biomass in rural Ethiopia is for fuelwood (EFAP, 1993).

Agricultural development theory suggests that farmers adopt agroforestry practices when there are substantial economic incentives to do so at the regional and household level and as long as associated risks can be managed. Understanding farmers' current agroforestry practice, and likely trends in economic incentives, would then be needed to identify effective technical and institutional interventions. This study attempts to examine tree-crop farming practices and factors that affect the adoption of *E. globulus* boundary planting in tree-crop systems. It also attempts to see the impact on household income in the smallholder farmer's production environment in the central highlands of Ethiopia.

Materials and Methods

Characteristic of the study area

The study was conducted at Ginchi watershed, 90 km southwest of Addis Ababa, located in the central highlands of Ethiopia (2200 m a.s.l., 38^o E and 9^o N). The watershed has a subhumid climate with an average annual rainfall of 1200 mm, 30 % of which falls before the onset of the main cropping season. Vertisols and Nitosols in that order are the two most important soils in the watershed. The crop production system is rainfed monocropping characterized by a three year cropping sequence: a grain legume in succession with tef and durum wheat (Gezahegn and Tekalign, 1995). Durum wheat and tef are the principle traditional crops. Cattle, the most important livestock species, provides income, draft power and manure. However, in this system the manure is dried as cooking fuel, thereby precluding its use as organic fertilizer.

Data sets

To understand farmers' current agroforestry practices and likely trends in economic incentives, primary and secondary data were collected. The primary data collection involved the use of structured and semi-structured questionnaires on randomly selected households in the Ginchi watershed area. A total of 60 farm households were selected in the watershed for interview. Data on age structure, sex, farming experience, household size, type of the soil, farm size, education level, crop production, purpose of tree growing, slope and drainage of soil, were collected. In addition data from secondary sources related to land use, input use and extension services, were elicited and used in the analysis.

Wood production potential of *E. globulus* boundary plantings was estimated from stand height and diameter measurement at breast height using the fresh mass equation of Pukkala and Pohjonen (1989), which then was multiplied by a factor of 0.52 to obtain the dry wood mass as suggested by Pukkala and Pohjonen (1989). In fuelwood production the biomass of branches and leaves are also important, thus 10 % of the stem dry mass was added to account for branches and leaves in calculating the total dry matter production per tree. Pukkala and Pohjonen (1989) demonstrated the validity of this assumption for *Eucalyptus globulus* plantations in the Ethiopian highlands. A total of 360 trees grown on Vertisols were randomly selected from four, eight and twelve years old eucalyptus boundary stands from eighteen farms (six farms from each age group). On the Nitosols, which dominate the upper part of the watershed a total of 340 four-year-old trees from the first, the second and third generations were randomly selected from thirty-six farms.

Methods of analysis

Economic evaluation of tree growing in combination with a crop can be viewed as the product of two sets of activities: adoption of farm boundary plantation/woodlot and its impact on crop production and households income. A probit model was used to identify factors affecting adoption of tree-crop integration within the farming system. In the estimation of the probit model, the inverse mills ratio, which indicates the probability of the household being an adopter, is used to address a self selection bias as farm boundary plantation is a voluntary choice exercised by households. It is not a sample selection problem of the type that requires truncated regressions, as data is also available for non-adopters.

The profitability of eucalyptus boundary planting was assessed in comparison to sole wheat production. Wheat is the major crop grown across both soil types in the Ethiopian highlands. Enterprise budgets for eucalyptus-wheat and sole wheat were drawn over an 8 years period, using data on inputs, outputs, and prices obtained from the farmers and other key informants (Table 1). The analysis assumes a tree rotation harvest cycle of 8 and 4 years at Vertisol and Nitisol sites respectively. Labor inputs and wage rates were obtained from the formal survey of 60 farmers in 2001/2002. Wheat seed and harvest prices were averages of market prices over the period of 2001-2002. Data on wheat yield losses incurred due to the eucalypt boundaries were obtained from previous studies made in the watershed (Selamyihun et al., 2001 and 2003).

Two types of financial analyses were conducted: returns to labor and returns to land. In calculating returns to land, land was not valued, but household labor was valued at its opportunity cost as estimated by the price for hired labor. Returns are expressed on a per hectare basis. For returns to labor, household labor was not valued and returns were expressed per unit of labor, that is, per workday. The variability of financial returns could not be statistically assessed because a complete set of economic data was not available for each individual farm. However, sensitivity analysis was conducted to determine the effects of changes in key parameters on the profitability of wheat with and without eucalypt boundaries. The parameters examined were wheat yield and price, wood yield and price and discount rate.

In order to assess the potential impact of eucalypt boundaries on saving dung and hence on improved nutrient recycling, secondary data were assembled on caloric values of dung and eucalyptus wood. Potential impact was then determined by estimating the amount of dung fuel and associated nutrients that would be saved in relation to the amount of nutrients removed with eucalypt boundaries at harvest.

Results and discussion

Management of Eucalypt boundaries

In Ginchi watershed, only a small portion of all farm trees was found in woodlots. Instead, the most important niches for tree-growing in recent years are croplands (boundary planting) followed by homestead. In part this is due to the small farm size, where most land is under crops. Livestock management has also influenced tree site selection. In Ginchi watershed where free grazing in the dry season is a common practice, there may be considerable damage to seedling and sapling in the field, so farmers concentrate planting of susceptible tree species around the homestead. In the homestead, trees are valued for shade and aesthetics, fuelwood and fodder. On farm land, eucalyptus trees are the dominant tree species and planted in a single line with one meter interrow spacing aligned in the east-west or north-south direction, though the former orientation (80 %) is predominant on bottom lands. Tree densities in this unilateral alley system range between 90 and 120 tree ha^{-1}.

Unlike in woodlot plantations, farmers usually apply 2-3 kg farmyard manure per pit at the time of planting these eucalyptus boundaries. They also mulch the bases of individual trees with trash and crop residues towards the end of the rainy season after a shallow cultivation. Most farmers believe that mulches are very effective in conserving soil moisture while manure and in situ decomposed plant residues are seen by the farmers as an important source of nutrients for the young eucalyptus trees. Particularly on Vertisols mulching is considered a standard farm tree planting practice. Because the water loss would be enormous once cracks develop during tree growth as the result of receding soil moisture conditions. Further, cracking might rupture active roots and hence reduce the utilization of available stored water within the reach of the rooting depth.

Under this environment eucalyptus produces a harvestable tree crop within four to five years after planting although farmers on Vertisols prefer a longer rotation period (8-12 years) to maximize wood production. In the second and third rotation cycles, farmers tend to maintain as many sprouting stems as possible until the age of two years. Thereafter, they thin these sprouts to two to three stems per stump. Although the intention of the thinning practice is to reduce competition between actively growing young shoots, it is also a good source of fuelwood for the farmers who grow eucalypt boundaries on their farmland. The stems remaining after thinning are allowed to grow for two more years before they are ready for the final harvest. Thus the stem density harvested at the end of the third and second rotation cycles was two or three times higher than the stand density harvested in the first rotation cycle.

Table 1. Inputs and outputs for eucalyptus boundary plantings in Ginchi, Ethiopia.

Variables	Parameter		Source of information
	Vertisols	Nitosols	
Wheat			
Wheat seed price	240 birr ha $^{-1}$	175 birr ha $^{-1}$	Market price 2001-2002
Wheat seeding rate	150 kg ha $^{-1}$	125 kg ha $^{-1}$	Research recommendation
Fertilizer rate kg ha^{-1} (N and P)	60N and 20 P	40 and 20	Research recommendation
Fertilizer cost	450 birr ha $^{-1}$	410 birr ha $^{-1}$	Market price 2000/2001
Wheat grain yield, pure stand	1560 kg ha $^{-1}$	1570 ha $^{-1}$	Selamyihun et al., 2001
Wheat grain yield with tree, year 1-3	1560 kg ha $^{-1}$	1570 ha $^{-1}$	Selamyihun et al., 2001
Wheat grain yield with tree, year 4	1496 kg ha $^{-1}$	1507	Selamyihun et al., 2001
Wheat grain yield with tree, year 5-8	1496 kg ha $^{-1}$	1413	Selamyihun et al., 2001
Wheat price	1.6 kg birr $^{-1}$	1.4 kg birr $^{-1}$	Market price 2000/2001
Trees			
Transplanting, cultivation, digging	20 trees day $^{-1}$	20 trees day $^{-1}$	Farmers' estimate
Transplanting cost	30 birr ha $^{-1}$	30 birr ha $^{-1}$	Farmers' estimate
Tree population (seedling stand)	120 stems ha $^{-1}$	110 stems ha $^{-1}$	Selamyihun et al., 2001
Tree population (coppicing stand)		220 stems ha $^{-1}$	Selamyihun e t al., 2001
Wood price	726 birr Mg $^{-1}$	726 birr Mg $^{-1}$	Market price 2000/2001
Wood yield seedling stand	8.8 Mg ha $^{-1}$	3.6 Mg ha $^{-1}$	Selamyihun et al., 2001 and survey data 2001-2002
Thinning		0.3 Mg ha $^{-1}$	Selamyihun et al., 2001
Wood yield coppicing stand		1.7 Mg ha $^{-1}$	Selamyihun et al., 2001 and survey data 2001-2002
Tree seedling price	15 birr ha $^{-1}$	15 birr ha $^{-1}$	Local Ministry of Agriculture Office
Others			
Wage rate	5 birr day^{-1}		Survey data, 2001-2002
Discount rate	10 %		Researchers' estimate
Labor requirement (days ha^{-1})			
Land preparation	16	16	Labor survey data 2001
Wheat sowing	3	4	Labor survey data 2001
Weeding	17	16	Labor survey data 2001
Fertilizer application	2.4	2.4	Labor survey data 2001
Wheat harvesting	15	15	Labor survey data 2001
Wheat threshing	25	25	Labor survey data 2001
Tree seedling transplanting & Management	20	17.4	Farmers estimates
Thinning		10.6	Farmers' estimates
Wood cutting	14	25	Farmers' estimates
Wood chopping	36	47	Farmers' estimates

Farmers use a number of strategies to reduce the cost of eucalyptus boundary establishment. Even when they plan to grow a large number of farm trees, they utilize a pattern of gradual establishment to spread risk and cost of establishment over several years. They plant more densely in the lines than recommended in the conventional silivicultural guidelines and utilize or sell the extra thinnings as fuelwood. This narrow establishment has the advantage that it avoids the risk of loosing space due to seedling mortality in subsequent years. This finding is consistent with farmer's practice elsewhere in Gonder, north Ethiopia (Assaye Asnake, 2001).

Biomass production of Eucalyptus

Tree height, diameter and interrow spacing within the same stand age were quite uniform presumably due to the ease of establishment and high seedling survival rates of boundary stands in contrary to tree planting experience on communal lands. The annual wood production rate of boundary stands on Vertisols ranged between 168 kg ha $^{-1}$ y^{-1} at the age of four years to 2900 kg ha^{-1} y^{-1} at the age of twelve years (Table 2). On Nitosols where farmers utilize short rotation cycles (four years) annual wood production was 903 kg ha, $^{-1}$ y^{-1} in the first cycle and increased by two fold in the second and third rotation cycles (Table 2). The high wood production in the second and third rotations was attributed to increased stand density rather than increased growth rate of individual trees. Tree growth was faster on Nitosols than on Vertisols, particularly at the early growth stages.

The wood production rates of boundary stands are three to four times higher than the maximum wood production rates reported by Stiles et al. (1991) for *E. globulus* woodlot plantations in the Ethiopian highlands. Beneficial effects in tree growth due to adjacent crops have been reported by several workers under different soil and climatic conditions (Singh et al., 1997; Dhyani and Tripathi, 1999). Higher biomass production rates in this particular study can be attributed to differences in land quality, low side competition for light and water and good management practices particularly during early seedling establishment stage where the tree growth is sensitive to weed competition (FAO, 1985). In addition, boundary stands may have had access to plant nutrients that were applied to the adjacent crops through their lateral roots which extends up to 10 and 20 m into the adjacent crop area on Vertisols and Nitosols respectively (Selamyihun et al, 2001; 2003).

Table 2. Biomass production of *Eucalyptus globulus* boundaries on two common highland soils in Ginchi, Ethiopia.

Vertisols*			Nitosols**		
Stand age (years)	Stem Volume (dm)	Biomass (kg ha^{-1} y^{-1})	Rotation cycle (4 years each)	Stem Volume (dm)	Biomass (kg ha^{-1} y^{-1})
4	12	168	First	60	903
8	120	1105	Second	58	1760
12	477	2900	Third	52	1841

* estimates based on first generation stands

** estimates in each cycle based on four year old stands

Objectives of tree planting

The purposes of tree planting vary among the different households (Table 3). About 27 % of the farmers plant trees for the purpose of timber production, followed by fuelwood (11 %). A sizable proportion (38 %) of the farmers also prefer planting trees in general for the purpose of fencing around the homestead and crop field boundary demarcation. Soil conservation and fertility management play a minor role in tree planting. This may suggests that ecological objectives are secondary for most farmers in the adoption decision. Due to the nature of the topography and the presence of deep soils in the watershed, farmers do not perceive the consequences of slow but continuous land degradation processes. The choice of farmers for boundary planting reveals a preference for multiple purposes (Table 3). About 54 % of the farmers choose farm boundary planting for the purpose of boundary demarcation followed by timber use (27 %) and fuelwood (15 %). This may indicate that in the process of deforestation, poles become scarce more quickly than does fuelwood for which many more species and plant forms can be used. The importance of farm boundary planting was also indicated by the opportunity for marketing of the various tree products and hence serving as a cash crop. About 26 % of the multiple responses show that farmers prefer tree planting on their farmland for their immediate cash demand.

Table 3. Farmers' response on different objectives of tree planting with single and multiple purposes.

Objectives	Multiple response		Single response	
	No. of farmers	% response	No. of farmers	% response
Timber	15	26.6	15	26.8
Fuelwood	9	15	6	10.7
Cash	15	26	10	17.9
Boundary demarcation	30	54	21	37.5
Fencing	5	8	3	5.4
Soil fertility / conservation	2	2.6	1	1.8
Total	75	132.2	56	100

Source: Results from a 2001 field survey

Farmer's preferences for attributes of tree planting

About 70 % of the farmers prefer to plant only one single species (mainly eucalyptus) followed by 22 % preferring 2 species. Farmers prefer fast growing species. Economic returns could probably be the driving force for this because compensation is needed for the loss in crop yield due to competition. *Eucalyptus globulus* is the most efficient tree species in converting solar energy and available water into biomass under the prevailing environmental conditions of Ethiopian highlands (Pohjonone and Pukkala, 1990). Not surprisingly it is the most preferred species (Table 4).

The farmers were requested to rank tree species based on selected attributes that they perceive to be important indicators on their farmlands. Fifteen attributes were identified related to tree species and boundary tree planting practices. The rating was conducted by assigning a value 1-10 against each tree species. Results indicate that the farmer's preferences for the species on boundary planting differ among species. Average ranking indicates that *E. globulus* is the most preferred species for boundary planting (3.1) followed by *A. Albida* (4.0) (Table 4). Attributes such as seedling availability, pole quality and growing experience makes *E. globulus* the most preferred tree. On the other hand, *C. aficana* (7.1) and *A. cynophylla* were among the least preferred tree species for boundary planting. Attributes that relate to animal browsing and trampling tolerance, coppicing ability and incompatibility with annual crops make these species less attractive for boundary planting.

Adoption of farm boundary

The various attributes and values attached to boundary tree planting indicate that farmers adopt tree planting for various reasons. Thus adoption and benefits of tree-crop interaction require examining attributes related to yield and income from boundary plantings. With the help of a probit model the first level factors influencing the tree crop interaction were examined. The dependent variable considered was the probability of adopting farm boundary tree growing by smallholders. Many independent factors were hypothesized to affect farm boundary planting but only those that were turned out important are presented in Table 5. Those households with a longer experience in farming were familiar with tree planting and feel more secure than relatively younger farmers with less experience. They are also well familiar with acquiring information and are relatively well educated.

In addition, agroecological factors have clearly influenced the adoption choice, as households with moderate slopes and black soils (Vertisols) are more likely to adapt the practice (Table 5). Drainage tends to positively affect the adoption of the practice. The more excess moisture at the soil surface the more likely is the adoption of the practice. This picture confirms that farmers perceive planting eucalyptus for the purpose of draining excess water along farm boundaries.

Land tenure plays an important role in increasing farm boundary planting, although there is no clear-cut evidence that indicates the cause and effect relationship. The average farmer in the Ginchi watershed owns and operates on average 2 hectares of land, which is more than the national average (less than 1.5 ha) (Table 6). On the average, farmers rent in about 0.6 ha of land while they rent out close to 1.2 ha. This trend clearly indicates that informal land transaction exists and farmers export and import land for various reasons. The number of farmers renting out land (15 %) is low compared to the relative magnitude of farmers who rent in land (85 %).

Table 4. Ranking by farmers (n=56) of preference for different tree species

Selection Criteria	E. globulus	C. lustanica	C. africana	A. cynophylla	J. procera	G. robusta	O. africana	A. albida	S. sesban	L. leucocephala
Adaptability	3	7	10	6	8	5	4	2	1	3
Growth rate	2	8	7	4	9	6	3	5	1	4
Pest tolerance	3	1	9	10	4	6	3	8	2	7
Growing experience	1	4	10	5	8	6	9	2	3	7
Fuelwood quality	3	5	6	7	4	9	2	1	10	8
Timber quality	4	1	2	8	3	5	6	7	10	9
Pole quality	1	2	6	8	4	5	3	8	7	5
Coppicing ability	2	10	7	8	9	6	3	5	1	4
Seedling availability	1	3	9	6	8	7	10	5	2	4
Browsing tolerance	2	4	9	10	5	8	6	2	3	7
Trampling tolerance	2	5	9	10	6	8	6	3	1	4
Fodder quality	9	10	4	5	8	7	6	2	1	3
Shade	3	4	2	8	6	7	5	1	10	9
Boundary planting	2	4	10	9	3	7	6	4	8	5
Crop compatibility	10	8	7	6	4	3	9	5	2	1
Mean	3.1	5.1	7.1	7.3	5.7	6.4	5.4	4.0	4.2	5.3

Table 5. Farm level factors influencing the farm boundary tree planting adoption in Ginchi, Ethiopia

Variables	Coefficients (β)	t-value	significance
Farming experience	0.032	1.815	0.110**
Plot owned in ha	0.336	2.405	0.020**
Level of education	0.260	2.156	0.036**
Drainage	0.328	1.817	0.097
Color of the soil	0.181	1.851	0.101***
Slope of the farm	0.015	0.052	0.959
Extension advice	-0.105	-0.521	0.605

, *, significant at 5 % and 10 % P level respectively

Table 6. Farm size owned and operated (ha) by farm households in Ginchi Ethiopia

	Land holding			No. farmers	
Year	own	rent in	rent out	rent in land	rent out land
1990	2.5	0.25	1.3	45	11
1991	2.5	0.50	0.8	43	13
1992	2.5	0.75	1.3	50	6
1993	2.5	0.85	1.3	53	3
2000	2.5	0.75	1.0	50	4
2001	2.5	0.85	1.3	53	3
Average	2.5	0.6	1.2	47.8	8.3

Source: Results from a 2001 field survey. Farm size data were collected in local area unit (*kert)* and then converted into hectare assuming that 1 *kert* = 0.25 ha.

Financial analysis of Eucalypt boundaries

Additional costs involved in eucalypt boundaries relative to sole wheat include costs associated with tree seedling, reduced wheat yield (year 4 and onwards) and labor for transplanting and wood harvesting (Table 1). Additional befits of eucalypt boundaries included the value of thinned wood (in case of Nitosols) and wood yield at the end of rotation cycle (Tables 7 and 8). On the average, the labor use in the wheat-tree system was increased by 10 % as compared to sole wheat cropping mainly due to increased labor use in wood harvesting years (18 to 38 %). However, this labor use can be spread over the long period during the farmers' slack season and managed by own household labor.

In spite of the low tree density and the long payoff period, tree-wheat production systems' net present values are 9741 and 10750 birr ha^{-1}, over 1.3 and 1.7 times higher than that of the sole wheat situation on Vertisol and Nitisol sites respectively (Tables 7 and 8). Likewise, returns to labor and land are slightly higher for tree-wheat than for sole wheat. The net returns to land is relevant for farmers whose most scarce resource is land while the net returns to labor is relevant for those who lack household labor. In this particular study, however, returns to the land seems more relevant to farmers than returns to labor because, land is much more scarce than labor. Eucalyptus-wheat systems, thus, allows farmers to substitute land and labor for their most scarce resources: cash, timber and wood products.

Sensitivity analysis showed that the performance of the eucalyptus-wheat system relative to sole wheat is fairly stable across a wide range of changes in important parameters (Table 9). Increases or decreases of 30 % in the price of wheat, or in yield of wheat or wood do not affect the superiority of the eucalyptus-wheat system. Increasing the discount rate from 10 % to 20 % or reducing it to 5 % also does not affect the ranking. Among variables examined, the profitability of the eucalyptus–wheat system is most sensitive to changes in discounting rate, wheat price and wheat yield.

Several case studies have documented endogenous agroforestry intensification in permanent cropping systems with a rising demand and a reduced natural supply of tree products (Amacher et al., 1993; Dewees, 1989). But scarcity alone is insufficient to explain farmers' agroforestry innovation. Pressure on tree product supply may result instead in product substitution if there is an economic alternative (Dewees, 1989) or in reduced consumption. Informal interviews with Ginchi farmers suggest that the reduced consumption of tree products is widely practiced. There is increasing use of inferior fuelwood sources (including crop residues and cow dung), less and low quality timber in house building (including sorghum stover), declining numbers of household animals, which resulted in declining soil fertility and draught power availability and hence to low crop productivity. Under the economic conditions prevailing in the Ginchi watershed, most farmers can counteract this trend only by increasing farm tree supplies. Hence in addition to the pressure on tree product supply, farmers may adopt eucalypt boundary planting practice because it provides returns to the household factors of production and consumption. On-farm tree products are more cost effective than the alternative options.

Table 7. Financial analysis of eucalypt-wheat system as compared to sole wheat cropping (birr ha^{-1}) on Vertisols at Ginchi, Ethiopia.

	Wheat with tree								Wheat without tree		
Benefits and costs	Y1*	Y2	Y3	Y4	Y5	Y6	Y7	Y8	Y1	Y2-Y8	Total
Benefits											
Wheat yield	2496	2496	2496	2396	2396	2396	2396	2396	2496	17472	19968
Wood yield								6392			
Total benefit	**2496**	**2496**	**2496**	**2396**	**2396**	**2396**	**2396**	**8689**	**2496**	**17472**	**19968**
Labor cost											
Land preparation	80	80	80	80	80	80	80	80	80	560	640
Planting & weeding	100	100	100	100	100	100	100	100	100	700	800
Fertilizer application	12	12	12	12	12	12	12	12	12	84	96
Harvesting & treshing	200	200	200	200	200	200	200	200	200	1400	1600
Transplanting & Mgt.	90	25									
Wood harvesting								250			
Total cost	**482**	**417**	**392**	**392**	**392**	**392**	**392**	**642**	**392**	2744	3136
Other costs											
Tree seedlings	15										
Wheat seed & fertilizer	740	740	740	740	740	740	740	740	740	5180	5920
Total	**755**	**724**	**740**	**740**	**740**	**740**	**740**	**740**	**740**	**5180**	**5920**
Summary data											
Grand total cost	1237	1157	1132	1132	1132	1132	1132	1382	1132	7824	9056
Discounted cost	6271								6039		
Net benefit	1259	1339	1364	1264	1264	1264	1264	7406	1364		
Workdays	80	69	65	65	65	65	65	107	65		
Net benefit to labor	1660	1687	1690	1591	1591	1591	1591	7941	1794		
Net present value	9741								7277		
Discounted workdays	385								345		
Disc. benefit/ disc. workdays	30								25.8		

Price and quantities of inputs and output are from Table 1. * Y= yea

Table 8. Financial analysis of eucalypt-wheat as compared to sole wheat cropping (birr ha^{-1}) on Nitosols at Ginchi, Ethiopia.

Benefits and costs	Wheat with tree								Wheat without tree		
	Y1	Y2	Y3	Y4	Y5	Y6	Y7	Y8	Y1	Y2-Y8	Total
Benefits											
Wheat yield (grain and straw)	2198	2198	2198	1980	1980	1980	1980	1980	2198	15384	17582
Wood yield				2880		360		5728			
Total benefit	**2198**	**2198**	**2198**	**4580**	**1980**	**2340**	**1980**	**7708**	**2198**	**15386**	**17582**
Labor cost											
Land preparation	80	80	80	80	80	80	80	80	80	560	640
Planting & weeding	100	100	100	100	100	100	100	100	100	700	800
Fertilizer application	12	12	12	12	12	12	12	12	12	84	96
Harvesting & treshing	200	200	200	200	175	175	150	150	200	1400	1600
Transplanting & Mgt.	75	24									
Thinning						53					
Wood harvesting				110				250			
Total cost	**467**	**412**	**392**	**477**	**367**	**395**	**342**	**642**	**392**	2744	3136
Other costs											
Tree seedling	15										
Wheat seed & fertilizer	595	595	595	595	595	595	595	595	595	4165	
Total	**610**	**595**	**595**	**595**	**595**	**595**	**595**	**595**	**595**	**4165**	**4760**
Summary data											
Grand total cost	1077	1007	987	1072	962	990	937	1237	987		
Discounted cost	5557								5312		
Net benefit	1121	1191	1211	3788	1018	1350	1043	6471	1211		
Workdays	93	82	78	95.4	73.4	79	68.4	128	78		
Net befit to labor	1588	1603	1603	4265	1385	1745	1385	7113	1603		
Net present value	10750								6517		
Discounted workdays	468								422		
Disc. net benefit/ disc. workdays	28								18.7		

Table 9. Sensitivity analysis of the results of the financial analysis to changes in key parameters.

Parameters	Vertisols				Nitosols			
	With tree		Without tree		With tree		Without tree	
	Return to land	Return to labor	Return to land	Return to labor	Return to the land	Return to labor	Return to land	Return to labor
	birr ha^{-1}							
Base analysis*	9741	30	7277	26	10750	28	6517	21
30 % decrease in wheat yield	6284	19	4203	16	4569	17	2697	13
30 % increase in wheat yield	12921	35	10909	32	10933	33	9207	30
30 % decrease in wheat price	5528	18	2976	13	4693	17	2968	13
30 % increase in wheat price	13398	36	11019	32	14473	36	10066	30
30 % decrease in wood yield	8489	25	6914	22	7000	23	5952	21
30 % increase in wood yield	10297	29	6914	22	12238	31	6517	20
30 % decrease in wood price	8489	25	6914	22	9259	23	6517	20
30 % increase in wood price	10277	29	6914	22	12339	26	6517	20
20 % discount rate	6124	25	4973	22	7006	27	4647	21
5 % discount rate	12053	28	8376	22	13323	30	7827	21

*Data from Tables 7 & 8.

Soil fertility improvement potential

Use of cow dung, which contains 1.46 % N, 1.3 % P and 0.57 % K (Newcombe, 1989) as a source of organic fertilizer and the retention of crop residues in agricultural fields plays an important role in nutrient cycling, erosion control and maintenance of appropriate soil physical and chemical properties. However, in the Ethiopian highlands the use of manure and crop residues for the purpose of recycling nutrients and improvement of soil organic matter is unthinkable without having a substitute for its domestic fuel consumption. It is equally unthinkable to get other tree species, be it indigenous or exotic, that can substitute *Eucalyptus* in its full range of benefits it provides in the near seeable future. The heating value of *Eucalyptus* wood (stem and branches) is 19 MJ kg^{-1} (Frederick et al., 1985; Dalianis et al., 1996) while that of cow dung is 13.8 MJ kg^{-1} (Newcombe, 1989). Therefore, 0.73 kg *Eucalyptus* wood can supply the same amount of energy as 1 kg of dung. The wood harvest from 8-year-old eucalypt boundaries planted on a hectare of land would have a potential to replace 12 ton of dung which could bring back 176 kg N, 156 P and 60 kg K as organic fertilizer to the farming system. At harvest, eight year old eucalypt boundaries on a hectare of land remove 18 kg N, 6 kg P and 12 kg K (Selamyihun et al., 2003) of which about 45 % is accumulated in the leaf fraction (Selamyihun under preparation). Thus 1 kg of nitrogen removed with wood harvest (stem and branches) for fuel enables to bring back 20 kg N as organic fertilizer. In case of P, every kg removed with wood biomass enables to bring 26 kg of P as organic fertilizer. Likewise every kg of K removed with wood biomass enables to bring back 10 kg K as organic fertilizer. On the other hand, if the natural woodlands, with an estimated wood yield of 1.2 m^3 $ha^{-1}y^{-1}$ (EFAP, 1993), are to supply the same amount of fuelwood as eucalypt boundaries on a hectare of land, each household needs about 1.22 ha of woodland every year.

Competition with crops for water, and groundwater depletion are common arguments against planting *Eucalyptus*. This may be particularly serious when *Eucalyptus* trees are planted in drought prone regions. In our case, competition for water between crops and eucalypt trees occur close to the tree line, particularly during early crop establishment stages and cause substantial crop yield loss particularly with boundary stands older than four years (Tables 7 and 8). However, later in the season stored soil moisture can buffer the short dry spells that can occur between two rainfall events. Preliminary assessments in the Ginchi watershed suggests that negative hydrological effects may occur locally over a few meters beneath the tree rows (Selamyihun et al., 2001; 2003). However, given the high prospects for deep soil moisture recharge at Ginchi and the low stand density of eucalypt boundaries in relation to the total watershed area it is less likely that the negative hydrological effects would occur at landscape-level.

Conclusion

Eucalypt boundaries can produce large volumes of timber and wood products within a short time without requiring a major shift in land use. This has advantages for land-constrained smallholder farmers who cannot spare land for block plantations. The finding indicate that the profitability of eucalyptus-wheat on Nitosols appears to be somewhat higher than on Vertisols. Nevertheless, on both soils the tree component compensates crop yield losses and generates additional income. Farmers actually sale the products from the *Eucalyptus* at any part of the year, whenever, they are encountered with cash shortage. When, for instance, there is a fall in prices of grain they prefer to sell eucalyptus products and to sell their grain later at a higher price. The practice may also lead to efficient use of scarce land resources. It can therefore be considered as a smoothing mechanism and security to avoid income risk. Risks associated with weather and price are higher for sole cropping than for a mixed tree–crop system. This study also suggests that *Eucalyptus* boundaries would help the smallholder farmers to increase income and achieve food security, which leads to stabilizing the livelihood of resource poor farmers.

In addition, the greater availability of wood may reduce the demand for dung and crop residues as fuel sources and thus may contribute to improved soil management on croplands. Under appropriate management practices dung is a renewable and sustainable soil improvement resource because of its role in soils' physical and chemical properties maintenance. Boundary plantings can also help to preserve woodland and biodiversity by providing substitutes for forest products. This would be achieved by stimulating households to practice intensive forest farming along farm boundaries not exceeding a tree rotation period of 4 years.

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Chapter 6

Allelopathic potential of *Eucalyptus globulus* in a tree-crop production system on highland Vertisols in Ethiopia

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Agroforestry System (Submitted)

Abstract

Rapid expansion of eucalyptus in an integrated land use system in the Ethiopian highlands has been a subject of concern, particularly at policy and planning level. Apart from its competitive effects on water and nutrients eucalyptus is alleged to reduce the productivity of adjoining crops through the release of toxic chemical substances. In the current study the allelopathic potential of *Eucalyptus globulus* boundary plantings was investigated with three crops: chickpea (*Cicer arietinum*), in rotation with tef (*Eragrostis tef*) and durum wheat (*Triticum turgidum*) under laboratory and field conditions. In the field the annual litterfall production pattern of eucalypt boundaries and its potential allelopathic effect was examined. In a separate field experiment the allelopathic potential and crop response to eucalyptus litter application were investigated. In a laboratory litter extract bioassay, microbial activity and tef root growth on soil-litter mixtures were examined in a long-term aerobic incubation study.

Litterfall over the first 10 m from the tree lines is on the average 233 kg ha^{-1} y^{-1}. Six dry months (October to March) accounts for 75% of the total annual litterfall while the wet season (June to September) contributes less than 8 %. Mineral concentrations of the litterfall were low because nutrient withdrawal might have occurred before the litterfall. Soil bioassay studies with three test crops revealed that bioactive compounds from decomposing litterfall did not accumulate in sufficient concentration under the tree canopy to affect seed germination and root growth. However litter extract with 5 % concentration significantly inhibited germination and root growth of the test crops. Among the three crops, tef was the most susceptible with regard to germination and root growth. In the long-term aerobic incubation study, tef root growth on soil litter mixtures was significantly affected by water potential at incubation, litter addition dose and incubation period. When soil–litter mixtures were incubated at a water potential of –0.033 MPa for more than 8 weeks litter addition dose had no effect on tef root growth. This period increased to 12 weeks when soil-litter mixtures were incubated at water potential of –0.066 MPa. In contrast when the litter amended soils were incubated at a water potential of –0.5 MPa tef root growth decreased significantly with increasing dose of litter addition throughout the experimental period. Cumulative CO_2-C respired increased with increasing dose of litter addition and water potential at incubation, which indicates that litter application enhanced microbial activity in the soil. Under field condition the inhibitory effect of litter, which persisted for 3 to 4 months after incorporation closely followed the seasonal soil moisture recharge. Nevertheless the grain yield of tef planted after 4 months of litter incorporation was declined by 32-65 % in N unfertilized plots. No or minor effects were observed at N fertilized plots. The yield reduction is thus largely ascribed to nutrient immobilization due to the poor quality of the litter rather than to inhibitory effects.

Key words: Eucalyptus, allelopathy, Vertisols, chickpea, wheat, tef, and microbial activity

Introduction

Eucalyptus trees are widely grown in the East African highlands as exotics to meet the ever-increasing demand for fuelwood and other wood products. In Ethiopia alone, *Eucalyptus globulus* plantations cover more than 100 000 ha (Pohjonen & Pukkala 1990). Eucalypts trees convert energy and available water into biomass more efficiently compared with exotic coniferous tree species under most conditions of the Ethiopian highlands (Pohjonen & Pukkala 1990). However under the current per capita biomass energy consumption, estimated at 0.75 m^3 y^{-1}(EFAP 1993), tree planting at the scale that satisfies the biomass energy demand alone would occupy 6% of the total utilizable land area in Ethiopia by 2014; requiring a major land use shift (Bojo and Cassells, 1995). Hence, introducing short-maturing multiple-product tree species that can be combined with annual crops may of considerable importance in addressing the current biomass energy crisis in Ethiopia.

Traditional agroforestry practices in Ethiopia involve planting trees in various spatial patterns to meet the wood, fuel and fodder requirements of the farmers. In recent years, however, a single row of *Eucalyptus globulus* trees planted along the borders of croplands has come to dominate the central highland landscape. *Eucalyptus globulus* trees, unpalatable to cattle, sheep and goats (Pukkala and Pohjonen, 1989), have a distinct advantage as a boundary planting in the Ethiopian highlands where the protection of privately planted trees on farmland is difficult because of dry season free grazing practices. Eucalypt boundaries on a hectare of land with a rotation cycle of 8-12 years would satisfy 50 to 75 % of the total annual biomass energy requirement of rural households (Selamyihun et al., 2001). The greater availability of wood may reduce the demand for dung and crop residues as fuel sources, which currently accounts for 81% of the biomass energy consumption of rural households. In addition, by providing substitutes for indigenous forest products, eucalypt boundary plantings could help to preserve indigenous woodland and biodiversity. Fuelwood accounts for 95 % of the total demand for wood and woody biomass in rural Ethiopia (EFAP, 1993).

However, rapid expansion of *Eucalyptus globulus* in an integrated land use system in the Ethiopian highland Vertisols has been the subject of some concern, particularly at the policy and planning level. There is the idea that eucalyptus trees release toxic allelochemicals to the environment, which interfere with the growth of associated agricultural crops, and its subsequent accumulation in the soil could have far-reaching implications for sustainable land use over time. In the current eucalyptus-crop production system significant crop yield reduction occur within the first 8 to 12 m across the tree-crop interface (Selamyihun et al., 2001). This area possibly overlaps with the allelopathic interference zone if eucalyptus releases toxic chemicals to the environment in sufficient concentration.

E*ucalyptus* leaves have been reported to have phenolic acids, tannins and flavonoids (Babu and Kandasamy, 1997 and Chapuis-Lardy et al., 2002) and these chemicals have inhibited the growth of some test plants (Babu and Kandasamy, 1997). Similarly bioassay experiments with eucalyptus litter extracts exhibited high level of phytotoxicity (Bernhard-Reversat, 1999, Igboanugo, 1988; Lisanework and Michelsen, 1993). Molina et al. (1991) suggest that eucalyptus releases toxic allelochemicals into the soil system mainly through litter decomposition products. However, Inderjit and Dakshini (1999) have recently stressed the need to explicitly consider soil processes to make allelopathy research relevant to agricultural systems. In the soil environment the organic chemicals undergo sorption, metallic oxidation and chemical/physical degradation (Ohno, 2001). In the process of chemical oxidation allelochemicals may loose their phytotoxicity and this may happen long before these allelochemicals reach the plant roots (Lehmann et al., 1987, Ohno, 2001). Mere presence of phenolic compounds in eucalyptus does not demonstrate probable involvement of alleopathy in the soil-crop system.

In the above context it is necessary to address how the source (in this case the litterfall) affects the soil system and its subsequent bioactive residence time in the eucalyptus-crop production system to advise management decisions regarding the current practice. The purpose of the present study was to assess the bioactivity potential of E. globulus in Ethiopian highland Vertisols given the interest to integrate *Eucalyptus globulus* into an agroforestry system. The specific objectives were (i) to determine the annual litterfall production pattern and their allelopathic potential across the tree-crop interface (ii) to determine the allelopathic potential and residence time of litter when used in litter mulches for soil improvement.

Materials and Methods

Environmental setting and crop production system

The eucalyptus leaves and soil samples for this study were collected from the Ginchi watershed in the central highlands of Ethiopia (2200 m a.s.l., 38^0E, 9^0N), 90 km southwest of Addis Ababa. It has a subhumid climate with an average annual rainfall of 1200 mm of which 30 % falls before the onset of the main cropping season. The mean annual temperature is 26 ^{0}C with little annual variation, except a slightly warmer period from October to March and a cooler period from June to September. The Vertisols and Nitosols, in that order, are the two most important soils in Ginchi watershed.

The watershed represents a typical tef based cropping system on highland Vertisols. The crop production subsystem is monocropping, predominantly rainfed, and is characterized by a three-year cropping sequence: a grain legume, commonly chickpea (*Cicer arietinum*), in rotation with tef (*Eragrostis tef*) and durum wheat (*Triticum turgidum*) (Gezahegn and Tekalign, 1995). Eucalypt boundaries on highland Vertisols are planted with one-meter inter-row spacing aligned east–west or north-south along the crop fields.

Litter collection and treatment

The annual litterfall pattern across the tree-crop interface was determined from four farms with uniform 9-10 years old eucalyptus boundary stands by collecting litter at a month and a week interval in dry and wet seasons, respectively, for two years commencing June 2000. The tree lines were 40-50 m long and aligned in north-south direction. To exclude possible livestock interference in the dry season the stands were fenced at 10 m distance from both sides of the tree line. Once collected, leaves were taken to the laboratory, homogenized and allowed to dry for three days at 72^0C after which total dry weight was determined. The annual litterfall production per hectare was calculated by dividing annual litterfall dry weight by the total ground surface area contributed to the litterfall collection, i.e. a band of 10 m along the tree line. One way ANOVA was used to compare litterfall production rates among the sampling dates. The dried leaves were milled using a five-millimeter mesh, bulked and kept in plastic bags for further analysis.

Litter from bulked samples was grinded to pass a 1mm screen for chemical analysis. Total nitrogen was determined using Kjedhal digestion. Other mineral nutrients were determined after ashing (6 h at 450 ^{O}C) and dissolving in HCl. K, Mg and Ca were measured by atomic absorption spectrophotometer, and P by the ascorbic acid method (Wantanabe and Olsen, 1965). Aqueous litter extract was prepared by soaking 1 mm milled dry leaves in distilled water: ten g dry litter weighed into a 100 ml beaker shaken for 10 minutes with 10 ml distilled water and kept in the dark for 24 hours. Then the solutions were passed through a sieve to remove the organic material. Organic materials were leached with distilled water while on the sieve until 10 ml stock solution was recovered and this was kept in refrigerator at temperature of 4^0C for further use.

Bioactivity: in situ litterfall

Surface soils (0-10 cm) were sampled from the above four farm plots in May 2000 to investigate the accumulation of bioactive compounds in the soils from decomposing litterfall under the eucalyptus canopy. The samples were taken from three points: in the tree rows (SR), 3 to 4 m from the tree line (ST) and in the open field 30 m away (with zero litter fall) from the tree line (SO) in three replicates. The plots under investigation were cropped with tef the previous season. The soil was passed to through a 4-mm sieve to remove coarse fragments and root debris and then air-dried and kept for further analysis.

From each sampling point 200 g soil was brought at field capacity (-0.033 MPa) in Petri dishes, covered with pre-wetted Whatman paper No. 1, and 20 seeds of durum wheat, tef or chickpea were placed to asses the effect of decomposing litterfall on seed germination and root growth. The Petri dishes were placed in an incubator at 20 ^{0}C with relative humidity of 90 $\pm$ 5 %. The number of germinated seeds and the length of the emerged radicals were recorded. Seed germination and root growth data per crop was subjected to variance analysis using MSTAT-C procedure (MSTAT-C, 1991).

Bioactivity: litter extract

To investigate soil reactivity to bioactivity of litter extract a bioassay experiment was conducted with litter extract with and without soil reaction. Aqueous litter extract stock solutions diluted with 190 ml distilled water and distilled water only with and without soil reaction were bioassayed to provide a reference bioassay value. Ten g of soil from the ST and SO locations were weighed into 100 ml vessels and incubated at water potential of -0.033 MPa for a week. Ten ml of litter extract stock solution was then transferred into the vessels and incubated in an incubator at 20$\pm$2^{0}C in the dark for two days. Simultaneously 10 g soil from each of the two sampling points was incubated in the same way after addition of 22 ml distilled water as control. For easy of handling only soils from farm 1 were considered in this bioassay.

After the incubation, 180 ml distilled water was added to each vessel and suspensions were filtered through a double layer muslin cloth followed by Whatman No.1 filter paper. The concentration of litter extract in solutions extracted from soils was about 5 %. Previous bioassay studies showed that a litter extract concentration as low as 1 % was sufficient to inhibit growth of test crops used in this study (Lisanework and Michelsen, 1993).

The osmotic effects of aqueous extracts may be capable of severely inhibit germination and growth and hence were determined with a freezing-point osmometer. Solutions derived from litter extract treated with soil had potentials between -103 and -120 kPa (Table 1). According to Lisanework and Michelsen (1993), this is generally not inhibitory to germination and root growth and hence any inhibition observed in germination and root growth experiments would be chiefly due to allelopathic substances present in the extracts.

The bioassay was conducted in 100 mm diameter Petri dishes lined with pre-wetted Whatman No. 1 filter paper. Twenty seeds of durum wheat, tef or chickpea were distributed evenly in a Petri dish and 20 ml solution from each treatment was added. The individual Petri dishes were sealed with paraffin to minimize evaporation loss of the solution. The dishes were placed in an incubator at 20 $\pm$ 2 ^{0}C for 24 hours. Thereafter, seed germination and root growth was monitored for a 10 days period. All treatments were replicated three times and arranged in a randomized block design. Percent seed germination and root growth data per crop were subjected to standard analysis of

Table 1. Osmotic potential (kPa) and pH of litter extract (LE) and litter + soil extract (SO or ST) and soil extract with distilled water (DW)

Parameters	SO+ DW	SO+LE	ST+DW	ST+ LE	LE
pH	7.5	6.5	7.0	6.5	5.5
Osmotic potential (kPa)	-46	-103	-32	-120	-38

LE refers to stock litter extract solution diluted with 190 ml distilled water
SO and ST refers soils in the open field and under the tree canopy, respectively

variance procedure using MSTATC (MSTAT-C, 1991). Differences between means were identified using LSD test at $P < 0.05$.

Bioactivity: decomposing effect in the laboratory

A laboratory aerobic incubation experiment was established using a completely randomised design in three replicates, 5 rates of litter addition rates [R_0= 0 g (0 Mg ha^{-1}), $R_{0.5}$= 0.08 g (0.5 Mg ha^{-1}), $R_{1.25}$= 0.21g (1.25 Mg ha^{-1}), $R_{2.5}$= 0.42 g (2.5 Mg ha^{-1}), R_5= 0.84 g (5 Mg ha^{-1}), three water potential levels (=-0.033, -0.066 and -0.5 MPa) and six incubation periods (7, 14, 28, 56, 84, 112 days). Milled litter (5mm size) was mixed with 200 g ST soil taken from farm 1. Except for the highest dose which is included for comparison, other litter addition doses were based on the measurements of litterfall under eucalypt boundaries and green leaves on standing eucalyptus trees in a short rotation agroforestry system (Selamyihun, under preparation). The moisture levels imposed at incubation approximate a range of field soil moisture contents in the small rainy season (April to May) and the main rainy season (June to September).

Samples were incubated uncovered at 20 $\pm$ 2^0C in the dark. At 7, 14, 28, 56, 84, 112 and 112 days after the day of their incubation three samples from each treatment combination were randomly taken from the incubator and transferred into Petri dishes. The litter-soil mix moisture content was adjusted to -0.033MPa by the weight difference method. Then covered with pre wetted Whatman No. 1 paper, and 20 tef seeds were placed on it. The Petri dishes were placed in an incubator at 20^0C with relative humidity of 85$\pm$ 5 %. Each Petri dish was sprayed every day with 10 ml distilled water. After 10 days, root growth of ten seedlings per treatment was measured. The average root growth expressed as percentage of root growth reduction compared to the control treatment was subjected to standard analysis of variance procedure using MSTATC (MSTAT-C, 1991). Differences between means were identified using LSD test at $P< 0.05$.

In a separate experiment microbial activity was measured at the same litter addition rate (excluding $R_{0.5}$= 0.08 g (0.5 Mg ha^{-1}) and water potentials explained above in three replications. 200 g ST soil was incubated at –0.5 MPa for a week before it was mixed with the litter. Soil–litter mixtures at different water potential were kept in one litre airtight jars. Respiration from these jars was measured as CO_2 evolution at seven-day interval for 16 weeks. The CO_2 released was absorbed in a 1.0 M NaOH solution and its amount was determined by two-phase titration with HCL. CO_2–C output was expressed in μ g CO_2-C g^{-1} dry soil. Cumulative CO_2-C g^{-1} dry soil at 7, 14, 28, 56, 84, 112 and 112 days were compared using one-way ANOVA per incubation periods.

Bioactivity: decomposing effect in the field

Eucalyptus litter at a dose of 0, 1.25, 2.5 and 5 Mg ha^{-1} was incorporated on 7 m wide and 11 m long plots at Ginchi research farm, which is located 6 km west of the watershed in the end of March

2000. The dried leaves were milled into 5 mm to ensure uniform incorporation of the litter material in the upper 10 cm soil (maximum plow depth at that time). The plots were plowed in mid April and early May as farmers usually do. Each plot was divided into six 3 m by 3 m sub-plots leaving a 1m-alley between the sub-plots. Three nitrogen rates (0, 30 and 60) kg N ha^{-1} with two replications were superimposed on the subplots. Tef was planted at seeding rate of 30 kg ha^{-1} in the second week of August 2000. 10 kg P ha^{-1} was applied at time of planting. Weeds were controlled manually as frequently as necessary. The fertility levels compare the research-based recommendation (60 kg N ha^{-1}) with the farmer's practice (30-40 kg N ha^{-1}). Two hundred g of surface soil (0-10 cm) samples were collected in triplicate for bioactivity test every month from April 2000 to August 2000. The soils were bioassayed the same way as described in the aerobic incubation experiment.

Results

Litterfall

Monthly litterfall of eucalyptus boundaries are presented in Table 2. In all study plots occurrence of litter fall was significantly ($P > 0.05$) greater (except in few cases in October) during the dry season (October-February) as compared to litterfall during the rainy season (June–September). Six dry months of the year (October to February) accounted for 75 % of the total annual litter fall while four wet months (June to September) contributed less than 8 % to the total annual litterfall. Annual litterfall over a two years period, ranged from 167 to 276 kg ha^{-1} $y^{-1}$with an average value of 233 kg ha^{-1} y^{-1}.

Mineral concentrations in the litter fall were low probably because nutrient withdrawal might have occurred prior to litter fall (Table 3). Hence the agronomic significance of litterfall to the associated agricultural crops was limited. For instance, the N contribution was within a range of 1.5 to 2.2 kg ha^{-1} y^{-1} under the assumption that all litterfall is mineralized within the season of incorporation.

Bioactivity: in situ litterfall

None of the treatment effects (farms and sampling points) significantly influenced the percent seed germination and root growth of the test crops (Table 4). The percent seed germination ranged between 87-97 % while the root length attained a length of 35-55 mm in a ten days period. The germination pattern across all soil sampling positions and farms was uniform. This suggests that bioactive compounds in two soils locations (SR and ST), which received on the average 233 kg litterfall ha^{-1} y^{-1}, may not accumulate in sufficient concentration to affect seed germination and root growth of the test crops.

Bioactivity: litter extract

The percent seed germination of durum wheat, tef and chickpea in response to litter extract with and without soil reactivity is shown in Table 5. The litter extract (LE) was bioactive as determined by a significant percent seed germination difference from seed germination in distilled water (DW). Significant percent seed germination differences between the open field soils (SO+DW) and soils under the tree canopy (ST+DW) were not apparent and were not significantly different from the distilled water control treatment (DW). However, the importance of soil to litter bioactivity is evident by comparing the bioactivity of litter extract before and after reaction with the soil. Bioactivity of litter extract brought into contact with soil was not significantly different from the

Table 2. Monthly litterfall (kg ha^{-1}) of 9-10 years old eucalypt boundaries from four farms at Ginchi, Ethiopia

Months	2000-2001				2001-2002			
	1	2	3	4	1	2	3	4
June	3 d	6 cd	3 d	4 d	4 d	7 c	6 d	8 d
July	3 d	3 d	3 d	4 d	3 d	8 c	4 d	4 d
August	3 d	4 d	3 d	3 d	4 d	5 c	6 d	3 d
September	4 d	6 cd	3 d	3 d	3 d	7 c	8 d	7 d
October	24 ab	25 ab	11 cd	15 d	15 cd	22 b	14 cd	12 cd
November	25 ab	24 ab	16 bc	33 ab	21 bc	32 ab	19 bc	23 c
December	24 ab	30 a	25 ab	36 ab	34 ab	33 ab	28 b	43 b
January	44 a	34 a	25 ab	24 bc	50 a	42 a	46 a	58 a
February	40 a	26 ab	35 a	32 ab	36 ab	44 a	56 a	57 ab
March	34 ab	25 ab	20 bc	39 a	36 ab	32 ab	32 b	26 c
April	14 bc	13 cd	12 cd	26 abc	29 bc	21 b	19 cd	24 c
May	10 cd	16 bc	11cd	23 bc	11 cd	23 b	26 c	16 bc
Total	228	212	167	242	230	276	264	245

Values within the same column without common letters differ significantly at P< 0.05.

Table 3. Concentration (mg g^{-1}) of mineral elements in *Eucalyptus globulus* litterfall from six fields at Ginchi, Ethiopia.

Field No	N	P	K	Mg	Ca
1	6.9	0.23	2.8	1.9	12.2
2	8.6	0.18	2.7	1.6	15.7
3	5.6	0.15	3.0	2.1	18.9
4	5.9	0.28	3.0	2.5	16.5
5	7.9	0.24	2.8	1.4	11.4
6	7.3	0.27	3.6	1.7	10.7

level of distilled water control for wheat. In tef and chickpea, however, litter extract after soil reaction (SO+LE and ST+LE) was still bioactive, though the level of bioactivity significantly decreased compared with the litter extract treatment. The litter extract solution delayed days to germination compared with the distilled water control. Of the total seed, 98 %, 90 %, 87 % of tef, durum wheat and chickpea seeds were germinated within the first five days in the distilled water control treatment as opposed to 50 %, 66 %, 44 % in litter extract treatment, respectively.

Similarly, litter extract significantly depressed root growth of the three crops and more so on tef than on chickpea and more on chickpea than on durum wheat. Differences in root growth due to the two locations (soils under the tree and in the open field) were not significant. The importance of soil reactivity to litter bioactivity is evident. Litter extract that has reacted with soil had significantly lower root growth than the root growth of distilled water control. Root growth difference between litter extract before and after soil reaction was as high as 35 %, 19 % and 38 % in tef, chickpea and wheat, respectively, and significantly higher compared with root growth of litter extract treatment.

To gain further understanding litter amended soils under controlled aerobic incubation were selected for a bioassay study using tef as bioassay species.

Table 4. Percent seed germination and root growth of three agricultural crops at Ginchi Ethiopia as affected by in situ eucalyptus litterfall.

Farm	Sampling	Percent seed germination			Root length (mm)		
No.	Position	wheat	tef	chickpea	wheat	tef	chickpea
1	SR*	94	97	91	55	44	36
	ST	93	96	93	54	43	35
	SO	92	94	91	49	39	38
2	SR	96	92	94	51	39	39
	ST	93	95	93	48	42	40
	SO	89	94	89	50	42	36
3	SR	94	91	87	47	41	37
	ST	95	92	86	46	42	36
	SO	96	97	91	45	46	38
4	SR	97	92	93	47	39	39
	ST	95	94	87	52	38	42
	SO	93	93	91	46	43	45

In all cases, the effects of soil sampling position, farm and their interaction effects were not significant at $P<0.05$. *SR,= soils in the tree row, ST= soils under the tree canopy and SO= soils in the open field.

Bioactivity: decomposing effect in the laboratory

Tef root growth on incubated litter-soil mixtures was significantly influenced by the water potential at incubation, litter addition doses and incubation period and their interaction (Table 6). When litter-soil mixtures were incubated at a water potential of -0.033 MPa, root growth inhibitory effects were increased with increasing dose of litter addition in the first 3 incubation periods. Thereafter the influence of litter dose on root growth inhibition was not apparent. When litter-soil mixtures were incubated at a water potential of -0.066 MPa, the root growth inhibitory effects disappeared after 12

Table 5. Percent seed germination and root growth of three agricultural crops as affected by various extractions of eucalyptus litterfall.

Treatments	Percent seed germination			Root growth (mm)		
	wheat	tef	chickpea	wheat	tef	chickpea
Distilled water (DW)	96.3 a	97.3 a	97.3 a	48.0 a	38.3 a	31.3 a
Litter extract (LE)	47.1 b	24.9 c	31.2 c	21.7 c	14.7 c	18.0 d
SO+DW	97.6 a	91.5 a	96.0 a	44.7 a	37.7 a	28.7 a
ST+DW	97.9 a	94.2 a	94.6 a	46.1 a	34.3 a	29.7 a
SO+LE	89.8 a	64.2 b	63.8 b	36.3 b	21.4 b	22.0 b
ST+LE	87.7 a	69.7 b	74.0 b	34.2 b	20.7 b	23.0 b

Values within the same column without common letters differ significantly at $P< 0.05$.
ST= soils under the tree canopy and SO= soils in the open field.

weeks of incubation. In contrast at water potential of -0.5 MPa root growth inhibition was significantly influenced by amount of litter added. Litter addition dose except at 0.5 Mg ha^{-1} had significantly higher inhibitory effect at water potential of –0.5 MPa than their counterparts at –0.033 MPa. Significant difference in root growth inhibitory effect between litter amended soils incubated at water potential of -0.033 and –0.066 MPa disappeared after 12 weeks.

Cumulative CO_2-C respired increased linearly with incubation time (data not shown). Cumulative CO_2-C respired was significantly affected by both amount of litter added and water potential imposed at incubation (Table 7). Cumulative CO_2-C respired at and after 2 weeks incubation period was significantly higher in soils incubated at water potential of -0.033MPa and -0.066 MPa than in soils incubated at water potential of -0.5 MPa except at R_0. Significant differences in cumulative CO_2-C respired in soils incubated at -0.033 and –0.066 MPa water potential appeared after 4 weeks but became more explicit at and after 8 weeks incubation except for $R_{1.25.}$ When litter-soil mixtures were incubated at a water potential of -0.033 MPa, cumulative CO_2-C respired significantly increased with increasing amount of litter added at and after 2 weeks incubation period in the order of R_5>$R_{2.5}$> $R_{1.25}$ >R_0 except in week 2 and 4 where $R_{2.5}$=$R_{1.25}$. In contrast, when the soils were incubated at water potential -0.5 MPa significant differences in cumulative CO_2-C respired due to the amount litter added was only apparent towards the end of the incubation period.

To investigate the effect of microbial activity on the level of phytotoxicity, the cumulative CO_2-C respired in 1.25 and 2.5 Mg ha^{-1} treatment incubated at –0.033 and –0.066 MPa were regressed on root growth reduction data given in (Table 6). The result (Figure 1) showed that the level of expressed phytotoxicity (in the form of growth reduction) decreased exponentially with increasing amount of cumulative CO_2-C respired. The correlation coefficient (r^2) was high (0.77) and significant at P>0.05. This may suggest that easily degradable water soluble compounds determine the level of expressed phytotoxicity and products of biodegraded compounds may lose their bioactivity or remain on the surface of the soil and do not interact with plant roots.

Bioactivity: decomposing effect in the field

The results indicate that the litter was bioactive to tef at all doses of application in April and May (Figure 2). During this period the inhibitory effects increased significantly with increasing dose of litter. Root growth reduction relative to the control treatment (soil without litter) varied from 48 % at 1.25 Mg ha^{-1} to 75 % at 5 Mg ha^{-1} litter addition. With an additional 153 mm of rainfall in June however, significant root growth differences were only apparent between the control and the two highest litter application doses. Relative to the control the root growth reductions at 2.5 and 5 Mg ha^{-1} litter application were 33 % and 44 %, respectively. The root growth at 2.5 and 5 Mg ha^{-1} litter application was comparable and significantly lower than the root growth at 1.25 Mg ha^{-1} litter application. With further soil moisture build up in July the soils ameliorated the bioactivity of litter at dose of 1.25 and 2.5 Mg ha^{-1} significantly. Fifteen days later, at the time of tef planting, significant inhibitory effects of the litter at all application doses had disappeared.

Table 8 shows grain yield of tef in response to eucalyptus litter application dose. Both main and sub plots factors and their interaction effects significantly influenced tef yield. In absence of nitrogen application crop yield declined significantly when litter was added at a dose higher than 1.25 Mg ha^{-1}. When the different amounts of litter additions were superimposed on 30 kg N ha^{-1} the yield continue to decline but the magnitudes were not large enough to induce significant yield differences except at 5 Mg ha^{-1}. Significant effects of litter additions were not apparent in plots that received 60 kg N ha^{-1}.

Table 6. Root growth of tef on soils with decomposed litter expressed as percent root growth reduction relative to control (Soils without litter).

Water Potential	Litter (Mg ha^{-1})	Weeks after incubation 1	2	4	8	12	16
-0.033 Mpa	0.50	0.1c	1 d	0 e	1 f	2.0 c	1.0 c
	1.25	41 b	26 c	10 d	7 ef	1.7 c	0.2 c
	2.50	53 b	33 c	18 d	9 ef	1.9 c	1.0 c
	5.00	65 b	49 b	32 c	11 ef	1.0 c	0.1 c
-0.066Mpa	0.50	2.2 c	1.5 d	0.0 e	1.0 f	2.0 c	0.1 c
	1.25	51b	45 b	33 c	17 de	1.5 c	0.6 c
	2.50	83 a	71 a	43 bc	23 cd	8 c	1.5 c
	5.00	81 a	74 a	59 b	42 b	4 c	1.0 c
-0.5 MPa	0.50	2c	1 d	1.6 e	1.0 f	1 c	0.2 c
	1.25	72 ab	48 b	39 c	31 c	31b	15 b
	2.50	83 a	70 a	65 ab	48 b	30 b	10 b
	5.00	93 a	84 a	75 a	67 a	45 a	45 a

Values within the same column without common letters differ significantly at P< 0.05.

Table 7. Effect of eucalypt litter on cumulative CO_2-C respired (μ g g^{-1} soil) in Ginchi Vertisols, incubated at different water potential.

Water potential at incubation	Litter (Mg ha^{-1})	Weeks after incubation 1	2	4	8	12	16
-0.033MPa	0	1.3 c	27 d	43 de	75 f	112 f	117 e
	1.25	16 a	60 b	91 c	142 c	183 cd	191 c
	2.5	26 a	74 b	101 bc	164 b	239 b	248 b
	5.0	38 a	102 a	166 a	234 a	270 a	280 a
-0.066MPa	0	5 c	14 d	23 e	49 gh	82 g	97 e
	1.25	12 bc	57 b	65 d	111 d	137 e	149 d
	2.5	28 a	56 b	86 cd	129 c	170 d	186 c
	5.0	36 a	94 a	123 b	171 b	196 c	203 b
-0.5 MPa	0	6 bc	11de	16e	23 h	38 h	49 g
	1.25	5 c	13de	19 e	47 gh	87 gi	91e
	2.5	4 c	19 de	18 e	45 gh	75 gi	94 e
	5.0	8 c	29 de	31 e	45 gh	75 gi	84 e

Values within the same column without common letters differ significantly at P< 0.05.

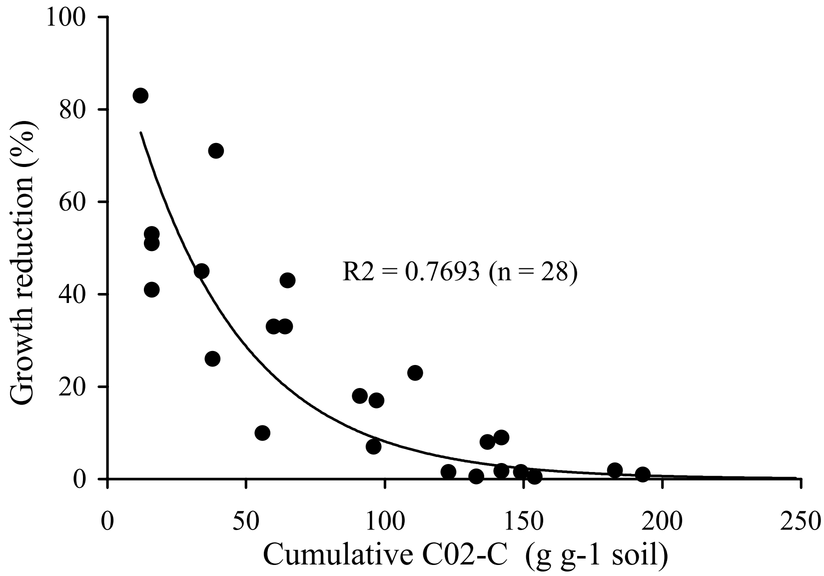

Figure 1. Cumulative CO_2-C respired versus percent tef root growth reduction in 1.25 to 2.5 Mg litter amended soils incubated at water potential of -.033 and –0.066 MPa. Each point is the mean of three independent measurements.

Table 8. Tef grain yield (kg ha^{-1}) as influenced by nitrogen fertilizer and litter application in Ginchi Vertisols, Ethiopia.

N (kg ha^{-1})	Litter application dose (Mg ha^{-1})			
	0	1.2	2.5	5
0	600 a	455 b	350bc	250c
30	900 a	815 b	850 b	650 c
60	1400 a	1300 a	1250 a	1209 a

Values within the same row without common letters differ significantly at $P< 0.05$.

Discussion

Litterfall production

Periodicity of litterfall largely followed annual rainfall (Table 2). One major peak of litterfall occurred during the dry season (October- February) and reached the highest peak in January–February. The significant seasonal variation in litter production with the highest value in the dry months is in agreement with the result of Hopkins (1966).

Bioactivity: in situ litterfall

The results of the bioassay on soils collected from all sample plots revealed that the bioactive chemicals across the tree-crop interface either do not accumulate in sufficient concentration to affect seed germination and root growth of the associated agricultural crops or oxidized on the soil surface and do not interact with the plant roots.

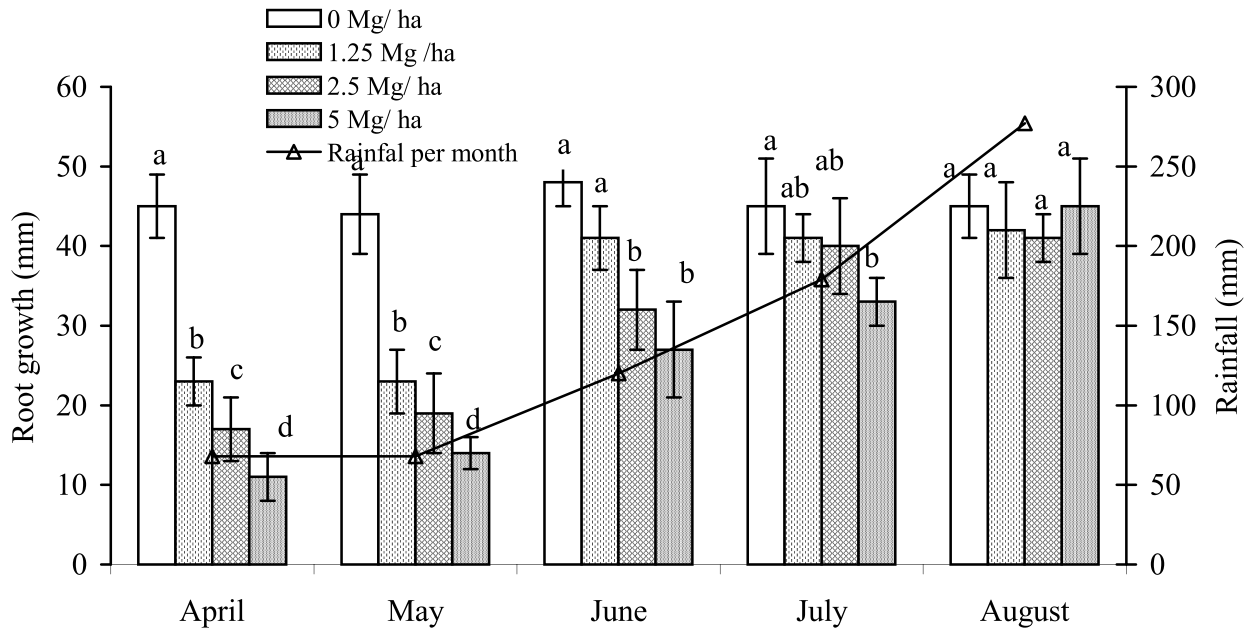

Figure 2. Tef root growth as influenced by litter application rate and length of decomposition period in the field. Mean values followed by the same letter are not significantly different at 0.05 level, LSD test. Comparison was limited to within litter application rate per duration. Error bars represent the standard errors of the means (n=3). Litter was incorporated at the end of March 2000, soils for bioassay were sampled on the last day of each month and on August, 15.

The soil samples were collected shortly after the small rainy season while the soil was moist but not wet enough to induce significant leaching. Thus it is hard to believe that the bioactive compounds (allelochemicals) were leached out before the soil samples were collected. From the above discussion it seemed that the amount of litter added through annual litterfall was small and subsequently the expressed level of phytotoxicity altered through biotic and abiotic soil processes. The peak litterfall season, the major pathway through which bioactive compounds are added to the soil system, is well separated in space and time from the cropping period. The first incorporation of litter in the soil (with the primary tillage operation) starts shortly after the small rains in April and May. Subsequent tillage operations, which continue until the end of July, further fragment and homogenize decomposing litter in the soil system. As a result no litterfall from the dry season accumulates on the soil surface to enrich the soil-litter interface with bioactive compounds during wet seasons. It has been suggested that microbial activity and turnover increases when fragmented high C-N ratio plant residues are incorporated into the soil compared with the surface placement method (Aggangan et al., 1999). Hence bioactive compounds, which serve as a C- source in the soil may have less residence time compared with bioactive compounds in the litter-soil interface. This may partly explain why bioactive compounds did not accumulate under eucalypt boundaries in sufficient concentration to affect percent seed germination and root growth in our experiment. Secondly the amount of annual litterfall is quite small in the face of soil reactivity levels measured in the field. Nevertheless, nutrient immobilization by litter decomposition may induce nitrogen deficiency, which is already critical in these soils. Although litterfall is the primary source of initiating a chain of reactions, poor crop yield across-tree interface may be from nitrogen deficiency, rather than from allelopathy.

Bioactivity: litter extract

In the current study the bioactivity of litter extract might be attributed to the solubility of low molecular weight phenolics (Harborne, 1997). Chapuis-Lardy et al. (2002) demonstrated that distilled water litter extract contains about 90 % of the total phenolic compounds in eucalyptus litter. Similarly, Bernhard-Reversat (1999) observed that bioactivity of eucalypt litter leachates to rice seedlings was correlated with soluble carbon content of litter leachates during early decomposition period.

Tef was the most inhibited crop with respect to germination and root growth in litter extract. Weidenhamer et al. (1987) found that the amount of allelochemical available per seed affected inhibition. Tef seeds are very thin compared with durum wheat and chickpea seeds, which may explain grater sensitivity to litter extracts. However, the extent to which eucalyptus litter extract inhibits the growth of herbaceous plants might also be species specific as chickpea with much bigger seed was more sensitive than durum wheat. Root growth of the test crops was also affected by litter extract. In comparison to seed germination root growth had shown a more sensitive indicator of inhibition.

Soils under the tree canopy and in the open field had comparable seed germination and root growth before and after reaction with litter extract. This suggests that there is no significant difference in their biotic and abiotic reaction towards litter extract. The importance of soil reactivity on the litter extract bioactivity is evident by comparing the bioactivity litter extract before and after reaction with the soil. Litter extract in contact with soil showed significantly lower bioactivity indicating that the reaction with the soil counteracts the bioactivity of soluble compounds in the litter. These results affirm the speculation of Lehmann et al. (1987) that the role of soil, abiotic and biotic, is important in the expression of alleopathy in a litter soil system.

Because of methodological differences it is difficult to compare the level of soil reactivity in this study with other studies involving eucalyptus allelopathy. However it has been reported that eucalyptus litter leachates mobilize iron in soil-leachates suspensions (Ellis, 1971; Bernhard-Reversat, 1999), which suggests that organic compounds in litter leachates were being oxidized upon sorption to the soil. The process of chemical oxidation of allelochemicals may result in loss of their phytotoxicity and this may happen long before these allelochemicals reach the root of the plants (Cheng, 1995; Lehmann et al., 1987). Iron mobilization is closely related to soil mineralogy, particularly through the occurrence and activity of iron oxides in the clay fraction (Bernhard-Reversat, 1999). Soils used in this study have high and active free and total iron contents, as Nontronite is the most prevalent smectite in the clay mineral in highland Vertisols (Asnakew, 1987). In addition to the abiotic sorption reaction, it is likely that soil microbes present in the unsterilized soil used in this study degraded some soluble organic compounds during the incubation period.

Bioactivity: decomposing effect in the laboratory

As plant residues are incorporated in the soil, the soil microbial activity increases as decomposition products provide energy and nutrients to the microbial population (McKenney et al., 1995) and this is reflected in greater respiratory output from the soil (Jensen, 1997). Respiration rate reflects the overall biological activity and is known to be affected by availability of substrate, nutrients, moisture and temperature (Orchard and Cook, 1983; Alvarez et al., 1995). In the current study, nutrients and temperature at incubation were the same, thus cannot be the reason for the observed differences in respiration rates. Two variables, the substrate availability (i.e. the amount of eucalyptus litter added) and the water potential imposed at incubation significantly influenced rates of microbial respiration.

Decomposing litter bioactivity to tef root growth varied significantly with water potential levels imposed at incubation (Table 7). Litter moisture content, being lower in soils incubated at -0.5 MPa water potential might have affected the population and activities of soil microbes compared with soils incubated at -0.033MPa and–0.066 MPa. Smith and Paul (1990) noted that as the system becomes drier, bacteria start to lose activity usually at - 0.5 MPa to a lower limit of -8 MPa while fungi have a wider activity range, being active from -0.4 MPa to –10 MPa.

In the current study microbial activity as measured by microbial respiration rates increased significantly with increasing levels of water potential at incubation. Litter bioactivity to tef crop decreased exponentially with cumulative CO_2-C respired throughout the experimental period. This suggests that water potential at incubation controls litter bioactivity indirectly through its control on microbial activity. In his recent review Blum et al. (1999) demonstrate that microbial activity will alter phenolic compounds in the soil and subsequently alter the expressed level of phytotoxicity.

The input of C largely determines the size of microbial biomass (Anderson and Domsch, 1985). In the current study it seemed that litter addition influenced microbial biomass as this was reflected in a greater respiratory output with increasing dose of litter addition (Table 7). Decomposition rate is measured by weight loss; it is also measured by carbon dioxide release in numerous studies (Bernhard-Reversat, 1998). In our study exponential decrease in litter bioactivity with cumulative CO_2–C suggests that microbial population in the soil mineralizes relatively easily degradable compounds, generally assumed to be low molecular weight phenolics, which likely determine the level of expressed phytotoxicity. Furthermore it may indicate that allelopathy is a transient process and hence toxic effects demonstrated for litter extracts are ecologically irrelevant at least in an environment where soil moisture does not limit microbial activity.

Litter bioactivity increased significantly with increasing amount of litter added and this is in agreement with the results of other authors (Sanginga and Swift, 1992; Lisanework and Michelsen, 1993). Significant interaction effects between MPa at incubation and litter application dose indicates that the relative importance of water potential on litter bioactivity was higher at high than at low amount of litter addition. Likewise significant interaction effect between water potential at incubation and incubation period means that litter bioactivity differences due to water potential at incubation were higher at the initial stages of decomposition than at later stages. Similarly, significant interaction between litter addition and incubation period indicates that bioactivity of litter differences due to the amount of added litter addition was higher with short incubation period than with long incubation period.

Bioactivity: decomposing effect in the field

Under natural conditions, microbial biomass tends to change its activities hence, time series measurement of litter bioactivity in the field may provide an understanding of changes over the prevailing conditions. Expressed level of bioactivity in the field closely followed the pattern of seasonal soil moisture recharge (Figure 2). In the months of April and May, which were relatively dry, the litter showed a high degree of bioactivity to tef plants compared with the result of aerobic incubation studies particularly in soils incubated at higher water potentials. The rainfall during this period was 30-40 % lower than the long-term average. However, with the advance of the season and subsequent soil moisture recharge litter bioactivity declined at a rate faster than those observed in controlled incubation studies. Under field conditions where alternate wetting and drying of the soil-litter system had occurred, the decomposition of litter tends to be higher probably due to a subsequent flush of nitrogen mineralisation. At the end of July litter bioactivity was completely ameliorated except in plots that received 5 Mg ha^{-1}. At this dose significant inhibition was not detected in samples taken 15 days later at the time of tef planting. It seemed that under field conditions litter bioactivity is a transit process even at a higher litter application than that would naturally occur under the canopy of eucalypt boundaries.

Tef yield was significantly declined with increasing amount of litter added and the effect was more apparent in N unfertilized plots than in N fertilized counterparts. It has been suggested that the soil N availability is reduced to a greater extent when eucalyptus residues are incorporated in the soil (Aggangan et al., 1999). In the current study, reduced tef yield in response to litter dose in unfertilized plots is due in part to poor quality of the litter as indicated by its low N concentration (0.5%). Because its of high C/N ratio, eucalyptus litter decomposes slowly and nutrient immobilization can persist over several months after litter addition (Sanginga and Swift, 1992). Changes in N dynamics following litter addition in seasonally waterlogged soils such as on Ginchi Vertisols may also result from loss of N through denitrification. Thus the use of well-decomposed eucalypt litter, which can be applied at time of crop planting, may be an attractive alternative from both allelopathic and safe nutrient recycling perspective.

Conclusions

Under the current eucalyptus tree-crop production system the bioactive chemicals released from litterfall either do not accumulate in sufficient concentration to affect seed germination and root growth of the test crops or oxidized fast enough in the soil to be harmful. Periodicity of litterfall, the source of bioactivity compounds in the soil system, largely followed the annual cycles of soil moisture recharge. This makes that litterfall is well separated in space and time from the cropping period. Presumed environmental impact of eucalyptus on associated agricultural crops is less likely to occur under this condition. However, nutrient immobilization as a result of litter decomposition can persist over several months after litter incorporation and possibly overlap with early crop establishment where nitrogen deficiency can limit crop growth and hence crop yield across the tree-crop interface.

The findings of the study reported here may explain why phytotoxicity effect of eucalyptus litter incorporated into the soil did not persist for more than 60-90 days under wet soil conditions. The moisture content of the litter-soil mix determines the concentration of soluble organic compounds which influences microbial activity and hence the level of expressed phytotoxicity. When the litter releases bioactive compounds into the soil this enhances microbial activity. Microbes use the bioactive compounds as C- source and subsequent mineralisation decreases the concentration of bioactive compounds in the soil solution. Byproducts of biodegraded compounds either lose their toxicity or do not interact with plant roots as deduced from the relationship between expressed level of phytotoxicity and cumulative CO_2-C respired over the experimental period. This bioassay study's results also indicate that abiotic soil reactions are important in the expression of litter bioactivity in the soil system. In other words bioactive compounds that are released from litterfall may be absorbed in soil solutions with subsequent oxidation. The process of chemical oxidation further decreases the concentration of bioactive compounds in the soil solution.

From allelopathic perspective, i.e. plant-to-plant chemical interaction, *E. globulus* can be used in an integrated land use management system in an environment such as in Ginchi. However, when eucalyptus boundary plantings are established on land previously used for conventional agriculture, significant change in the N-dynamics in the surface layer could be expected. Allelochemicals aside from playing an important role in plant-plant interference, do play an important role in influencing soil microbial ecology (Chander et al., 1995) and nutrient dynamics (Blum et al., 1999). Hence further research should be conducted to assess a possible shift in microbial population and the extent to which nutrient dynamics, particularly N, is influenced by eucalypt boundaries given the interest to the integration of *Eucalyptus* species into agroforestry systems.

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Chapter 7

Biomass production of Eucalyptus boundary plantations and their effect on crop productivity on Ethiopian highland Vertisols

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Abstract

In recent years, *Eucalyptus globulus* planted along field boundaries has come to dominate the central highland landscape of Ethiopia. Although evidence is scanty, there is a perception that this practice adversely affects crop productivity. An on-farm trial was conducted on Pellic Vertisol at Ginchi to determine the production potential of eucalypt boundaries and their effect on the productivity of adjacent crops of tef (*Eragrostis tef*) and wheat (*Triticum sp*.). The experiment comprised three stand ages, four field aspects and six distances from the tree–crop interface, using a split-split plot design with three replicates. Wood production rates ranged between 168 kg ha^{-1} y^{-1} (four years old) and 2901 kg ha^{-1} y^{-1} (twelve years). Thus eucalypt boundaries planted on a hectare of land would satisfy 50 to 75 % of the annual biomass energy requirement of a rural household of five persons. Significant depression of tef and wheat yields occurred over the first 12 m from the tree line: the reduction was 20 to 73 % for tef and 20 to 51 % for wheat, equivalent to yield losses of 4.4 to 26 % and 4.5 to 10 % per hectare respectively. Nevertheless, in financial terms, the tree component adequately compensated for crop yield reduction and even generated additional income. Therefore, eucalypt boundaries have great potential to satisfy the rising demand for wood, without requiring a major change in land use on the highland Vertisols. The greater availability of wood will reduce the demand for dung and crop residues for fuel, and thus may contribute to improved soil management on croplands while relieving the increasing pressure on indigenous forest and woodlands.

Key words: *Eucalyptus globulus*, on-farm, tef, tree–crop interface, wheat, watershed

Introduction

The rapidly increasing population pressure in the Ethiopian highlands has led to changes in land use with the aim of increasing agricultural production. Forest cover has fallen from an estimated 87 % in 1850 to below 4 % (IUCN, 1990). With the remaining forest and woodland cover estimated to be diminishing at a rate of 50 000 - 200 000 ha yr^{-1}, the need to increase wood production significantly in the near future is critical (EFAP, 1993). Therefore, in many parts of Ethiopia, afforestation with exotic species, in particular with *Pinus* (*P. radiata* and *P. patula*) and *Eucalyptus* (*E. globulus*, *E. camaldulensis*, *E. sligna*, *E. citriodora*, and *E. tereticornis*); has become a high priority in recent years. Eucalypt plantations alone cover more than 100 000 ha (Pohjonen and Pukkala, 1990).

Under most conditions prevailing in the Ethiopian highlands *Eucalyptus globulus* trees are more effective in converting solar energy and available water into biomass than exotic coniferous tree species (Pohjonen and Pukkala, 1990). However, to satisfy the biomass energy demand of the country, 6 % of the total utilizable land area would have to be put under tree plantations by 2014; this would entail a major shift in land use (Bojo and Cassels, 1995). Given the urgency of food security, this is not an attractive future for policy-makers. The past emphasis on eucalypt plantations underscores the importance of introducing early maturing, multiple-product tree species into agroforestry systems in the Ethiopian highlands, where trees can be combined with the production of annual crops.

Traditional agroforestry practices in Ethiopia involve planting trees in various spatial patterns to meet the wood, fuel and fodder requirements of the farmers. In recent years, however, single rows of *E. globulus* trees planted along field borders have become a dominant feature of the central highland landscape. These eucalypt boundaries are usually planted with one metre inter-row spacing and are aligned east–west or north-south direction. In this environment, eucalypt boundaries produce a harvestable tree crop within four to five years after planting. *Eucalyptus globulus* trees are unpalatable to goats, sheep and cattle (Pohjonen and Pukkala, 1990). Thus they have a distinct advantage as boundary planting in mixed farming system of the Ethiopian highlands where the protection of privately planted trees on farmland is difficult because of dry season free grazing practice.

Although solid empirical evidence is scanty, there is a perception that this practice has a negative impact on the crop, to the detriment of food security and livelihood; this is not the message the policy-makers want to hear. In a subhumid, subtropical climate, Khybri et al. (1992) recorded a 41 to 61 % reduction in wheat yield in a unilateral open alley system containing 100 trees ha^{-1} of unpruned *Eucalyptus* hybrid. Similarly, in a semiarid climate, crop yield losses as high as 47-50 % have been reported by Malik and Sharma (1990) and Onyewotu et al. (1994) due to intense competition for water between *Eucalyptus* and agricultural crops. It is inadvisable to extrapolate such data to Ethiopian highland conditions, because the spatial pattern of interactions between trees and agricultural crops in agroforestry system changes over time as the components grow in both horizontal and vertical dimensions (Ong et al., 1996). They are also highly influenced by the growth environment and management system (Verinumbe, 1987; Onyewotu et al., 1994). There is, therefore, a need to determine the extent to which crop yields are influenced by eucalypt boundaries under the actual production environment. This paper presents findings from a study aimed at evaluating the biomass production potential of eucalypt boundaries and their competitive effects on traditional small-grain cereal based cropping systems on highland Vertisols in Ethiopia.

Materials and Methods

Study area

The study was conducted in the Ginchi watershed in the central highlands of Ethiopia (2200 m a.s.l., 38^0 E, 9^0 N), 90 km southwest of Addis Ababa. The watershed has a subhumid climate with an average annual rainfall of 1200 mm, 30 % of which falls before the onset of the main cropping season. About 40-50 % of the annual rainfall is lost as runoff (Teklu et al., 1999) between July and September, as rainfall events are intense and the infiltration rates of Vertisols are low.

Vertisols and Nitisols, in that order, are the two most important soils in Ginchi watershed. The crop production subsystem used on Vertisols is monocropping, predominantly rainfed, and is characterized by a three-year cropping sequence: a grain legume, commonly chickpea (*Cicer arietinum*), in rotation with tef (*Eragrostis tef*) and durum wheat (*Triticum sp.*) (Gezahegn and Tekalign, 1995). In Ginchi watershed farmers usually apply 30 to 40 kg N ha^{-1} and 5 to 10 kg P ha^{-1} on cereals: including tef, wheat and barely (*Hordeum vulgare*). Fertilizer use on other crops is very rare.

Experimental design and analysis

Under farmers' production circumstances, the competitive effects of four, eight and twelve-year-old boundary plantings of *Eucalyptus globulus* on adjacent tef and wheat crops were evaluated in the 2000 cropping season on the Vertisols which dominate the lower part of Ginchi watershed. The second experimental variable considered within each age group was the orientation of the rows of trees: these were oriented either north–south or east–west (the two most frequent tree line orientations in the watershed). North–south tree lines divide farmlands into an east–west aspect, while east–west oriented tree lines divide farmlands into a north–south aspect with respect to the tree lines. At crop maturity, plot areas of 48 m^2 were harvested at distances of 2-4, 4-8, 8-12, 12-16, 16-20 and 20-30 m from the tree lines. These strips represent uniform yield strata (Rao and Coe, 1991). Both crops were threshed manually and grain yield determined. The experimental variables, three stand ages, four field aspects and six uniform yield strata, were arranged in that order in a split-split plot design with three replicates.

The test crops were DZ-01-354 and ET-13, the most commonly grown tef and wheat varieties respectively within the experimental area. Wheat was planted between 25 June and 5 July 2000 and harvested towards the end of October, 2000. Tef was planted one month after wheat and harvested around mid-December, 2000. Both crops were fertilized with 60 kg N ha^{-1} and 20 kg P ha^{-1} at the time of planting. According to Gezahegn and Tekalign (1995) these rates are optimal for small-grain cereal production on Ethiopian highland Vertisols. Tef followed chickpea and wheat followed tef in the rotation. For comparison, wheat and tef yields obtained on open fields (without farm boundary) were surveyed on 20 farms (10 each) managed in the same way as the farms with eucalypt boundaries. The field plots were rectangular in shape and approximately 50 m wide and 100 m long.

Root distribution beneath eight-year-old *Eucalyptus globulus* boundary stands aligned in a east-west direction was studied to a depth of 1 m by digging 1.5 m wide and 1.5 m deep profile pits. The pits were opened in April, 2000 at distances of 5, 10, 15 and 20 m at both sides of the tree lines (north and south facing plots). A metal frame of 1 x 1 m in area and divided into a 5 x 5 cm grid was hung on the profile wall. Root were separated into four diameter classes (>20, 10-20, 5-10 and 1-5 mm) with the aid of a venire calliper. Each root was counted once where it crossed the plain of observation. The root distribution at each distance and root diameter class was pooled over north and south facing plots and mean values were reported excluding the last sampling point (20 m) where no tree roots were detected.

Soil moisture dynamics along the tree–wheat and tree–tef interfaces were monitored gravimetrically at 15 day intervals throughout the growing period. For gravimetric determination of soil water content, soil samples were taken at distances of 0, 5, 10, 15 20 and 30 m from both sides of the tree line (north and south facing plots) using an Edelman auger at 10 cm increments to a depth of 1 m. The wet mass of the soil was determined immediately after sampling. The soil samples were then dried for 48 h at 105 ^oC before being reweighed and determining gravimetric soil water content. At each sampling time two undisturbed cores (100 mm in diameter and 79 mm in length) were taken from each soil depth for soil bulk density determination using thin walled stainless steel rings. These were used to convert the gravimetric soil water content values to volumetric water content for each respective soil depth.

Available soil water content was calculated as the difference between the quantity of water in the soil and that retained at permanent wilting point (-1.5 MPa). The value for the whole 1m profile was estimated using the values obtained for each 10 depth incumbent. Bulk density and soil moisture content at -1.5 MPa were determined from five cores samples taken from each sampling depth and distance from the tree rows using the core method (Peter, 1965) and pressure plate technique respectively.

The wood production potential of *Eucalyptus globulus* boundary plantings was estimated using the fresh mass equation of Pukkala and Pohjonen (1989). In this equation, the fresh mass of a stem (kg) is calculated from stand height (H) and diameter measurement at breast height (dbh) as:

$$Fresh\ mass = 0.0887 * D^{1.868} * H^{0.8423}$$

The fresh mass was then multiplied by a factor of 0.52 to obtain the dry mass of the stem as suggested by Pukkala and Pohjonen (1989). In fuelwood production the biomass of branches and leaves is also an important, thus 10 % of the stem dry mass was added to account for the branches and leaves when calculating the total dry matter production per tree based on the assumption that leaves and branches account about 10 % of the total biomass. Pukkala and Pohjonen (1989) demonstrated the validity of this assumption for *Eucalyptus globulus* plantations in the Ethiopian highlands.

Grain yield data were analyzed using the MSTAT-C statistical package (MSTAT-C, 1991). Analysis of variance and mean separation were carried out using a model for three-factor plus split-split plot design. The means were compared using Duncan's Multiple Range Test (DMRT) at 5 % probability levels.

Results

Biomass production of Eucalyptus

Eucalypt boundaries of the same age were relatively uniform in terms of tree height, diameter at breast height (dbh) and within-row spacing, presumably due to the ease of establishment and their high seedling survival rates in subsequent years (Table 1). The tree densities in this unilateral alley system ranged between 100 and 110 trees ha^{-1}. The annual wood production rates of eucalypt boundaries ranged between 168 kg ha^{-1} y^{-1} in four year old plantings to 2901 kg ha^{-1} y^{-1} at the age of twelve years. These rates were quite high and increased substantially with stand age, as would be expected

Table 1. Height, diameter at breast height, inter-row spacing and wood production of *Eucalyptus globulus* boundary plantings established on Vertisols at Ginchi, Ethiopia.

Stand age (years)	No. of farms sampled	Height (m)	Diameter (cm)	Spacing (m)	Stem volume (dm^3)	Wood production (kg ha^{-1} y^{-1})
4	6/ 24*	3.06(1.80)	5.6(1.4)	1.0(0.05)	12(4.2)	168.2 a (12.9)
8	6 /16	11.1(1.25)	15.9(3.7)	1.1(0.13)	120 (12.3)	1105.5 b (98)
12	6 /16	19.9(2.76)	25.9(5.6)	1.1(0.10)	477(44.8)	2900.6 c (123)

Values within the same column without common letters differ significantly at P< 0.05.
* number following the slash is the number of trees sampled per farm
** s.d. shown in brackets

Soil moisture use

Rainfall in 2000 was not markedly different from the long-term pattern. Across tree-wheat interface, the stored soil moisture within the upper 1 m soil profile was increased with increasing distance from the tree rows (Figure 1). For example, the stored soil moisture at a distance of 5 m from the tree was two to three times higher than the stored soil moisture within the tree rows throughout the growing period. Similarly stored soil moisture at 10 m distance from the tree row was higher than stored soil moisture at 5 m distance and the differences were more conspicuous at the beginning than towards the end of the growing season. This may suggest that at early crop establishment stages competition for water between the tree and wheat is likely to occur close to the tree rows. However, beyond 10 m distance the stored soil moisture gradient across tree-wheat interface was not apparent, probably due to lack of extensive horizontal root spread deep into adjacent cropped area, particularly in the upper soil horizons (Table 2). As a result substantial quantities of available water along the tree–crop interface remained in the upper 1m depth when wheat was harvested in October. Similar seasonal soil moisture dynamics were observed along tree-tef interface (data not presented).

Root distribution of eucalypt boundaries

After eight years, fine roots (< 10 mm diameter) accounting for more than 95 % of the total root mass per unit area mostly extend less than 10 m into the adjacent crop area (Table 2). The greatest proportion of eucalyptus roots in cropped areas were in the 60-100 cm horizon and consisted mainly of root fibres with a diameter in the 1-5 mm class, rootlets in the 5-10 mm class, and a few roots in

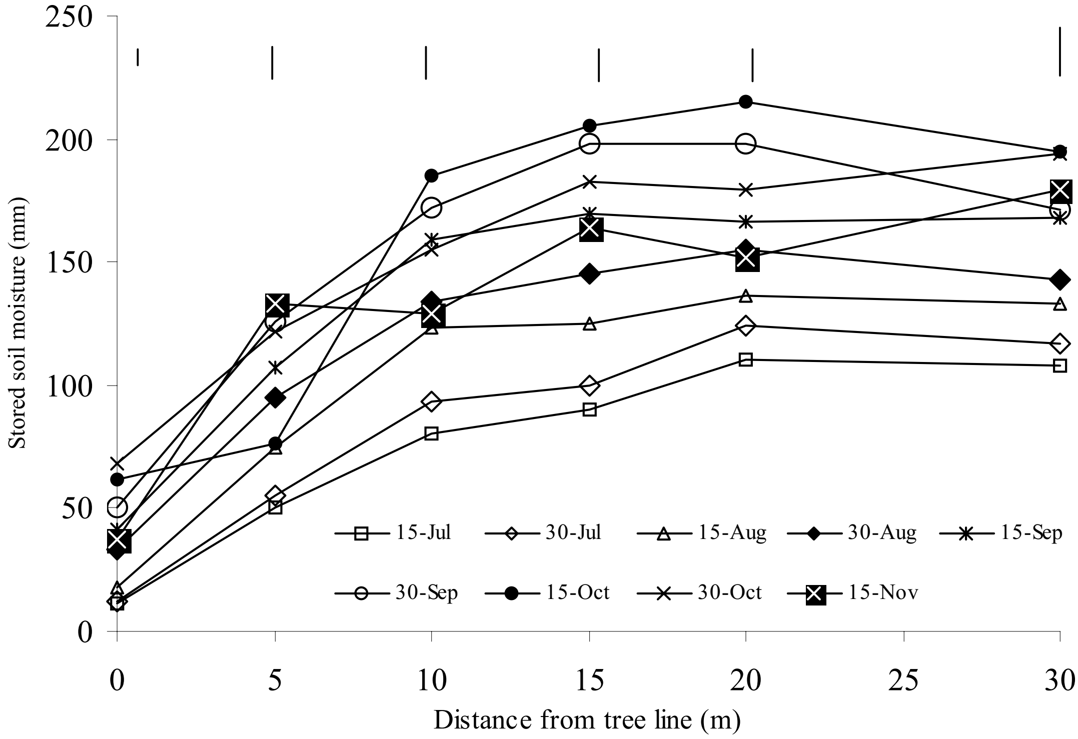

Figure 1. Available soil moisture in the top 1 m of wheat fields during the 2000 growing season as a function of the distance from eucalypt boundaries in Ginchi, Ethiopia. Bars at the top represent significant difference ($P \leq 0.05$) between different sampling dates.

Table 2. Root number (m^{-2}) for different root diameter classes (a = > 20 mm; b = 10-20 mm; c = 5-10 mm and d = 1-5 mm) beneath *Eucalyptus* boundary plantings as a function of distance from tree line and soil depth at Ginchi, Ethiopia.

Soil depth (cm)	Distance from tree line											
	5 m				10 m				15 m			
	a	b	c	d	a	b	c	d	a	b	c	D
0-10	0	0	0	0	0	0	0	0	0	0	0	0
10-20	0	0	0	0	0	0	0	0	0	0	0	0
20-40	0	3	3	1	0	2	0	0	0	0	0	0
40-60	3	34	35	22	4	13	47	30	1	0	0	0
60-100	7	54	87	120	1	65	33	142	0	3	0	3
Sub total (m^{-2})	10	88	132	123	5	78	80	173	1	3	0	3
Total number of roots, all diameters and depths (m^{-2})			**353**				**336**				**7**	

the 10-20 mm classes. The roots within the first 60 cm soil depth accounted for 28 % of the total root mass. The proportion of roots in the 1-5 mm and in 5-10 mm diameter class did not change markedly over the first 10 m distance from the tree rows. In contrast, the proportion of roots in the 10-20 mm diameter class, which was 17 % at a distance of 5 m, accounted for only 5 % and 2 % of the total root mass at 10 m and 15 m distance, respectively.

Effects of trees on wheat production

Wheat grain yield in open fields ranged between 1250 to 1800 kg ha^{-1} with mean of 1775 kg ha^{-1}. Crop yields were substantially reduced near the tree lines relative to mean grain yield on the open field (Table 4). Stand age, field aspect, distance from the tree line and interactions between these factors significantly influenced wheat yield at the tree-wheat interface (Table 3). A significant interaction between stand age and distance from the tree line (Table 3) indicated that the competitive ability of eucalypt boundaries as measured in terms of crop yield losses at the tree crop interface increased with stand age (Table 4).

The significant interaction between distance and aspect was attributed to small differences in the intensity and duration of shadow cast by the boundary stands, which was obviously higher on east-west facing plots than on north-south facing plots. Likewise the existence of a significant interaction between stand age and field aspect suggests that the shadow cast by taller eight and twelve-year-old stands extended further than that cast by four-year-old stands (Table 4).

The grain yields obtained with eight- and twelve-year-old boundary stands were similar (1339 versus 1362 kg ha^{-1}) and significantly lower ($P \leq 0.05$) than the yield (1485 kg ha^{-1}) obtained with four-year-old stands (Table 3). In four-year-old stands the reduction yield associated with distance from the tree row was significant ($P \leq 0.05$) within the first 8 m (Tables 3 and 4).

Yield was reduced on average by 48 % and 27 % within 2 to 4 m and 4 to 8 m zones respectively relative to the mean grain yield obtained in the open field (Table 4). With the two older stands, however, the significant reduction in yield ($P \leq 0.05$) associated with distance from the tree row extended over the first 12 m, with average yield losses being 62 %, 45 % and 19 % in the 2-4, 4-8 m and 8-12 m strips respectively (Tables 3 and 4).

Within the first 12 m, the mean grain yield on north-south facing plots was significantly higher ($P \leq 0.05$) than that obtained on east-west facing plots (Tables 3 and 4), probably because east-west facing plots were shaded more than north-south facing plots as the tree trunks and crowns cast dappled shade early in the morning on the west-facing plots and late in the evening on the east-facing plots. The shade effect, as deduced from distance, stand age, field aspect and their first and second order interactions, probably did not extend beyond 12 m (Table 4). Over this distance, the grain yield advantage of north-south facing plots over east-west facing plots ranged between 10 and 30 %, depending on stand age.

Effects of trees on tef production

In the open field, the grain yield of tef ranged between 800 and 1250 kg ha^{-1}, with a mean of 1130 kg ha^{-1}. The effect of trees on the yield of tef was similar to that on wheat. In the case of tef, the significant reduction in yield ($P \leq 0.05$) adjacent to four years old eucalyptus boundaries extended over the first 8 m from the tree lines (Tables 3 and 4). With the two older stand ages, however, this distance was extended over the first 12 m. The average decline in grain yield in four-year-old *Eucalyptus* stands relative to that obtained in the open field was 52 % and 23 % respectively within 2 to 4 m strip and 4 to 8 m zones. With the other two older stands, however, yield losses within the 2-4, 4-8 and 8-12 m strips ranged between 61-93 %, 28-74 % and 10-50 % respectively (Table 4). Within the distance of the first 12 m from the tree row the average grain yield advantage of north-south facing plots over east-west facing plots ranged from 15 % with four-year-old stands to 34 % in older stands.

Economic impact of eucalypt boundaries

Traditionally, farmers distinguish various assortments of tree parts and wood products on the basis of their selling price. In this study, the price used to estimate returns from eucalypt boundaries was based on average fuelwood price in Ginchi local market during 2000-2001 while the average seed price of the respective crops during the same period was used to estimate the cost incurred due to crop yield losses. In wheat-tree system, tree age had little influences on the cost incurred due to wheat yield loss while the corresponding income from the tree component slightly increased with increasing tree age (Figure 2). In contrast, in tef-tree system, the cost incurred due to tef yield loss in the last two older stands was higher than that incurred in four year old stands and hence the corresponding net benefit declines slightly with stand age in tef-tree system as compared to wheat-tree system. This may suggest that with stands older than four years planting wheat as buffer strip between tef and tree rows may help to increase the net befit derived from tef-tree system.

Table 3. Grain yield of tef and wheat as a function of stand age, field aspect and distance from eucalypt boundary plantings on Vertisols at Ginchi, Ethiopia.

Aspect	Distance (m)	Boundary stand age (years)							
		Tef (kg ha^{-1})				Wheat (kg ha^{-1})			
		4	8	12	Mean	4	8	12	Mean
North	02-04	635p-r	488 r-v	337s-w	487f	1114 p-s	937p-u	824 s-t	959i
	04-08	1061b-j	878 j-o	624 p-r	654e	1347 l-o	1215j-o	1031n-s	1197h-g
	08-12	1126a-h	1125a-h	941h-m	1065c-d	1646 c-i	1635a-f	1488 e-i	1590d-e
	12-16	1167a-h	1142a-g	1236a-b	1182a	1651 b-i	1633a-f	1802a-d	1695b-d
	16-20	1270a	1068b-j	1070b-g	1136a-c	1707a-h	1718a-e	1802a-d	1756a-b
	20-30	1080a-h	1157a-f	1164a-f	1134a-c	1693a-h	1762a-d	1843a-b	1762a-b
South	02-04	803k-l	404 s-v	319 t-w	509f	1165 o-r	810s-v	559w-x	845i-j
	04-08	955g-l	767l-p	615 m-r	779e	1285 l-p	1123l-q	975o-t	1128h
	08-12	1079a-h	1011e-j	975 f-k	1022a	1563 h-k	1692a-e	1434 f-j	1563e
	12-16	1126a-e	1227a-c	1155a-f	1169a-b	1765 a-h	1735a-e	1588b-g	1696b-d
	16-20	1183a-h	1156a-f	1133a-h	1157a-c	1669a-i	1699a-e	1828a-c	1732a
	20-30	1117a-h	1038c-j	1138a-g	1098a-d	1851a-b	1790a-d	1858 a	1833a
East	02-04	500q-t	147 w-z	62 z	237g	628 y-z	489xy	477x-y	531k
	04-08	750m-p	301u-x	352 s-v	468f	1174 n-r	781t-w	865r-u	940i
	08-12	1154a-f	682p-q	685o-q	841e	1613a-g	1374g-k	1267i-n	1418f
	12-16	1090a-h	1216a-d	1247a-b	1184a	1740a-e	1437f-j	1708a-e	1628c-e
	16-20	1156a-f	1089a-h	1190a-e	1145a-c	1733a-e	1740a-e	1778a-d	1751a-b
	20-30	1124a-h	1147a-g	1197a-e	1156a-c	1710a-e	1679a-f	1757a-d	1715a-c
West	02-04	385s-v	117 x-z	84 y-z	195g	720 u-w	289y	597 v-x	536k
	04-08	887i-n	281v-x	264 v-y	478f	1088m-r	464xy	907q-u	820j
	08-12	1147a-g	733n-p	514 q-s	798e	1636 a-f	1005o-t	1105m-q	1249g
	12-16	1099a-h	1086a-h	1033d-j	1073b-d	1823a-c	1605a-g	1710a-e	1712b-c
	16-20	1129a-h	1165a-f	1182a-e	1159a-c	1752a-d	1761a-d	1702a-e	1738a-c
	20-30	1131a-h	1107a-h	1143a-g	1128a-c	1578c-h	1761a-d	1756a-d	1698b-d
Stand age		**1008a**	**855b**	**819b**		**1485a**	**1339b**	**1362b**	

For each crop type, the main, sub and sub-sub factors and their first, second and third order interaction means followed by the same letter(s) were not significant at (P≤0.05).

Table 4. Percent grain yield reduction as a function of stand age, field aspect and distance from the eucalypt boundaries on Vertisols at Ginchi, Ethiopia.

Distance (m)	Stand age (years) 4 N/S*	4 E/W	8 N/S	8 E/W	12 N/S	12 E/W
			Tef			
2-4	41b	62 a	61 b	80 a	73 b	93 a
4-8	17 d	29 c	28 c	61 b	48 c	74 b
8-12	10 de	5 e	10 d	26 c	19 d	50 c
12-16	7 de	2 e	2 d	4 d	8 de	9 de
16-20	3 e	1 e	1 d	1 d	4 e	4 e
20-30	0 e	0 e	0 d	1 d	0 e	0 e
Mean	13 a	16 b	17 a	28 b	25 a	38 b
Loss (ha^{-1})	**4.4**	**4.8**	**9.5**	**20.5**	**10.0**	**26**
			Wheat			
2-4	34 b	61a	47 b	72 a	55 b	73 a
4-8	21 c	33 b	31 c	55 b	44 c	51 b
8-12	4 d	7 d	7 de	21 c	19 d	28 e
12-16	3 d	2 d	7 de	17 de	3 e	3 e
16-20	1 d	0 d	3 e	4 e	1 e	1 e
20-30	0 d	0 d	0 e	0 e	0 e	0 e
Mean	10 a	17 b	15 a	28 b	20 a	26 b
Loss (ha^{-1})	**4.5**	**4.9**	**4.9**	**10.0**	**5.6**	**7.8**

For each crop type, values within the same stand age followed by the same letter(s) are not significantly different at ($P \leq 0.05$). For each crop type, mean values within the same stand age followed by the same letter are not significantly different at ($P \leq 0.05$).
*N/S= North and south facing plots, E/W= East and west facing plots.

Discussion

In the current study, the mean annual wood production rate of eucalypt boundaries ranged from 168.2 to 2900 kg ha^{-1} y^{-1} (Table 1). These were two to three times higher than the maximum wood production rates reported by Pukkala and Pohjonen (1989) for *Eucalyptus globulus* woodlot plantations in the Ethiopian highlands. Enhanced wood production from eucalypt boundaries can be attributed to low competition for growth resources (light, water and nutrients) from neighbouring trees and good management of the eucalypt boundaries, particularly during seedling establishment, when tree growth is more sensitive to weed competition (FAO, 1985). In addition, they may have had access to nutrients applied to associated crops as their fine roots extended 10 m laterally into adjacent cropped area (Table 2).

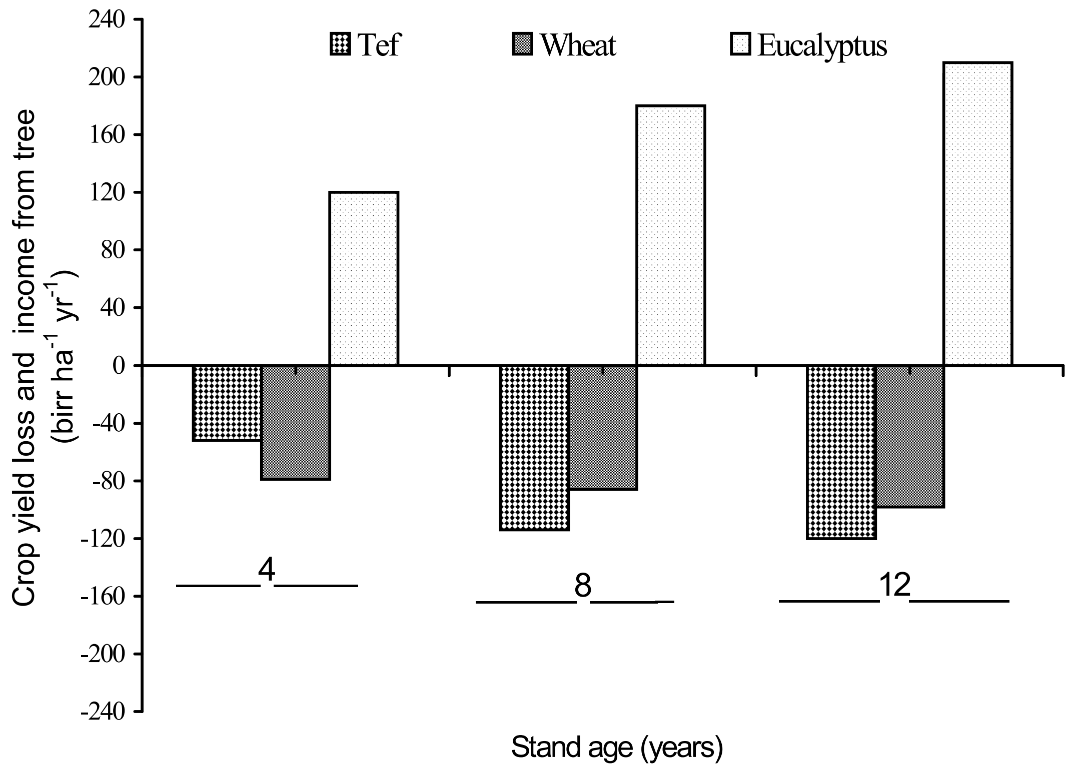

Figure 2. Crop yield losses incurred due to eucalypt boundaries versus additional income generated through the sales of wood and wood products at Ginchi, Ethiopia.
(1 US \$ = 8 Ethiopian birr in 2000)

Contrary to the practice in woodlots, farmers who grow eucalypt boundaries on their farmland commonly apply farmyard manure and mulch individual trees with tef/wheat straw towards the end of the rainy season, usually after a shallow cultivation. Most farmers believe that mulch is effective in delaying soil cracking and conserving soil moisture, while the manure and in situ decomposed plant residues are seen as an important source of nutrients for young *Eucalyptus* trees. Given the strong swelling and shrinking properties of Vertisols, water loss would be considerable once the cracks develop during tree growth under receding moisture conditions. Moreover, cracking might rupture active roots and hence reduce the utilization of available water within the rooting depth.

With Ethiopia's remaining forest and woodland cover estimated to be diminishing at a rate of 50 000-200 000 ha y^{-1}, the need to increase wood production significantly in the near future is critical (EFAP, 1993). The establishment of woodlots and plantations to satisfy demand for forest products has long been advocated as a strategy for relieving pressure on indigenous forest and woodland. This present study has shown that, although more time-intensive than woodlots, the planting of *Eucalyptus globulus* along field boundaries has great potential to satisfy the ever-increasing demands for timber and wood products without inducing a major shift in land use. This has advantages for land-constrained smallholder farmers who cannot otherwise allocate land for plantations.

If the current per capita fuelwood consumption, estimated at 0.75 ton y^{-1} (EFAP 1993), remains constant, eight-year-old eucalypt boundaries planted on one hectare of land (100-110 trees) can produce a biomass that could meet 50 % of the biomass energy requirement of a rural household of five people for eight years. At the age of twelve years they would satisfy about 75 % of the annual biomass energy requirement of the household for twelve years. Thus, eight to twelve-year-old boundary stands have the potential to replace 50 to 75 % of the dung fuel which currently accounts for 81 % of total household energy consumption per annum, releasing it to use as fertilizer.

In the Ethiopian highland Vertisol environment, the integration of eucalypt boundaries into the agricultural system may offer considerable potential for exploiting off-season rainfall, which accounts for more than 30 % of the annual rainfall. In addition, the reduction in runoff resulting from increased soil moisture abstraction during the rainy season would increase the proportion of the annual rainfall used for transpiration and hence used for productivity and CO_2 sequestration by the agricultural system.

However, the tree component affects the yield of adjacent agricultural crops by altering the availability of growth resources such as light, water and possibly soil nutrients. Competition for water between eucalypt boundaries and the annual crops may occur close to the tree lines, particularly during early crop establishment stages. The soil moisture gradient that one would expect to occur at 10 m distance was not detected, probably because of the confounding effect of periodic soil moisture recharge (by rain) throughout the growing season. Thus beyond 5 m distance, competition for water between eucalypt boundaries and the crops may have little impact on crop yield in years with normal seasonal rainfall distribution. However, in drought years, the area of tree-crop water competition across the tree-crop interface could potentially extend over the entire distance explored by the fine roots of eucalypt boundaries (10 m). The probability of drought in the study area is estimated as two years out of ten. Although light levels were not measured, it was observed that shaded areas were usually exposed to sunflecks rather than being shaded uniformly. In under story crop, the main source of radiation is diffuse radiation (Ong et al., 1996) which has previously been intercepted and transmitted, perhaps several times by the foliage of the *Eucalyptus* canopy. This process is known to deplete a significant amount of photosynthetically active light before it reaches the understorey crops (Ong et al., 1996).

Trees with a large horizontal spread of roots in the topsoil intensify competition with adjoining crops for nutrients and water (Van Noordwijk et al., 1996). The effective lateral range of root competition observed in the current study occurred over a shorter distance than that found for *Eucalyptus* by Zohar (1985) and Onyewotu et al. (1994), who reported 20 m lateral root spread of tree roots in irrigated cotton and rainfed millet systems respectively. Presumably the deep and wide cracks which commonly occur on Vertisols as a result of seasonal wetting and drying cycles restricted the lateral proliferation of tree roots in the present study, particularly in the upper horizons. The difference in surface cracks orientation across tree crop interface and adjacent cropped area is striking. Surface cracks along a tree–crop interface occur parallel to the tree rows while in adjacent cropped area they occur hexagonal pattern. This affirms the results of Eswaran and Cook (1988) who speculated that the orientation and pattern of surface cracks development in Vertisols influenced by moisture extraction pattern. In the current study, soil moisture extraction, as deduced from stored soil moisture measurement along tree-crop interface, was high closer to the tree rows than in the adjacent cropped area. These parallel-oriented cracks are about 50 cm deep and may act as natural root trench in the upper 50 cm soil depth. This intern result in a stratified root system whereby the roots of annual crops occupy the upper soil horizons while the tree roots are predominantly located in deeper horizons (Table 2). This is particularly important for annual species which otherwise are at disadvantage relative to trees, which have an established root system, particularly during the early part of the growing season.

Where the productivity of wheat and tef were influenced by the presence of trees, crop yields reduced by 25-75 %, which is equivalent to a yield loss of 4.5-26 % per hectare. Close to the tree line, the C3 wheat crop exhibited a significantly higher yield than the C4 tef crop, reflecting the superior adaptation of C3 crops to sub-optimal light conditions near the tree lines (Stirling et al., 1990). In a subhumid subtropical climate, Khybri et al. (1992) recorded reduction in wheat yield of 41 to 61 % in a unilateral open alley system containing 100 trees ha^{-1} of unpruned *Eucalyptus* hybrid. Similarly, in the semi-arid tropics, crop yield losses of up to 50 % over the first 18 m from the tree line were reported by Onyewotu et al. (1994) as a result of intense competition for water between *Eucalyptus* tree and associated crops. In the current study, yield reductions of similar magnitude occurred over a shorter distance (8 m), particularly on north-south facing plots. Probably in our case, competition for water during the critical crop growth stages (flowering and grain filling) when crops are more sensitive to moisture stress was less intense than in a semi-arid environment. Furthermore, the stratified root systems of the trees relative to the annual crop spices might have contributed to modest yield reduction we observed.

Conclusions

Eucalypt boundaries can produce large volumes of timber and wood products within a short time without requiring a major shift in land use. This has advantages for land-constrained smallholder farmers who cannot spare land for block plantations. The greater availability of wood may reduce the demand for dung and crop residues as fuel sources, and thus may contribute to improved soil management on croplands. Increased soil moisture abstraction along the tree–crop interface increases the proportion of rainfall used for transpiration, which would otherwise be lost as runoff, with the associated risk of soil erosion. In addition, by providing substitutes for forest products, eucalypt boundary plantations can help to preserve woodland and biodiversity.

The main way in which eucalypt boundaries affect the yields of adjoining agricultural crops is by modifying soil moisture conditions. In financial terms, the wood production adequately compensates for reductions in crop yield and may generate additional income. The present study suggests that eucalypt boundaries may help to raise farm income and stabilize the livelihood of resource-poor farmers by allowing households to practice intensive forest farming along the farm boundaries. In this context, its adaptability and fast growth makes *Eucalyptus globulus* the first choice tree species for the Ethiopian highlands.

However, care has to be taken in implementing this strategy as *E. globulus* may have allelopathic effects (Lisanework and Michelsen, 1993), deplete soil nutrients rapidly (Michelsen et al., 1993) and presumably deplete ground water reserves, which may have far-reaching long-term implications for sustainable land use. Further research should therefore be done to assess the possible allelopathic effect and extent to which soil fertility is influenced by eucalypt boundaries, as well as the rate of soil moisture depletion in the deeper soil layers during the off-season and over the growth cycle of the trees.

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Chapter 8

Eucalyptus-wheat interaction on Ethiopian Nitosols

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Agroforestry System (Accepted)

Abstract

Over the past few years a single row of Eucalyptus globulus trees planted along the borders of cropland has come to dominate central highland agroforestry practices. Although evidence is scanty, there is a perception that this practice adversely affects crop productivity. An on-farm trial was therefore conducted at Ginchi to determine the biomass production potential of eucalypt boundaries and their effect on the productivity of the adjacent wheat crop (Triticum aestivum) on highland Nitosols. Three rotation cycles of four years each, two stand ages within each rotation, four field aspects and six yield strata perpendicular to the tree-crop interface were arranged in a split-split plot design with three replications. The annual wood production rate, which was 345 kg ha-1 y-1 to 903 kg ha-1 y-1 with two-and four-year old stands in the first cycle, was increased more than two fold in the subsequent two rotation cycles. With these productivities, eucalypt boundaries on a hectare of land in the second and third cycle would satisfy about 70 % of the annual biomass energy requirement of a rural household with a family size of five for four consecutive years. However, adjacent wheat yields were substantially reduced because of the combined effects of water, light and nutrient competition. In the last two rotation cycles, significant yield depressions occurred over the first 16 m from the line of trees as opposed to only the first 8 m in the first cycle. The yield drop was 4.5 to 8.1 %, and 8.1 to 10.4 % in the first and last two rotation cycles, respectively. Nevertheless, the benefit accrued from the tree component adequately compensated for this reduction in wheat yield and generated additional income. The implications of these results are discussed in the context of the suitability of the practice in the region and its role in relieving the increasing pressure on indigenous forest and woodland.

Key words: *Eucalyptus globulus,* agroforestry, tree–crop interface, wheat

Introduction

Eucalyptus trees are widely grown in the East African highlands as exotics to meet the ever-increasing demand for fuelwood and other wood products. In Ethiopia alone, Eucalyptus globulus plantations cover more than 100 000 ha (Pohjonen & Pukkala, 1990). Under most of the conditions prevailing in the Ethiopian highlands, eucalypts convert energy and available water into biomass more efficiently compared with exotic coniferous tree species (Pohjonen & Pukkala, 1990). However, to satisfy the biomass energy demand of the country, 6 % of the total utilizable land area would have to be under tree plantations by 2014; this would entail a major shift in land use (Bojo & Cassells, 1995). Hence, introducing short-maturing multiple-product tree species that can be combined with annual crops may be of considerable importance in addressing the current biomass energy crisis in Ethiopia.

Traditional agroforestry practices in Ethiopia involve planting trees in various spatial patterns to meet the wood, fuel and fodder requirements of the farmers. In recent years, however, a single row of Eucalyptus globulus trees planted along the borders of croplands has come to dominate the central highland landscape. Eucalyptus globulus trees, unpalatable to cattle, sheep and goats (Pohjonen & Pkkula, 1990), have a distinct advantage as a boundary planting in the Ethiopian highlands where the protection of privately-planted trees on farmland is difficult because of dry season free grazing practices. Trees are usually planted one metre apart in line and are aligned in an east-west or north-south direction. The former orientation (80 %) is predominant on bottomlands. In this environment, eucalypt boundaries produce harvestable trees within four to five years of planting.

Although evidence is scanty, there is a perception that this practice adversely affects crop productivity. In a sub-humid, subtropical climate, Khybri et al. (1992) recorded a 41-61 % wheat yield reduction in a unilateral open alley system with 100 trees ha-1 of unpruned Eucalyptus hybrid. Similarly, with Eucalyptus in a semi-arid region, Malik & Sharma (1990) reported a wheat yield reduction of 47 % in the most active zone of competition. It is inadvisable to extrapolate such data to Ethiopian highland conditions, because the interaction effects between the tree and agricultural crops are affected by the crops' spatial configuration (Ong et al., 1996) and are highly influenced by growth environment and management systems (Verinumbe, 1987; Sanginga & Swift, 1992; Onyewotu et al., 1994).

There is, therefore, a need to determine the extent to which crop yields are influenced by eucalypt boundaries in the current production environment of Ethiopia. This paper presents the results of a study aimed at evaluating the biomass production potential of eucalypt boundaries and their competitive effects on wheat (Triticum aestivum), as a function of rotation, stand age and aspect, under farmers' production circumstances on highland Nitosols in Ethiopia.

Materials and Methods

The study area

The study was conducted in the Ginchi watershed in the central highlands of Ethiopia (2200 m a.s.l., 38oE and 90N), 90 km southwest of Addis Ababa. As is the case with most of the Ethiopian highlands, population pressure has substantially changed the land use/cover. In the last forty years, the area under annual crops has increased from 34 % to 61 %, while areas under pasture and woodland have shrunk by more than half (JVP, 1995). The watershed has a sub-humid climate with an average annual rainfall of 1200 mm, 30 % of which falls outside the main cropping season (Figure 1) and under the traditional small cereal-based cropping system, 40-50 % of the seasonal rainfall is lost as runoff with considerable risk of soil erosion (Teklu et al., 1999). For these reasons, effective rainfall for crop production is therefore appreciably lower than the annual amounts.

Pellic Vertisols and Nitosols, in that order, are the two most important soils in the watershed. On both soils, the cropping system is characterized by a three-year cropping sequence: a grain legume followed by two years of small-grain cereal production. The average farm size per household is about 2.5 ha, 0.5 ha of which is used to carry the livestock during the wet season (June to September) or to produce hay to supplement the dry season feed. Fallow land accounts for less than 1 % of the total land holdings on both soil types.

Livestock is herded on communal pasture, private grazing lands or kept in sheds, depending on the season. During the dry season (February to early June) animals are traditionally allowed to roam freely on private land. Wthin this system, animal manure is dried for use as cooking fuel, thereby precluding its use as organic fertiliser.

Experimental design and analysis

On the Nitosols, which dominate the upper part of Ginchi watershed, eucalypt boundaries at three different rotation cycles (first, second and third) were identified based on stand uniformity. 'Second' means second generation, i.e., trees that have grown after coppicing the originally planted trees.

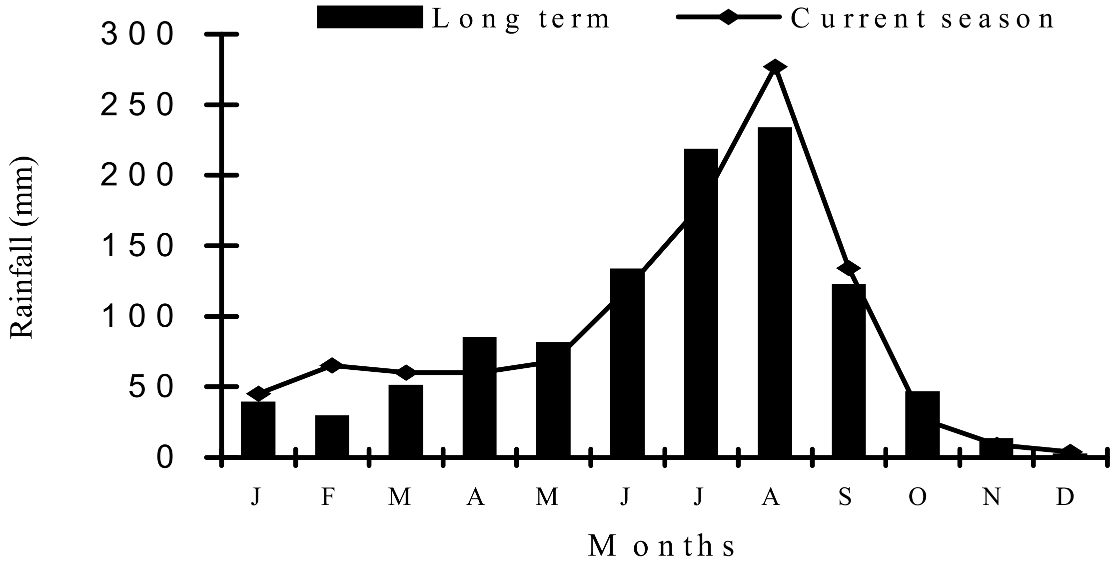

Figure 1. Rainfall distribution during the 2000/2001 growing season compared with long- term (1995-2001) mean rainfall data for Ginchi, Ethiopia.

'Third' means grown after a second coppicing. Within each rotation cycle, two stand ages (two and four years) were selected from line of trees oriented either north-south or east-west. North-south-oriented lines of trees divide the farmlands into east-west aspects while the east-west- oriented lines of trees divide the farmlands into north-south aspects.

The test crop was ET-13, a commonly grown bread wheat variety. Wheat plots were fertilized with 40 kg N ha-1 and 10 kg P ha-1 at time of planting. According to the National Fertilizer and Inputs Unit (1991), these rates are considered optimal for wheat production on Ethiopian highland Nitosols. The wheat crop followed faba beans. Crop yield data were taken from 2-4 m, 4-8 m, 8-12 m, 12-16 m, 16-20 and 20-30 m strips which represent uniform yield strata (Rao & Coe, 1991) perpendicular to the tree-crop interface. At crop maturity, 48 m2 were harvested from each strip. After threshing, the grain yield was measured and adjusted to 12% moisture content.

Root distribution was studied by excavating roots down to 1 m depth by digging profile pits 1.5 m wide and 1.5 m deep. The pits were opened at both sides of eight-year-old Eucalyptus globulus stands (second cycle at an age of four years) aligned in the east-west direction at distances of 5, 10, 15 and 20 m from the tree line.

Wood production potential of Eucalyptus globulus boundary plantings was estimated from stand height and diameter (at breast height) measurements using the fresh mass equation of Pukkala & Pohjonen (1989), which was then multiplied by a factor of 0.52 to obtain the dry mass of the stem as suggested by Pukkala & Pohjonen (1989). In fuel wood production the mass of branches and leaves are also important characteristics. Thus, 10 % of the stem dry mass was added to account for the branches and leaves in calculating the total dry matter production per tree.

At intervals of 15 days throughout the growing period, soil moisture dynamics across the tree-wheat interface were monitored gravimetrically at 10 cm depth intervals over the top 1 m rooting depth. These measurements were made at both sides of the tree line at distances of 0, 5, 10, 15, 20 and 30 m from the tree line in three replications. The stands were four years old in their second rotation cycle and aligned in the east-west direction, as for the root distribution quantification.

Available soil water for plant use was calculated as the difference between the amount of water in the top 1 m soil and that retained at permanent wilting point (-1.5 MPa). The soil moisture at -1.5 MP was determined by the pressure plate technique on five core samples (100 mm in diameter and 79-mm long) taken from each point where gravimetric soil moisture measurements were made using thin walled steel rings. Bulk density values were determined simultaneously on the same core samples using the core method (Peter, 1965).

Crop yield data were analyzed using the MSTAT-C statistical package (MSTAT-C, 1991). Data were analyzed using a model for four-factor plus split-split plot design. Rotation cycle constituted the main factor, the sub-factor was stand age, and factorial combinations of field aspect and distance representing the uniform yield strata were assigned to sub-sub-plots. Multiple range subprograms within the MSTAT-C package were used to differentiate treatment effects and interaction means.

Results and discussion

The effect of eucalypt boundaries on wheat yield

All treatment variables and their first-and second-degree interactions significantly influenced crop yield across the tree-crop interface (Table 1). Wheat yields across the tree-crop interface were significantly depressed over a considerable distance in comparison with wheat yields in the open field (Table 3). Nevertheless, the tree influence was not large enough to induce significant yield differences across the tree-crop interface beyond a distance of 8 m and 16 m from the tree line in the first and the last two rotation cycles, respectively (Table 2). The mean crop yield obtained with the second and third rotations (964 vs. 982 kg ha-1) were of the same magnitude as, and significantly lower than the crop yield (1292 kg ha-1) obtained in the first rotation (Table 2).

Table 1. Analysis of variance for grain yield of wheat planted adjacent to eucalypt boundaries on Nitosols at Ginchi, Ethiopia.

Source of variation	Degree of freedom	Mean square values
Rotation cycle (R)	2	22,606,228*
Residual	4	4,666
Stand age within the rotation (S)	1	348,566*
R x S	2	187,923*
Residuals	6	7,403
Field Aspect (A)	1	919,503*
R x A	2	4,342
S x A	1	789
R x S x A	2	12,772
Distance from the tree line (D)	5	8,733,790*
R x D	10	252,199*
S x D	5	84,316*
R x S x D	10	45,325*
A x D	5	94,865*
R x A x D	10	48,396*
S x A x D	5	4,172
R x S x A x D	10	4,272
Residuals	132	5,800

* statistically significant at $P \leq 0.001$

Table 2. Grain yield (kg ha^{-1}) of wheat as a function of rotation cycle (R), stand ages (S), field aspect (A) and distance (D) from the eucalypt boundaries on Nitosols at Ginchi, Ethiopia.

Stand age (years)	Distance (m)	Rotation cycle and field aspect*						Interaction effects***			
		First rotation		Second rotation		Third rotation		R x A x D			
		NS [a]	EW [a]	NS	**EW**	NS	EW	NS	EW	A x D	S x D
2	02-04	1107^{C}	666^{e}	300^{i}	158^{j}	260^{i}	158^{j}	556^{g}	327^{h}	495^{g}	441^{g}
	04-08	1307^{b}	1157^{c}	583^{g}	350^{i}	477^{f}	354^{gh}	789^{e}	620^{f}	717^{f}	705^{e}
	08-12	1547^{a}	1521^{a}	1006^{d}	746^{f}	1147^{c}	707^{e}	1233^{c}	991^{d}	1117^{d}	1113^{c}
	12-16	1513^{a}	1524^{a}	1370^{b}	1150^{c}	1394^{b}	1134^{c}	1426^{b}	1269^{b}	1415^{b}	1348^{b}
	16-20	1561^{a}	1568^{a}	1563^{a}	1486^{a}	1544^{a}	1555^{a}	1556^{a}	1536^{a}	1558^{a}	1547^{a}
	20-30	1529^{a}	1567^{a}	1531^{a}	1527^{a}	1581^{a}	1574^{a}	1547^{a}	1556^{a}	1551^{a}	1552^{a}
4	02-04	752^{e}	355^{g}	282^{i}	174^{j}	267^{hi}	208^{ij}	434^{I}	264^{j}	286^{h}	340^{h}
	04-08	941^{d}	553^{f}	484^{h}	298^{i}	511^{f}	365^{g}	645^{f}	605^{h}	513^{g}	526^{f}
	08-12	1184^{c}	1007^{c}	833^{e}	655^{g}	937^{d}	669^{e}	1001^{d}	810^{e}	901^{e}	906^{d}
	12-16	1515^{a}	1521^{a}	1383^{b}	1104^{c}	1317^{b}	1162^{c}	1405^{c}	1262^{c}	1266^{c}	132^{b}
	16-20	1588^{a}	1560^{a}	1545^{a}	1520^{a}	1549^{a}	1545^{a}	1561^{a}	1541^{a}	1533^{a}	1545^{a}
	20-30	1544^{a}	1570^{a}	1566^{a}	1553^{a}	1556^{a}	1606^{a}	1564^{a}	1576^{a}	1566^{a}	1566^{a}
		2	4	2	4	2	4				
Stand age**		1341^{A}	1184^{B}	981^{B}	954^{B}	991^{B}	975^{B}				
Rotation cycle**		1281^{A}		964^{B}		982^{B}					

[*] Values within the same rotation cycle followed by the same letter are not significantly different ($P \leq 0.05$)

[**] Values within the same row followed by the same letter are not significantly different ($P \leq 0.05$)

[***] Mean values within the same factor interactions followed by the same letter are not significant ($P \leq 0.05$)

[a] NS and EW represent the pooled yield data on north and south, and east and west aspects, respectively

Table 3. Grain yield reduction (%) as a function of rotation cycle, stand age, field aspect and distance from eucalypt boundaries on Nitosols at Ginchi, Ethiopia.

Distance (m)	Rotation cycle and stand age (years)											
	First rotation				Second rotation				Third rotation			
	2		4		2		4		2		4	
	NS[a]	EW[a]	NS	EW	NS	EW	NS	EW	NS	EW	NS	EW
02-04	29	57	51	77	80	89	82	89	83	89	82	86
04-08	16	27	40	64	63	77	69	80	69	77	76	76
08-12	0	2	24	35	35	52	46	57	26	54	39	57
12-16	0	0	2	2	12	26	11	29	10	27	15	25
16-20	0	0	0	0	0	4	0	2	0	0	0	0
20-30	0	0	0	0	0	0	0	0	0	0	0	0
Loss ha^{-1}	4.7	4.5	8.1	7.7	9.7	10.0	8.8	0	8.1	10.3	10.0	10.4

[a] NS and EW represent the pooled yield data on north-south and east-west aspects, respectively

In Figure 3, crop yield data as measured along the six uniform yield strata expressed as percent of yield in the open field (1556 kg ha-1), were plotted against distance from the tree line. Because in the last two rotations, the effects of stand age and rotation were not significant, the yield in the respective strata was averaged over rotation and stand age. In this way, each data point came from the mean of 24 independent measurements.

In the first rotation, as data for the two stands were plotted separately every point represents a mean of 12 independent yield measurements. The relationship between crop yield and distance from the tree line was curvilinear in the first rotation cycle and linear in the second and third rotation cycles. In both cases, the functions explained about 98 % of the yield variability across the tree-crop interface.

Biomass production of eucalypt boundaries

Eucalypt boundaries in the same rotation cycle were relatively uniform in terms of tree height, diameter and inter-row spacing (Table 4). The annual wood production rates of two-year-old stands were 345 kg ha-1 y-1, 923 kg ha-1 y-1 and 765 kg ha-1 y-1 in the first, second and third rotation cycles, respectively. At the age of four years, the annual wood production rate, which was only 903 kg ha-1 y-1 in the first cycle, increased by two fold in the second and third rotations (Table 4). This high wood production rate in the second and third rotations was attributed to increased stand density rather than increased growth rate of individual trees (Table 4).

In the second and third rotation cycles, farmers tend to maintain as many sprouting stems as possible per stump until the age of two years. Thereafter, they thin these down to two to three stems per stump. The number of these sprouting stems ranged from 4 to 8 with a mean of 5 and 4 in the second and third rotation cycles respectively (Table 4). Although the intention of the thinning practice is to reduce competition between actively growing young shoots, it is also as a good source of fuelwood for the farmers who grow eucalypt boundaries on their farmland. The stems remaining after thinning are allowed to grow for two more years before they are ready for the final harvest. Thus the stem density harvested at the end of the third and second rotation cycles, respectively, was two and three times higher than the stand density harvested in the first rotation cycle.

Table 4. Mean tree height, diameter at breast height, number of stems per stump and wood production of *Eucalyptus globulus* boundary plantings at different stand ages and rotation cycles on Nitosols at Ginchi, Ethiopia.

Rotation Cycle	Stand age (years)	No farms sampled	Height (m)	Diameter (cm)	No. stems per stump	Stem volume (dm^3)	Wood production (kg ha^{-1} y^{-1})
First	2	12 (10)*	2.90 ± 0.08	5.0 ± 0.27	-	11	345
	4	12 (10)	6.80 ± 0.06	12.5 ± 0.27	-	60	903
Second	2	12 (20)	3.92 ± 0.02		5.0	8	923
	4	12 (20)	7.9 ± 0.02	4.8 ± 0.16	2.0	58	1760
Third	2	12(20)	3.09 ± 0.01	13.0 ± 0.29	4.0	6	765
	4	12(20)	6.98 ± 0.01		2.0	52	1841
				4.2 ± 0.12			
				11.0 ± 0.15			

*the number in brackets is the number of trees sampled per farm. The number behind the ± sign is the standard error.

Root distribution of eucalypt boundaries

After eight years, fine roots (< 10 mm diameter) accounting for more than 80 % of the total root mass per unit area mostly extend less than 20 m into the adjacent crop area (Table 5). The greatest proportion of eucalyptus roots in cropped areas were in the 0-60 cm horizon and consisted mainly of root fibres with a diameter in the 1-5 mm class, rootlets in the 5-10 mm class, and a few roots in the 10-20 mm classes. Total root number at a distance of 10 m, 15 m and 20 m declined by 66 %, 70 % and 98 %, respectively, compared with the total root number at distance of 5 m form the tree line. Nevertheless, the proportion of roots in the 1-5 mm and 5-10-mm diameter class did not change markedly with distance from the tree line. The fine roots in the 1-5 mm and 5-10 mm diameter class accounted for 50- 63 % and 29- 33 % of the total root number at each sampling point, respectively. In contrast, the proportion of roots in the 10-20 mm diameter class, which was 17 % at a distance of 5 m, accounted for only 5 % and 2 % of the total root mass at 10 m and 15 m distance, respectively.

Soil moisture use

The rainfall in the 2000/2001 cropping season was not markedly different from the long-term rainfall pattern (Figure 1). The seasonal soil moisture balance showed that Eucalyptus roots within the tree rows are capable of removing soil water close to the -1.5 MPa level. Nevertheless, in spite of the extensive lateral root spread, throughout the growing period this moisture extraction pattern did not in many cases extend as far as 10, m and in no case as far as 15 m, into the adjacent crop (Figure 2). The soil moisture beyond a distance of 5 m was two to three times higher than the soil moisture content encountered within the tree rows. As a result, substantial quantities of soil moisture along the tree-crop interface remained in the upper 1 m of the soil when wheat was harvested in October.

Table 5. Root number (m-2) in relation to distance from the line of Eucalyptus globulus and soil depth for four diameter classes: a = > 20 mm; b = 10-20 mm; c = 5-10 mm; d = 1-5 mm) on Nitosols at Ginchi, Ethiopia.

Depth (cm)	Distance from the line of trees 5m				10m				15m				20m			
	a	b	c	d	a	b	c	d	a	b	c	d	a	b	c	d
0-10	0	0	0	32	0	0	0	38	0	0	0	22	0	0	0	0
10-20	0	0	15	62	0	0	25	33	0	0	5	12	0	0	5	2
20-40	0	1	37	105	0	4	17	0	0	1	32	68	0	0	0	5
40-60	7	21	92	61	3	3	12	21	0	1	9	0	0	0	0	0
60-100	3	62	3	0	13	2	0	0	3	2	3	0	0	0	0	0
0-100	10	85	147	260	16	9	54	90	3	4	49	92	0	0	5	7
All diameters	**502**				**169**				**148**				**12**			

Economic impact of boundary plantings

Economic impacts of eucalyptus boundary planting for smallholder farming can be viewed from various angles. It is, however, a short-term outcome that is of primary importance to resource-poor farmers who can tolerate only limited risk and rely heavily on crops for survival. Thus our analysis was based on the effects on the crop component as compared with production from a sole wheat cropping system. In the highland Nitosols environment, the benefits from eucalypt boundaries and trade-offs in crop yield start at the beginning of the fourth year and onwards. Records of farms in the study revealed that the income from the sole wheat crop production system (grain + straw) averaged $ US 300 ha-1 y-1 in contrast to $ US 283, 273 and 270 ha-1 y-1 from wheat in the agroforestry system in the first, second and third rotation cycles, respectively. When the entire above-ground biomass is harvested as farmers normally do in the highland Nitosols, 18 kg nitrogen, 6 kg phosphorus and 12 kg potassium in the first cycle and 37 kg nitrogen, 13 kg phosphorus and 27 kg potassium in each subsequent rotation cycle were removed preferentially across the tree-crop interface. If these nutrients are replenished from inorganic fertilizer sources, they cost about $ US 1.5 and 2.5 ha -1 y-1 in the first and in the last two rotation cycles, respectively.

On the other hand, eucalyptus wood and wood products can make a significant contribution to the economics of the system and to the diversity of farm production. In cases where fuel is scarce, such as in Ginchi, the tree has value as fuel. Traditionally, farmers distinguish between the various parts of the tree because these products have different values. In this study, the price used in estimating the returns was derived from the average value of a tree by aggregating the price prevailing in the market for different tree ages. With this assumption, the income from the tree component was estimated at US$ 19, 46 and 52 ha-1 y-1 in first, the second and third rotation cycles, respectively. Thus across all rotation cycles the additional income generated from the tree component of the agroforestry system was higher than the total cost incurred because of crop yield loss and the nutrients used to produce wood and wood products (Figure 4). Along with a slight increase in crop yield loss and nutrients fixed in eucalypt biomass, the net benefits from the trees increased more than ten fold in the second and third rotation cycles, compared with what it was in the first cycle.

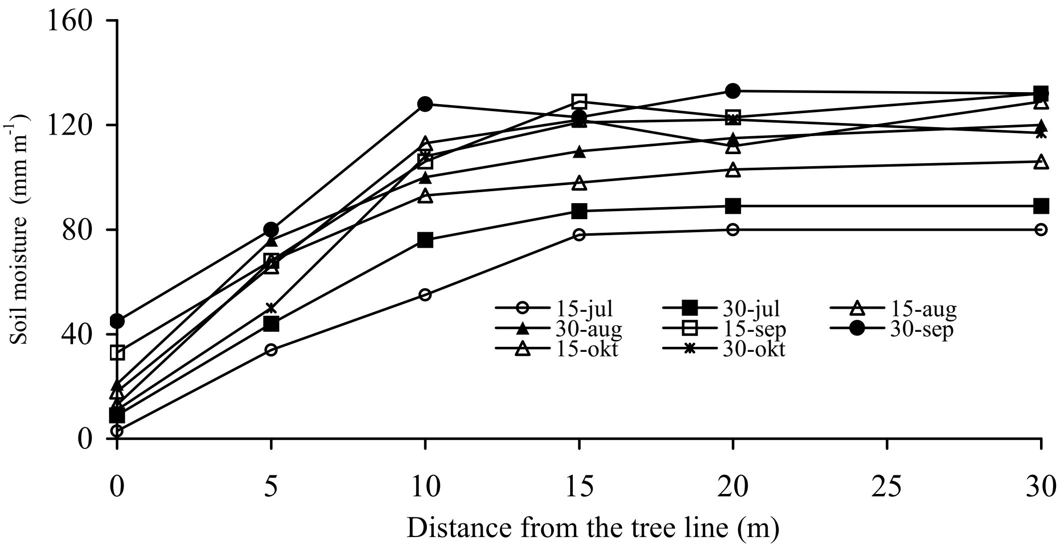

Figure 2. Available soil moisture in the top 1 m of wheat fields as a function of the distance from eucalypt boundaries in Ginchi, Ethiopia.

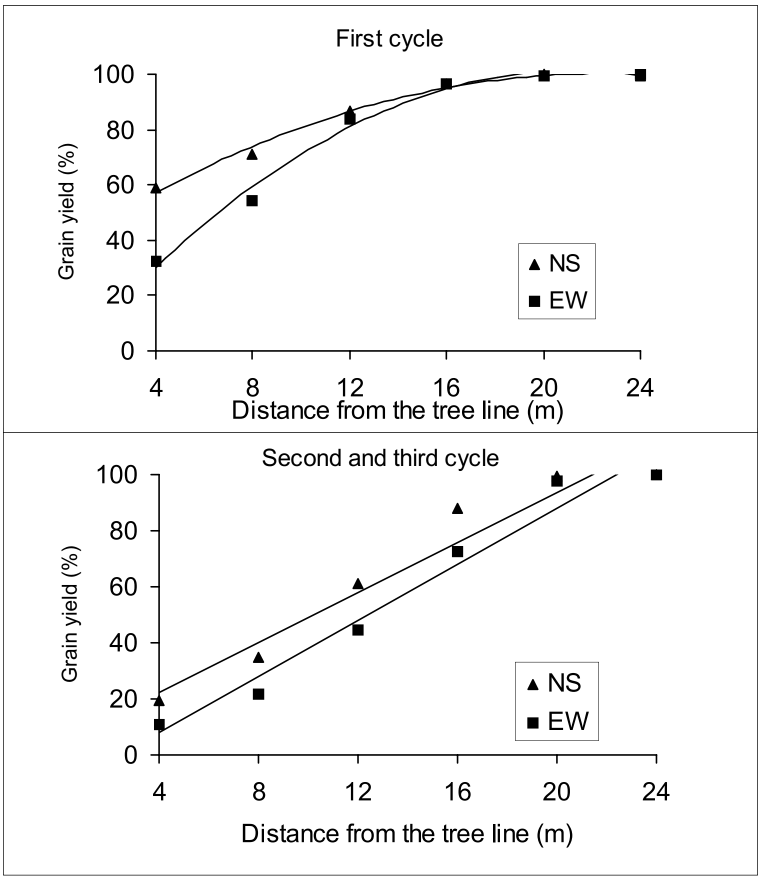

Figure 3. Wheat yield across the tree-crop interface expressed as a percentage of wheat yield in the open field on highland Nitosols at Ginchi, Ethiopia. (NS = north-south facing plots, EW = east-west facing plots).

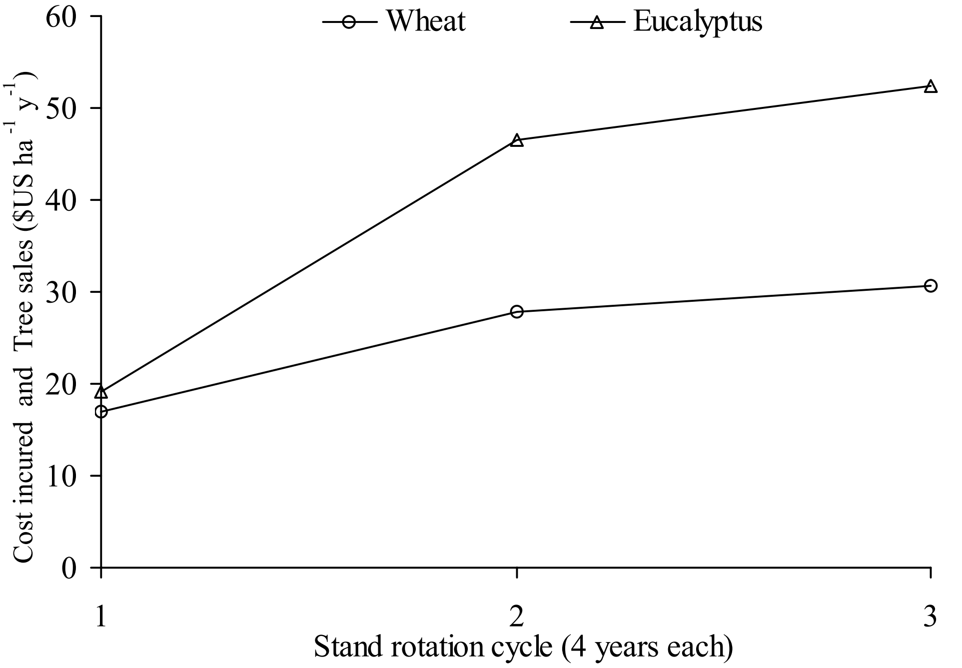

Figure 4. Cost incurred due to crop yield loss and soil nutrient extraction versus additional income generated through the sale of wood and wood products from eucalypt boundaries at Ginchi, Ethiopia.

Discussion of results

In the present study, the greatest proportion of eucalypt fine roots occurred in the 0-60 cm horizon. Their symmetrical distribution with respect to the mid-point of the soil profile facilitates the ability of Eucalyptus roots to take up water and nutrients. This is an important aspect of the detrimental tree-crop interaction of eucalypt boundaries, where the roots of both components are distributed within the same soil volume and hence compete for the same resources. In contrast, roots in the 10-20 mm and > 20 mm diameter classes were few in number and their distribution was skewed to the bottom horizons. This is probably because of the low plasticity of thicker roots to respond to favourable soil volumes, as pointed out by Eissentat (1992), or in response to repeated cultivation at shallow depth.

Fast-growing tree species such as Eucalyptus globulus deplete soil nutrient reserves particularly when grown in short rotations. However, if the leaf fraction was re turned back to the system, the differential nutrient depletion rate across the tree-crop interface can be reduced considerably. With few exceptions the leaf fraction of eucalyptus trees, although it accounts for less than 5-10 % of the total biomass, contains more than 50 % of the biomass store of nutrients (Holgen & Svensson, 1990). In addition, in the Ethiopian highlands, fuelwood production would displace huge amounts of dung fuel in favour of its higher value as fertilizer and part of this could be applied preferentially across the tree-crop interface to complement the nutrient recycling through leaf additions.

When young, eucalyptus trees are not as competitive as even the most common fast-growing multipurpose tree species (Jama et al., 1998). In the long term, the main concerns are, therefore, competition for water and possible allelopathic effects (Lisanework & Michele, 1993), particularly when mulches are used for soil improvements. As allelopathic effects are transient process and only limited to freshly decomposing leaf materials (Reversat, 1999), application of well-decomposed eucalypt leaves rather than fresh leaf mulch may be necessary for safe nutrient recycling. In addition, well-decomposed leaf material can be applied at the time of crop planting in contrast to fresh leaf mulch, which requires a sufficiently long period of time with a favourable environment for decomposition between application and crop planting. Because of a high C:N ratio, eucalyptus leaf mulches decompose slowly and nutrient immobilization phase are known to persist for several months after their application (Sanginga & Swift, 1992).

It seems probable that although the trees supplemented deep subsoil water with water from nearer the soil surface, most of the transpiration by eucalypt boundaries concerns water drawn from below the crop's rooting zone. Hence competition for water occurs close to the tree line, particularly during early crop establishment stages. However, later in the season when the crops are at sensitive growth stages, stored soil moisture can buffer the short dry spells that can occur between two rainfall events. The soil moisture gradient that one would expect to occur at a distance of 10 m and beyond was not detected, because of the confounding effect of periodic soil moisture recharge (by rain) throughout the growing season. Thus beyond this distance, competition for water between eucalypt boundaries and the wheat crop may have little impact on crop yield in years with normal seasonal rainfall distribution. However, in drought years, the area of tree-crop water competition across the tree-crop interface could potentially extend over the entire distance explored by the fine roots of eucalypt boundaries (15 m). The probability of drought in the study area is estimated as two years out of ten.

The wood production rate of boundary plantings is high compared with the maximum production rate reported by Pohjonen & Pukkala (1989) for 4-year-old stands of Eucalyptus globulus woodlot plantations in the highlands. Elsewhere, crops grown in tree plantations under different soil and climatic conditions have been reported to have a beneficial effect on tree growth (Dhyani & Teipahi, 1999). In this particular study, the high wood production rates of eucalypt boundaries can be attributed to site differences, low site competition for growth resources (light, nutrients and water) and good management, particularly at early seedling establishment stage, when tree growth is more sensitive to weed competition (FAO, 1985). In addition, through their lateral roots, eucalypt boundaries may have access to plant nutrients applied to associated crops.

Contrary to the practice in woodlot plantations, farmers who grow eucalypt boundaries on their farmland commonly apply 2-3 kg farmyard manure per pit at the time of planting eucalypt boundaries. Towards the end of the rainy season they also mulch the ground under individual trees with trash and crop residues after a shallow cultivation. Most farmers believe that mulch is very effective in conserving soil moisture, while the manure and in situ decomposed plant residues are seen by farmers as an important source of nutrients for the young Eucalyptus trees.

Significant interaction between rotation cycle and stand ages (Table 1) indicated that the competitive ability of eucalypts boundaries, as measured in terms of crop yield loss along the tree-crop interface at the two stand ages were more intense in the second and third rotations than it was in the first cycle (Table 2). Similarly, significant interaction effects between rotation and distance (Table 1) revealed that the area of tree influence in which significant crop yield reductions occurred was doubled in the second and third rotations compared with the 8 m distance encountered in the first cycle (Table 2).

The significant interaction effect between distance and aspect (Table 1) was attributed to differences in the intensity and duration of shading, which is obviously higher on east-west facing plots than on north-south facing plots and declines as the distance from the tree line increases. As a result, in the last two rotation cycles the crop yields measured within the first sixteen metres from the tree lines were significantly higher on the north-south facing plots compared with yields in east-west facing plots (Table 2). On the other hand, this trend was apparent only within the first eight meters (2-4 m and 4-8 m strips) in the first cycle (Table 2). When averaged across all rotations and stands ages, crop yields in north-south facing plots were significantly higher (1138 vs. 1011 kg ha-1) than in east-west facing plots, although the yield difference was modest. The interaction effects of aspect with either rotation or stand age were not significant (Table 1), probably because the above-ground competition between the two components has a second-order importance in determining crop yield.

Because of the combined effect of light and root competition, wheat yields on 2-4 m and 4-8 m strips was declined by 29 % and 16 % on north-south and 57 % and 27 % on east-west facing plots, respectively, in two-year-old stands in the first cycle, in comparison with wheat yields in the open field (Table 3)

The relationships between wheat yield and distance from the tree line (Table 3) can be used to estimate crop yield losses due to eucalypt boundaries from distance measurements across the tree-crop interface. The shift from a curvilinear to a linear relationship in the last two rotations probably reflects the time needed for the fine roots of eucalypt boundaries to penetrate to a more favourable part of the soil profile and exploit it to become more competitive.

General discussion

Population pressure in the Ethiopian highlands has led to changes in land use/land cover with the aim of increasing agricultural production. The indigenous forest coverage was 87%, which is now reduced to below 4% (IUCN, 1990). With remaining forest and woodland cover estimated to be diminishing at a rate of 50 000 to 200 000 ha yr-1, the need to increase biomass by significant volumes in the near future is critical (EFAP, 1993). The establishment of woodlots and plantations to satisfy demand for forest produce has long been advocated as a strategy for relieving pressure on indigenous forest and woodland. In this context, Eucalyptus globulus boundary plantings, although they are a more time-intensive activity compared with woodlots plantations, have great potential to satisfy the ever-increasing demands of wood and wood products without inducing major land-use shifts. This has advantages for land-constrained smallholder farmers who cannot allocate land for block plantations.

If the current per capita biomass energy consumption, is estimated at 0.75 m3 (EFAP 1993), remains constant, Eucalyptus globulus boundary stands on a hectare of land harvested at the age of four years (first rotation) would satisfy about 35 % of the annual biomass energy consumption of rural households with a family size of five people for four consecutive years. In the second and third rotations, however, the thinned-out stands at two years of age alone can easily meet about 15 % of the annual biomass energy requirement of the household for two consecutive years. In addition, boundary stands harvested at the end of the second and third rotations each would satisfy about 55% of the annual biomass energy requirement of the household for four consecutive years. In other words, eucalyptus boundaries on a hectare of land in the second and third rotation cycles could deliver 70 % of the annual biomass requirements, replacing much dung fuel, which currently accounts for as much as 81% of total household energy consumption per annum. This shift would promote the use of dung as fertilizer. In addition, preservation of indigenous woodland and biodiversity may be achieved when substitutes for indigenous forest products are established. Approximately 95 % of the total demand for wood and woody biomass in rural Ethiopia is for fuelwood (EFAP, 1993).

On Ethiopian highland Nitosols, integration of Eucalyptus into the agricultural system may offer considerable potential for exploiting the off-season rainfall, which accounts for more than 30 % of the annual rainfall. In addition, reduction in runoff resulting from the physical barrier presented by tree component and/or increased soil moisture abstraction during the rainy season would increase the proportion of annual rainfall retained for transpiration and hence the overall productivity of the system.

However, in the eucalyptus-wheat association the yield losses incurred because of eucalypt boundaries over the two stand ages were on average 8.2 % on north-south and 8.7 % in east-west facing plots for three rotation cycles, with somewhat lower values for the first rotation (6.3) and somewhat higher values for the second and third rotations (9.5) (Table 3). Although the eucalypt stands were of similar height, and hence had a similar shading effect, in the last two rotations wheat yields over the first 8 m from the tree line declined by more than 60 % in comparison with wheat yields obtained over the same distance in the first rotation (Table 3). This, in conjugation with the lack of significant yield differences between the two stand ages except in the first rotation cycle, indicates that tree root competition was more detrimental to the yield of wheat than light competition. Since competition for water is unlikely beyond a distance of 10 m given the results discussed above, it follows that the tree component affects the yield of an adjoining wheat crop primarily by altering the availability of soil nutrients.

An extensive lateral distribution of tree roots in the subsoil, particularly in areas of high rainfall such as Ginchi, can take up nutrients that leach below the rooting depth of annual crops. In a spatial association of trees and crops, however, a large lateral spread of tree roots in the topsoil may intensify the competition with adjacent crops for nutrients and water (Van Noordwijk et al., 1996). The effective range of root competition assessed in this study is comparable to that found with Eucalyptus by Onyewotu et al. (1994) and Zohar (1985), who reported a range of 20 m for rainfed millet and irrigated cotton, respectively.

Because trees have an established root system, they have an advantage compared with the adjacent wheat crop, particularly early in the growing season. It is therefore difficult to fertilize only the wheat crop without losing some of the fertilizer to the eucalypt boundaries. Thus, a larger fertilizer application along the tree-crop interface may offset the effects of root competition to a certain extent. However, the application of fertilizer increases root concentration near the soil surface (Campbell et al., 1994) and this may result in increased root competition. Hence it may be best to apply fertilizer in small doses several times during the active growing stages of the wheat crop.

Repeated deep ploughing between trees and crops during the cropping season may further reduce the competition from superficial and re-growing tree roots. Currently, farmers leave untilled strips of two to three metres between the line of trees and the annual crop, because they believe that this is the zone of the most active competition. Zero tillage in Leucaena leucocephala hedgerow intercropping has been reported to lead to yield depression because of root competition (Ssekabembe, 1985), but 30 cm deep ploughing along the hedgerow increased the soil water content under the crop and boosted the crop yield (Korwar & Radder 1994).

Lines of trees laid out from east to west, i.e., along the sun's path, maximize the penetration of direct sunlight in north-south facing plots. Tree trunks and crowns cast dappled shade early in the morning and late in the evening on the west-and east- facing plots, respectively. The main source of radiation in shaded areas has been intercepted and transmitted, perhaps several times, by the foliage of the Eucalyptus canopy before it reaches the understorey wheat crop. This process is known to deplete the photosynthetically active light in tree shaded zones (Ong et al., 1996). In shaded zones, the grain yield advantage of north-south facing plots over east-west facing plots was as high as 41 %. Lyles et al. (1984) reported a reduction of winter wheat yield over a distance twice the height of the trees, because of the combined effect of light and root competition. Onyewotu et al. (1994) noted a 50% millet yield reduction over a distance of 18 m from the tree line. The reduction in the wheat yield in our study occurred over a shorter distance than that reported by Lyles et al. (1984), at least in the first rotation cycle. The root distribution (Table 5) showed that root competition did not extend beyond 20 m.

Conclusions

Eucalypt boundaries produce large volumes of biomass within a short time without inducing a major land-use shift. This has advantages for land-constrained smallholder farmers who cannot spare land for block plantations. The greater availability of wood may reduce the demand for dung and crop residues as fuel sources, and thus may contribute to improved soil management on croplands. In addition, by providing substitutes for indigenous forest products, eucalypt boundary plantations could help preserve indigenous woodland and biodiversity.

Eucalypt boundaries affect the yield of adjacent agricultural crops by modifying water, light and soil nutrient conditions. The root competition between the two sub-systems is intense, not only because the Eucalyptus roots colonize the same soil horizon as the wheat roots but also because of the deep lateral spread of the tree roots into the adjacent crop area. Although we consider root competition the most critical factor determining crop yield, shading extending up to 8-12 m also contributed to reduced yields.

Under the prevailing environmental conditions of Ethiopian highland Nitosols, the practice of eucalypt boundaries seems economically viable, at least over the study period considered. Farmers actually sell Eucalyptus products at any time the year, whenever they encounter a cash shortage. Thus, the practice can be considered as a smoothing mechanism to help avoid income risk and increase security. Its adaptability and fast growth usually makes Eucalyptus globulus the first tree of choice in the Ethiopian highlands.

However, E. globulus may have allelopathic effects (May & Ash, 1990; Lisanework & Michelsen, 1993) and deplete soil nutrients (Michelsen et al., 1993), which over time may have far-reaching implications for sustainable land use. Further research should therefore be done to assess the possible allelopathic effects and the extent to which long -term soil fertility is influenced by eucalypt boundaries, especially given the interest in converting land under block plantations to crop cultivation, and for the integration of Eucalyptus species into agroforestry systems.

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Chapter 9

Nutrient removal and crop productivity in a *Eucalyptus globulus* based rotational agroforestry system on seasonally waterlogged highland Vertisols of Ethiopia

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Abstract

Chickpea (*Cicer arietinum*), tef (*Eragrostis tef*) and durum wheat (*Triticum turgidum)* were grown in rotation as sole crop, or in an agroforestry system containing eucalyptus trees (*Eucalyptus globulus*). Trees were planted at 2.83 m x 2.83 m, 3.5 m x 3.5 m and 4 m x 4 m spacing, which is equivalent to 1225, 833 and 625 stems ha^{-1} in July 2000. Crop rotations were: wheat-chickpea-tef (WCT), chickpea-tef-wheat (CTW) and tef-wheat-chickpea (TWC) for 3 consecutive years commencing July 2000. The tree densities and cropping sequences were arranged in a split plot design with three replications. Crop productivity, tree biomass and total N and P removed in harvested crop and tree biomass were examined over the 3 years rotation.

After 3 years eucalyptus trees at stand densities of 1225, 833 and 625 stems ha^{-1} had produced 5, 3.6 and 2.7 Mg oven dry aboveground biomass per hectare with cumulative crop yield losses of 6 to 21 %, respectively. In the agroforestry system cropping sequence significantly influences the system's productivity. This indicates that the crop sequence affects resource use complementarity. Land equivalent ratios (LER) in the agroforestry system were significantly above unity and ranged between 1.21 to 1.69. LER values increased in the order of CTW>TWC>WCT across all three stand densities. In the three years period, sole crops removed 3 to 4 times more N and 5 to 10 times P compared with three-year-old eucalyptus stands. However, provided that the leaf fraction, which accounted for 20 % of the total tree biomass, is recycled back into the soil system the total amount of N and P removed in the agroforestry system was not significantly different from sole cropping. The mean accumulation rates in the standing tree biomass ranged between 8 to 13 kg N and 1.5 to 2.5 kg P ha^{-1} with the tree densities from 625 to 1225 stems ha^{-1} respectively. Thus, the *Eucalyptus globulus* based short (3 years) rotational agroforestry system with proper cropping sequence and tree density can increase short-term fuelwood supply without compromising crop productivity and N and P depletion in seasonally waterlogged highland Vertisols.

Key words: Ethiopia, wheat, tef, chickpea, *Eucalyptus globulus,* Vertisols, agroforestry

Introduction

Natural resource degradation in terms of soil fertility decline, soil erosion, deforestation and disturbance of the hydrological cycle through land mismanagement is testimony to the fact that current land use systems in the East African highlands are far from sustainable. In the Ethiopian highlands, land degradation has reached a point where the prevailing land use systems cannot meet food and feed targets (FAO, 1983). Smallholder farming conditions in the Ethiopian highlands will worsen further as per capita land holdings are expected to decline from 1.8 ha in 1985 to 0.7 ha in 2015 due to rapid population growth (IUCN, 1990).

As productivity of prime land declines under traditional management, vast forest and woodland areas have been converted to arable agriculture at considerable cost to the environment. Wood collection, which accounts for 95 % of the total wood consumption in rural Ethiopia, has caused a dramatic decline in live tree biomass (EFAP, 1993). Therefore, high potential and more resilient land needs intensification to sustain human needs. The present study evaluates the fuelwood production potential of *Eucalyptus globulus* in a short rotational agroforestry system on high potential but seasonally waterlogged Vertisols.

Vertisols, spread across the moderate slopes and flat areas of the highlands, potentially are productive. On the average they receive 1000 mm rainfall per annum of which 70 % occurs between June and September. Nevertheless, the effective rainfall for crop production is appreciably lower than the annual amount. During the early part of the growing season, most of the 8 million hectares of highland Vertisols are left bare as there are no crops well adapted to waterlogged conditions. As a result 40-50 % of the seasonal rainfall is lost as runoff with considerable risk of soil erosion (Teklu et al., 1999). A land management method known as broadbed and furrows (BBF) method facilitates surface drainage and permits the advance of the cropping season (Mamo et al., 1992; Tedla et al, 1992; Astatke et al., 1995; Mohamed Saleem, 1995; Jutzi and Mesfin, 1986). However, farmers have been reluctant to adopt this technology partly because the practice is not suited to the crops that the farmers wish to grow for their subsistence.

As off-farm tree resources declined, *Eucalyptus globulus* trees planted along the borders of cropland has come to dominate the highland Vertisols landscape. *Eucalyptus globulus* is unpalatable to cattle, sheep and goats (Pukkala and Pohjonen, 1989), which is a distinct advantage in mixed farming systems of the Ethiopian highlands where the protection of privately planted trees on farmland is difficult because of dry season free grazing practices. In this environment, eucalypt boundaries on a hectare of land would satisfy 50-70 % of the annual biomass energy consumption of a rural household without inducing a major land use shift (Selamyihun, 2001). Nevertheless, owing to their low stand density farmers usually tend to use a long rotation cycle (8-12 years) to maximize wood production which occurs at considerable cost to crop productivity. In this system a crop yield loss as high as 10-26 % is not uncommon for stands older than 4 years (Selamyihun, et al., 2001). Scattered eucalyptus trees grown mixed with agricultural crops with a relatively high stand density but short rotation harvest cycle may offer better protective and productive functions than the current tree line system. Short rotation trees can be harvested with reasonable wood production before they become competitive to crops. Fast growing eucalyptus trees are vivacious consumers of water, particularly when the supply is adequate (Malik and Sharma, 1990). *Eucalyptus* trees that use the seasonal excess moisture may maximise the fraction of the rainwater that is used for biomass production and mitigate soil, water and nutrients erosion problems associated with the traditional rainy season fallow practice. Identification and promotion of multi-purpose tree species that can be used for soil and water conservation on Vertisols is difficult. It is thought that the damage to the roots during the seasonal cracking of Vertisols limits the number of tree species that can grow on Vertisols. However, apart from its fast growth eucalyptus is among the few tree species that can tolerate seasonally variable conditions of Vertisols (Probert, 1987).

Fast growing tree species deplete soil nutrient reserves particularly when grown in short rotation. Hence another concern about their sustainability focuses on the question of soil nutrient depletion, particularly when whole-trees are used as firewood (Heilman, 1992). The objective of the present work is to evaluate fuel wood production potential of *Eucalyptus globulus* in a short rotational agroforestry system as alternative to the current tree line system. Specific objectives were to investigate the effect of tree stand density on tree biomass production, nutrient uptake and crop productivity.

Materials and methods

Site description

The study was conducted from 2000 to 20003 at Ginchi Research Farm located in the central highlands of Ethiopia at 38^0E and 9^0N and at an elevation of 2200 masl. The site has a subhumid climate with an average annual rainfall of 1200 mm of which 30 % occurs before the onset of the main rainy season, between February and April. Runoff, which accounts for 30-50 % of the seasonal rainfall, only occurs between July and September. Mean monthly maximum and minimum temperatures range between 26 ^{0}C and 9 ^{0}C and the annual PET is 1400 mm. The study was conducted on deep Pellic Vertisols (FAO-UNESCO, 1974). The field capacity of the profile ranged from 55 to 60 % (w/w) and saturated hydraulic conductivity is about 2.5 mm h^{-1}. The soil had medium fertility, with 0.11 % total N, 6 ppm Olsen P, and 45 ppm AmmoAC extractable K. Nitrogen and phosphorus, in that order, are the two most plant growth limiting elements in Ethiopian highland Vertisols (Mamo et al., 1992).

Experimental setting

Eucalyptus globulus, the most common tree species in the Ethiopian highlands, were raised in a nursery and transplanted as six-month-old seedlings in 20 x 30 x 60 cm pits in July 2000. Each pit was filled with 2 kg farmyard manure after being thoroughly mixed with dugout soil. Seedlings were planted at a spacing of 2.83 x 2.83 m, 3.5 x 3.5 m and 4 x 4 m, which is equivalent to stand densities of 1250, 833 and 625 trees ha^{-1}, respectively, in three replications. To maintain constant stand density through the experimental period tree seedling lost before the age of six months were replaced by the ball planting method in June 2001. Three traditional Vertisol crops, durum wheat, tef and chickpea, were grown as sole and intercrop between *E. globulus* trees for three consecutive seasons (2000/2001, 2001/2002 and 2002/2003). Plots planted with tef, chickpea and wheat in the 2000/ 20001 cropping season were followed by wheat-chickpea, tef-wheat and chickpea-tef cropping sequences in the 2001/2002 and 2002/2003 cropping seasons, respectively. The treatments were arranged in a split plot design where the four tree spacing including the control sole crop with zero tree density constitute the main plot factor while the three cropping sequences (chickpea-tef-wheat (CTW), tef-wheat-chickpea (TWC) and wheat-chickpea–tef (WCT) represent the sub plot factor. Trees were planted on 286 m^2 (20.4 x 14 m) hydrologically isolated plots with 2 % slope.

Wheat (CV kilintto) was sown each season in the first week of July on broadbed and furrow (BBF) seedbeds with a basal dose of 60 kg N and 20 kg P per hectare and harvested towards the first week of November. Tef (CV DZ-354) was sown each season around mid August on flat seedbed and received the same amount of fertilizer as wheat and harvested towards the end of November. Waterlogging sensitive chickpea (CV Maryie) was planted in the first week of September and harvested in December-February.

Measurement and sampling

Tree diameter, height were measured and tree biomass samples taken towards the end of June, in 2001, 2002 and 2003 when the trees were 1, 2, 3 years old. Tree diameter was measured at ground level when they were one year old, but at breast height (1.4 m) thereafter. The mean tree method (Pared, 1980) was used for destructive sampling as the mean basal area seems to be the best method for biomass estimation in even-aged stands of single species. The mean trees were assessed according to tree mean height, and their mean diameter calculated from each plot also taking into account the crown width. Three mean trees were harvested from the third replication in 2001 and 2002 and from the first two replications in 2003.

The mean trees were divided into five components: foliage, twig (< 6.4 mm diameter), branch (6.5-25.4 mm diameter), bark and wood from stems and branches larger than 25.4 mm (Young and Carpenter, 1976). Samples of all these parts were weighed after being oven dried at 80^0C and sub samples were taken for chemical analysis. Before the chemical analysis the samples were grinded to pass a 1 mm sieve. Phosphorus was determined by the ascorbic acid method (Wantanabe and Olsen, 1965). Total nitrogen was determined using Kjedahl digestion (Bremner and Mulvaney, 1982). The oven dry biomass and N and P stored in tree biomass were estimated from mean tree oven dry biomass and the N and P contents using Guo's method (Guo, et al., 2002). In this method the oven dry biomass of standing trees per plot is calculated as:

$$W_P = A_P \frac{\sum W_T}{\sum A_T} \quad (1)$$

where W_P is the plot biomass (OD Mg ha^{-1}), A_P is the plot basal area (m^2 ha^{-1}), W_T is the sample tree biomass (OD Mg), and A_T is the sample tree basal area (m^2)

Whereas the total nutrient accumulation in the standing trees is estimated from the nutrient accumulation in each of the tree components:

$$N_P = \sum_1^n N_i \quad (2)$$

where N_P is the plot nutrient accumulation (kg ha^{-1}), Ni is the nutrient accumulation in each tree component in each plot (kg ha^{-1}), n = 5 (the number of tree components)

When mature, crops were harvested from the first two replications and plants were separated into seed and crop residue. After weighing fresh, sub samples were dried at 80 ^{0}C to calculate DM production of each plant part. The total amount of DM and nutrients removed from the field were calculated for each crop and then summed over the rotation period for each cropping sequence.

System productivity

When the combined yield of tree and crop components exceeds that of sole crop, agroforestry systems may be described as over-yielding and demonstrating complementarity of resource use (Ong et al., 1996). Of the various approaches developed to establish whether over-yielding is occurring in agroforestry and intercropping systems, the most common is the land equivalent ratio (LER; Willey, 1985; Rao, et al., 1990, 1991). LER may be defined as the land area required under sole cropping to produce the yield achieved by intercropping, and corresponds to the sum of performance ratios for tree and crop components. To facilitate comparison among the cropping sequences marketable produces under sole and agroforestry system in the respective cropping sequence was converted into tef yield equivalents considering the prevailing market price in the year 2002-2003. Crop productivity is often assessed in terms of grain production. However, farmers in the highlands frequently attributed considerable value to crop residues as dry season animal feed thus tef yield equivalents was calculated taking into account grain and crop residue yield of the crops. Then the system's performance ratios were calculated as:

$$TYER = \frac{TEY_A}{TEY_S} \quad (3)$$

where TEYR is tef yield equivalent ratio and represents the performance ratio for agroforestry system, and TEY_A and TEY_S denotes marketable produces under agroforestry and sole cropping conditions expressed in terms of tef yield equivalents.

Statistical analysis

Crop yields and tree growth data (diameter, height, and seedling survival) were analyzed per year. Amount of N and P removed under sole and agroforestry condition, tree biomass and system production performance (LER) were analyzed at the end of the 3 year using MSTATC- C statistical package (MSTAT-C, 1991). Means were separated by the least significant difference (LSD) test when tree density, cropping sequence and their interaction effect were significant ($P<0.05$).

Results

Precipitation

In general, the conditions for *Eucalyptus globulus* seedling establishment and growth were favorable. Although the total precipitation received in the 2000 cropping season was 266 mm less than the mean annual value of 1200 mm, rainfall distribution extended into the dry season which delayed soil surface crack development and subsequent fast soil moisture loss during the early part of the dry season (November and December). In 2001 and 2002 the mean annual rainfall exceeded the annual rainfall by 231 mm and 427 mm respectively. Nevertheless, precipitation during the 2000-2002 cropping growing season (i.e. June to September) was relatively uniform across the three years (Figure 1). Except for 2001, the cropping season's rainfall peaked during July and August and leveled off during September.

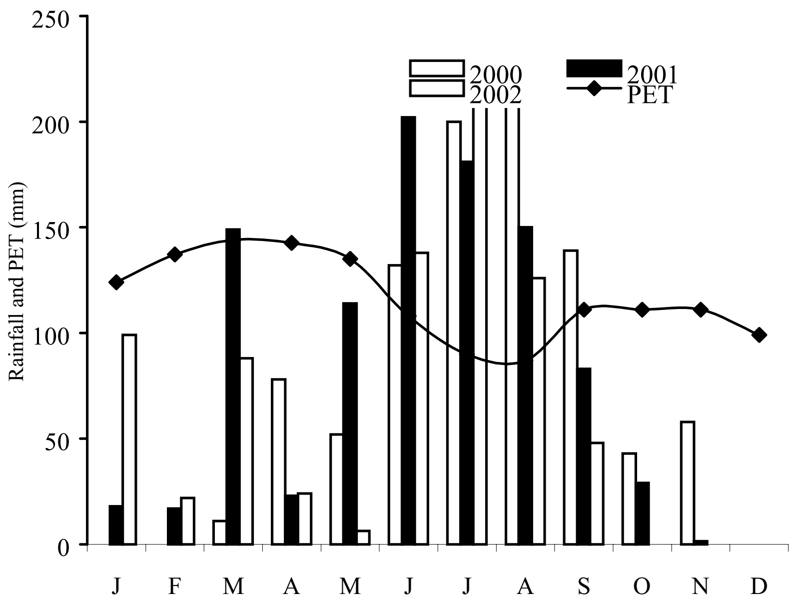

Figure 1. Annual rainfall distribution and mean PET between 2000-2003 at Ginchi, Ethiopia.

Table 1. *Eucalyptus globulus* height (m) in a short rotational agroforestry system at Ginchi, Ethiopia.

Cropping Sequence	Tree height (m) 2001			2002			2003		
	1225*	883	625	1225	883	625	1225	883	625
WCT	1.33	1.52	1.42	3.44	3.33	3.67	6.63	5.92	6.48
CTW	1.42	1.56	1.42	3.84	3.57	3.64	6.32	6.54	6.02
TWC	1,55	1.22	1.24	3.42	3.84	3.87	5.58	6.03	5.98

*tree stand ha^{-1}

Tree biomass

Seedling survival rate was excellent and exceeds 95 % through the experimental period (Data not shown). Subsequent tree growth was also good in the first year with the average tree heights in June 2001 of 1.5 m. Tree growth and survival at the start of the second growing season (2001/2002) confirm the continued health of the tree. During this period trees ranged between 3.3 to 3.8 m in height and 3 to 3.4 cm in diameter and canopy cover of 25% to 35 %. By the year 3 (June, 2003), June 2001 of 1.5 m. Tree growth and survival at the start of the second growing season (2001/2002) confirm the continued health of the tree. During this period trees ranged between 3.3 tree growth attained 4.5- 5.5 cm in diameter and 6.0 to 6.8 m in height (Table 1). Neither the tree density nor the cropping sequence significantly influenced the tree height, diameter and seedling survival.

At the end of the three years period the oven dry aboveground tree biomass (OD) was 2.7, 3.6 and 5.0 Mg ha^{-1} at tree stand density of 625, 833 and 1225 stems ha^{-1}, respectively, (Figure 2), and these differences were significant. The distribution of biomass in the various tree components increased in the order of stem wood > branches > foliage > bark. On the average the stem wood biomass accounted for 45 to 49 % of (OD) while branches and foliages contributed 25% and 16-20 % to the total (OD), respectively (Figure 2). The summery of variance analysis revealed that cropping sequence and its interactions had no significant effect on tree biomass per ha (Table 2). Stand density, however, had a significant effect on the amounts of above ground biomass.

Crop productivity

Grain yields varied significantly between crop species, stand density and stand age (Table 3). In comparison to sole cropping, chickpea yield intercropped between 1225 trees ha^{-1} declined with 44 % and 76 % in year 2 and 3, respectively. This was significantly lower than the chickpea yield intercropped between 625 and 833 trees ha^{-1}. In year 2, the yield of chickpea intercropped between the latter two stand densities was not significantly different from the sole chickpea yield. However, in year 3 yield difference between sole and intercropped chickpea was significant, indicating that competition between the two components in the agroforestry system increased with tree stand age.

In comparison to sole tef, the yield of tef intercropped between 625, 833 and 1225 trees ha^{-1} was declined by 2 % 5 % and 12 % in year 2, respectively. In the following season, tef yield intercropped between the three stand densities in same order as above, was declined by 32 %, 47 % and 52 % in comparison to the sole tef yield. In both years, grain yield differences among the three tree densities were not significant (Table 2). In year 3, grain yield differences between sole and intercropped tef were significant except at tree density of 625 trees ha^{-1}.

Table 2. Analysis of variance summary for tree biomass, N and P in aboveground tree biomass

		Biomass	Nitrogen	Phosphorus
Source of variation	df	error mean square		
Year (y)	2	31761958**	1385**	514**
Tree density (td)	2	9276654**	520**	139*
y x td	4	812988**	13*	12.1
Residuals	6	43716	3.5	6.5
Cropping sequence (cs)	2	24010	4.8	0.68
y x cs	4	5991	0.92	0.16
Td x cs	4	46546	2.5	0.11
y x cs x td	8	382775	3.1	0.76
Residuals	18	29968	3.3	2.64

**, * Statistically significant at ($P \leq 0.01$) and ($P \leq 0.05$) respectively

The grain yield differences between sole and intercropped wheat were not significant except at 1225 trees ha^{-1} in year 3.

Crop residue yields revealed a similar trend. However, the magnitude of the reduction in crop residue yield was less severe than in the grain yield (data not shown). The treatment by year interaction was significant showing that treatment effect differed from year to year. From the three crop species, chickpea was the most affected crop with regard to grain and straw yield under intercropped condition. Thus, it should only be planted during the tree establishment year and not in subsequent years in the (short) rotation.

Tef yield equivalents and land equivalent ratios (LER) (cumulative over the 3-year rotation period) varied with tree stand density and cropping sequence. LER values were higher in the tree-crop system than under sole cropping conditions and increased with increasing tree stand density (Table 4). Within the same stand density, LER values increased in the order of CTW >TWC>WCT. This suggests that the complimentarity in resource use in the tree-crop system can be optimized by a proper sequence of crop species used in the different stages during the life cycle of a specific agroforestry system. Cumulative crop yield losses in the tree-crop system (expressed as tef yield equivalent) compared to sole cropping ranged between 5 and 21 % (Table 4). However, LER values greater than unity indicate that the tree component completely compensates the incurred crop yield losses and generated additional income.

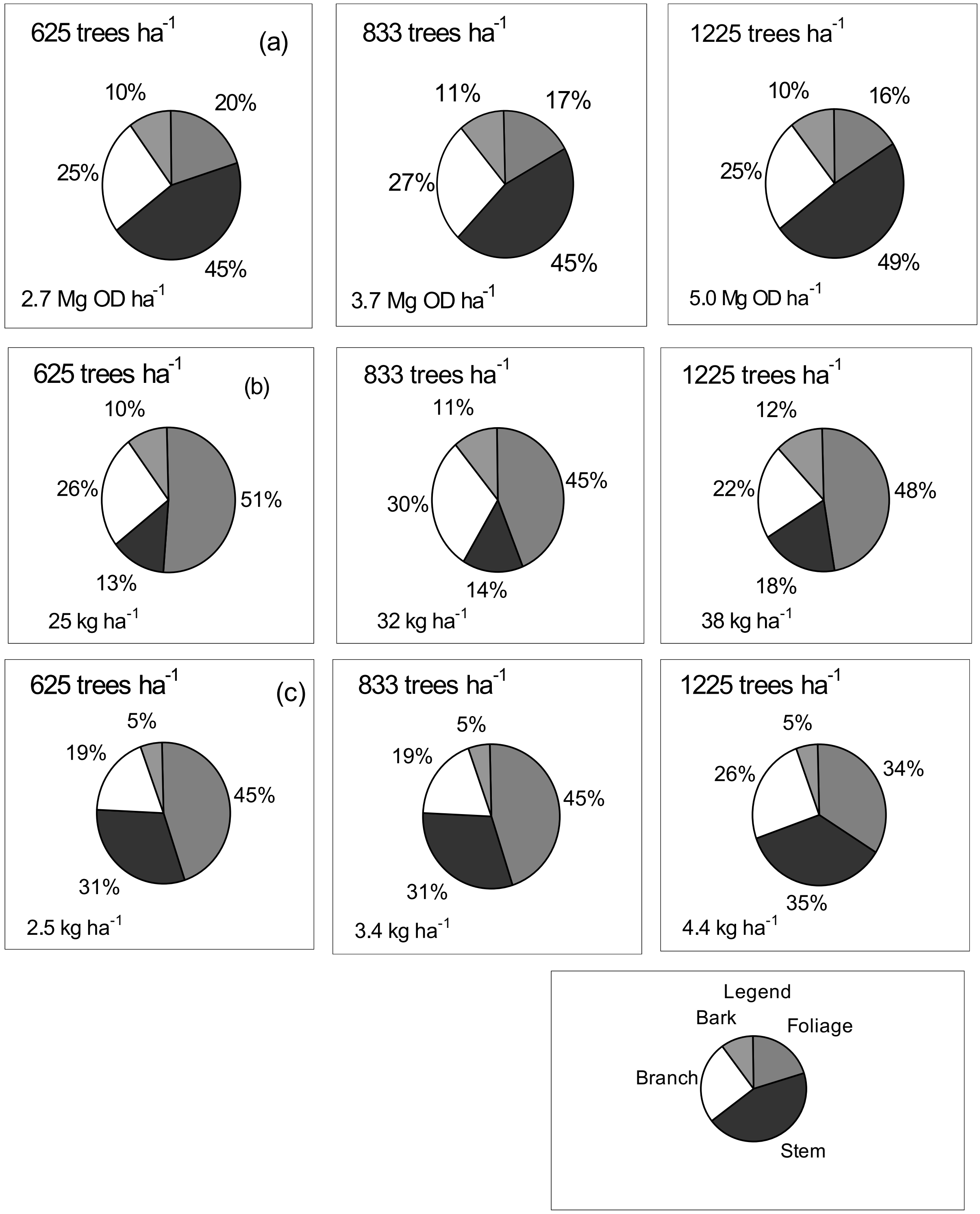

Figure 2. Biomass and nutrient distribution in the harvestable aboveground biomass components of *Eucalyptys* trees at the end of the 3 year rotation period: (a) biomass, (b) N, and (c) P (the area of each chart depicts the relative contribution of the components).

Table 3. Gain yield (kg ha^{-1}) of wheat, tef and chickpea under sole cropping and in an *E. globulus* agroforestry system at Ginchi, Ethiopia.

Stand Density (tree ha^{-1})	Wheat			Tef			Chickpea		
	2000*	2001	2002	2000	2001	2002	2000	2001	2002
0	1651a	1627a	1520a	1520a	1923a	1643a	1870a	1520a	1608a
625	1713a	1590a	1448ab	1555a	1503a	1118ab	1975a	1328a	979 b
833	1573a	1695a	1451ab	1625a	1678a	1101ba	1905a	1276a	611bc
1225	1608a	1865a	1171b	1608a	1520a	786b	1835a	856b	384c

Values in the same column without common letter differ significantly at P< 0.05.
*Year 2000, 2001 and 2002 refers to wheat yield in WCT, TWC and CTW; tef yield in TWC, CTW and WCT and chickpea yield on CTW, WCT and TWC cropping sequence, respectively.

Table 4. Tef yield equivalent and land equivalent ratios at the end of a 3 years rotational agroforestry system in Ginchi , Ethiopia

Cropping Sequence	Stand density (tree ha^{-1})	Tef yield equivalent (kg ha^{-1}y^{-1})	LER	Cumulative yield loss (%)
CTW	0	1865		
TWC	0	1572		
WCT	0	1676		
CTW	625	2225	1.31de	9.0
TWC	625	2051	1.21 e	14
WCT	625	2017	1.19 f	15
CTW	833	2526	1.49 c	6.0
TWC	833	2290	1.35 d	17
WCT	833	2229	1.31 de	17
CTW	1225	2830	1.69 a	13
TWC	1225	2729	1.61 ab	16
WCT	1225	2617	1.54 ab	21

LER values with out common letters differ significantly at P< 0.05.

Nutrient removal

At the end of 3 years rotation period total amounts of N and P removed in sole cropping and in the agroforestry system are presented in Table 5. The results show that, with some exceptions, the total amount of N removed in harvested grains was significantly higher under sole cropping conditions than in the agroforestry system. On the average sloe crops in the CTW, WCT and TWC cropping sequences removed 10-33 kg more N in harvested grain as compared with WCT and TWC cropping sequences in agroforestry system. Under sole cropping condition total amount of N removed in harvested was slightly higher in CTW than in TWC and WCT. In the agroforestry system, however, the CTW cropping sequence removed a significantly higher amount of N in harvested grain than the TWC and WCT cropping sequences. On the contrary, the differences in total amount of N removed through crop residues in the sole and agroforestry system were not significant. Similarly, the amount of P that left the system with harvested crops in the sole and agroforestry system was not significant different either.

The concentrations of N and P varied greatly between different tree parts, with foliage having the highest concentration followed by branches, stem wood and barks (Table 6). Neither the tree density nor the cropping sequences influenced the concentration of N and P in the different tree parts. The amount of N and P removed through harvesting after 3 years varied significantly with stand density (Table 2). In the three years period, 1225 trees ha^{-1} removed 10-16 kg more N than 625 trees ha^{-1} did and the difference was significant. The amount of N removed at stand densities of 625 trees ha^{-1} and 833 trees ha^{-1} was not significantly different though eucalyptus trees in the latter stand density removed a slightly higher N than the former. Similarly, the total P removed at stand densities of 833 and 1225 trees ha^{-1} was not significantly different. Significant stand density effect on total amount of P removed in harvested tree biomass was apparent only between the lowest and the highest tree density.

The amount of N and P accumulated over 3 years in the different parts of the above ground tree biomass is shown in Figure 2. Foliages accounted for 45-48 % of the total N in above ground biomass while branches and stem wood contributed 22-30 % and 13-18 %, to the total biomass store of N, respectively. Similarly, P biomass accumulation was highest in foliages, which accounted for 32 to 42 % of the total P in the above ground biomass, followed by stem wood. In a three years period sole crops removed 3 to 4 times more N and 5 to 10 times more P compared to what was removed by the three years old eucalyptus trees.

In most cases N and P removal due to eucalyptus trees together with the agricultural crops, even at the highest stand density, was not significantly different from the sole cropping condition provided that the leaf fraction of the trees is recycled back to the soil system (Table 5).

Table 6 Average total N and P concentration of various tree parts at different age in Ginchi, Ethiopia.

Tree parts	N (g N kg^{-1})			P (g P kg^{-1})		
	2001	2002	2003	2001	2002	2003
Foliage + twig	25.1	22.3	20.3	1.80	1.74	1.78
Branches	12.0	10.0	9.0	0.60	0.82	0.82
Stem wood	4.1	3.3	2.7	0.50	0.50	0.50
Bark	9.3	9.0	8.0	0.93	0.90	0.86

Table 5. Total N and P removed (cumulative over 3 years) under sole cropping and from a rotational agroforestry system at Ginchi Vertisols Ethiopia.

Cropping Sequence	Tree Density (tree ha^{-1})	N and P removed (kg ha^{-1}) by component						Total N and P removed (kg ha^{-1}) when			
		Crop N		Crop P		Tree		whole tree harvested		Tree leaf recycled	
		G	R	G	R	N	P	N	P	N	P
CTW	0	91 a	40 a	14 a	10 a			131 b	24a	131a	24a
TWC	0	82 ab	38 a	12 a	10 a			120 c	22a	120abc	22a
WCT	0	84 a	38 a	13 a	10 a			122 bc	23a	122ab	23a
CTW	625	81ab	37 a	13 a	10 a	23 b	2.39 b	141 b	23a	129a	23a
TWC	625	70 c	34 a	12 a	9 a	24 b	2.24 b	128 bc	21a	115bc	21a
WCT	625	73 bcd	32 a	11 a	8 a	26 b	2.24 b	131 b	23a	117bc	23a
CTW	833	82 ab	42 a	14 a	11 a	28 b	2.99 ab	152 a	24a	139a	23a
TWC	833	65 d	34 a	12 a	8 a	30 ab	3.19ab	129 bc	22a	115bc	22a
WCT	833	69 cd	34 a	11 a	8 a	37 a	3.23ab	140 b	22a	133a	22a
CTW	1225	68 cd	37 a	12 a	9 a	37 ab	4.44a	142 ab	23a	124a	23a
TWC	1225	57 e	33 a	11 a	8 a	39 a	4.20a	129 bc	22a	110c	23a
WCT	1225	57 e	35 a	10 a	9 a	37 a	3.96 ab	129 bc	22a	110c	22a

Values within the same column without common letters differ significantly at $P< 0.05$

G=grain, R= residue

Discussions

Tree biomass

This study demonstrates the potential of a rotational agroforestry system for intensifying food and fuelwood production on Vertisols in the Ethiopian highlands. The biomass production of scattered eucalyptus trees among agricultural crops ranged between 2.7 to 5.0 Mg ha^{-1} in the 3 years rotation cycle with a mean annual increment of 0.9 to 1.7 Mg ha^{-1} y^{-1}, respectively (Figure 2). These rates are quite high in comparison to biomass production rates of eucalypt boundaries in a similar environment; i.e. 0.14 Mg ha^{-1} y^{-1} at 4 years age and 2.9 Mg ha^{-1} y^{-1} at the age of 12 years (Selamyihun, et al., 2001). It has been reported that rotation length influences the proportion of woody biomass accumulated in the total above ground biomass (Guo, et al, 2002 and George and Varghese, 1990). The shorter the rotation, the more leaves and branches in the total aboveground biomass relative to the proportion of stem wood biomass. This may explain the low stem wood percentage (45-49 %) found in the current study (Figure 2). In fuelwood production, wood is the main product desired from the system. The reported heating value of eucalyptus branches (18.4-19.5 MJ kg^{-1}) is similar to that of its stem wood (18.4-19.5 MJ kg^{-1}) (Frederick et al., 1985; Dalisnis et al., 1996). Thus, 75-80 % of the total above ground tree biomass from harvesting eucalyptus rotational agroforestry system can be utilised as fuelwood.

Fuelwood is the most important agroforestry product on the world scale, perhaps matched in a few countries (eg India) by fodder (Young, 1987). In this regard the described eucalyptus based short rotational agroforestry system has a great potential to satisfy the ever increasing fuel wood demand in rural Ethiopia without inducing a major land use shift. In addition, by providing substitutes for indigenous forest products, the eucalyptus agroforestry system could help preserve indigenous woodland and biodiversity. Stiles et al. (1991) predicted, based on the total forest area, biomass density and per capita biomass energy requirement, that Ethiopia's indigenous woodland would be completely exhausted by year 2010.

Nutrient removal

Fast growing tree species produce a large amount of biomass within a short period of time. However, much of the concern about their sustainability focuses around soil nutrient depletion, particularly when whole-trees are removed together with harvested crops (Heilman, 1992). As expected, age had a significant effect on N and P removed in the harvested tree biomass (Table 2). The weight of most tree parts increased substantially with age and so did the N and P removed in harvested aboveground tree biomass. Significant interaction between tree density and tree age (Table 2) indicates that the total amount of N and P removed in the harvested tree biomass increases with increasing tree density. The mean annual N accumulation in eucalyptus trees ranged between 8 to 13 kg N $ha^{-1}y^{-1}$. However, if the leaf fraction, which accounts for less than 20 % of the total biomass, is recycled back into the soil system the amount of N exported in harvested tree biomass can be easily reduced by 40-45 %. Similarly, leaf recycling has a potential to cut down P removed in harvested tree biomass by 32 to 45 %. Under this situation the N and P removed in the rotational agroforestry system as proposed here, is less likely to induce significant nutrient depletion. Rather, tree N and P uptake may help in N and P conservation in the system, which would have been lost through run-off as the nutrient use efficiency of the crop plants would not be 100 %.

In the long term, the main concern is, therefore competition for water and possibly also for allelopathic effects (Lisanework & Michele, 1993), particularly when eucalyptus mulch is used for soil improvement. As allelopathic effects are transient process and only limited to freshly decomposing leaf materials (Reversat, 1999; Selamyihun, under preparation), application of well-decomposed eucalypt leaves (rather than fresh leaf) mulch may be necessary for safe nutrient recycling. In addition, well-decomposed leaf material can be applied at the time of crop planting. Fresh leaf mulch, in contrast, requires long period of time between application and crop planting with a favourable environment for decomposition. Because of the high C:N ratio, eucalyptus leaf mulch decomposes slowly and nutrient immobilization is known to persist for several months after its application (Sanginga & Swift, 1992).

Concentration of N and P varied greatly between different tree parts, with foliage having the highest concentration followed by branches, stem wood and barks (Table 6). This corresponds well with other nutrient uptake studies of eucalyptus forest plantation (Guo et al., 2002; Harrison et al., 2000). The N and P concentrations in the different tree parts in our study were within a range of values reported for three years old *Eucalyptus globulus* (Guo et al., 2002) and *Eucalyptus camaldulensis* (Harrison et al., 2000) plantations. In the CTW cropping sequence no significant treatment effect on N and P removed in the sole and the agroforestry cropping system was found except at the highest tree density. In contrast, both tree density and cropping sequence had no apparent influence on the amount of N removed in harvested crop residue (Table 5). This together with low mean annual N and P accumulation rates in eucalyptus, suggests that water competition in the later stages of crop development may be important in the WCT and TWC in crop-tree systems, particularly in the third season. Nitrogen accumulation studies on rain-fed wheat in Western Australia have shown that the most N is accumulated between tillering and stem elongation (Palta and Fillery, 1993) and moisture availability enhances N translocation to the grain (Garabet et al., 1998). In the current study, in the third season wheat intercropped between 1225 trees ha^{-1} (CTW) had a low grain N concentration and a slightly higher crop residue N concentration compared with grain and crop residue N concentration of wheat intercropped between the other two stand densities and sole wheat (data not shown). Similar mechanisms may explain the low N removal in harvested grains of tef and chickpea in the WCT and WCT cropping sequences in the studied agroforestry system.

Crop yield

Mixing trees with crops is likely to lead to a greater total resource capture due to the differing phenology and root architecture of the two components. How these resources are partitioned between tree and crop seems to determine the overall system's productivity. In the current study, tree-crop system productivity varied with stand density and sequence of crop species. The CTW cropping sequence productivity was comparable with that of the sole cropping condition. This may indicate that crops in the agroforestry system either had increased resource capture or make more efficient use of the available resources than their sole crop counterparts. From the above discussion it is clear that sole and intercropped crops in the CWT cropping sequence have the similar N and P concentration. Thus, complementarity in resource use might have been due to differences in seasonal water use.

In the CTW cropping sequence, chickpea was planted during the tree establishment season when tree water use was still low. Thus, complementarity in resource use was emanated from efficient utilization of stored soil moisture as waterlogging sensitive chickpea was planted towards the end of the rainy season. On the contrary, early-planted wheat had the benefit of frequent rainfall replenishing the water used by both components of the agroforestry system. Water use by tree-wheat is higher than by the sole crop of wheat. This implies that a larger fraction of the rain is used for the production of biomass, i.e. the rain water use efficiency (RWUE) of the agroforestry system is higher than that of the sole crop (Stroosnijder, 2003). Likewise in tef-tree system though tef was planted late in the season compared to wheat but still increased seasonal rainfall capture may explain the mode of resource use complementarity.

Despite high evaporative demand in the dry season, sole tef and chickpea grew well on stored soil moisture. In agroforestry system, however, the water used by the tree seems to induce terminal moisture stress for the crops, which may explain the low tef yield in WCT and low chickpea yields in the WCT and TWC cropping sequences. Among the three crops in the agroforestry system chickpea was the most affected crop with regard to grain and crop residue yield. Chickpea is C_3 crop and the reduced flux of photosynthetically active radiation may have little effect on assimilation (Stirling, et al., 1990) in comparison to the C_4 tef crop. Unlike tef and wheat which enjoyed substantial amount of the seasonal rainfall chickpea received 20 %, 14 % and 9% of the total seasonal rainfall (532-693 mm) in 2000, 2001 and 2003 cropping season, respectively.

In the current study, LER values of agroforestry system are significantly higher than unity. This situation occurs when there is a niche differentiation between the system components or when the green area duration is extended (Loomis and Conner, 1992), and provides evidence of complementarity. In comparison to sole cropping, cumulative yield losses (expressed as tef yield equivalent) in CTW cropping sequences in agroforestry system ranged between 6 to 13 % which is less than 5 % per year (Table 4) as opposed to yield losses of 10 to 26 % per year in eucalypt boundaries older than four years in the same environment (Selamyihun et al., 2001).

Conclusions

Eucalyptus globulus trees in a short rotational agroforestry system produce large volumes of biomass within a short period of time without inducing substantial losses in crop yield. The traditional three-year cropping sequence where a grain legume, preferably chickpea, is followed by two years of small cereals (tef and wheat) fits very well in this agroforestry system and results in a better production efficiency compared to sole crop situation. The greater availability of wood may reduce the demand for dung and crop residues as fuel sources, and thus may contribute to improved soil management on croplands. In addition, by providing substitutes for indigenous forest products, the tested eucalyptus rotational agroforestry system could help to preserve indigenous woodland and biodiversity. Nutrient depletion, particularly N and P, is less likely to affect the sustainability of the system provided that the leaf fraction of the trees which accounted for 32-45 % of the total N and P biomass nutrient store is recycled back into the soil system. The drawback of the system is it requires new seedling establishment every three years and that small sized stems are less suitable for construction purposes. However, a short-term output is of primary importance to resource poor farmers who can only tolerate limited risk and rely heavily on crops for survival. The system can be an attractive alternative to the current eucalyptus boundary planting practice.

Future research efforts need to focus on several issues. First, more research is needed to assess the high demand for water imposed by fast growing trees on the local and landscape hydrology. Second, more work is needed to diversify species especially in the highland Vertisols where farmers at present plant only *Eucalyptus globulus*. Third, more research is needed to optimize system densities for the tree component and establish the extent to which this can be adjusted without compromising crop productivity.

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Chapter 10

Soil erosion and seasonal water use in *Eucalyptus globulus* based rotational agroforestry system on Ethiopian highland Vertisols

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Abstract

During the early part of the growing season, most of the 8 million hectares of highland Vertisols in Ethiopia are left bare, as there are no crops well adapted to waterlogged conditions. It is thought that integration of fast growing trees to agricultural system may maximise the fraction of the rainwater that is used for biomass production and mitigates soil, water and nutrients erosion problems associated with the traditional rainy season fallow practices. Three crops: chickpea (*Cicer arietinum*), tef (*Eragrostis tef*) and durum wheat (*Triticum turgidum)* grown in rotation as sole crop, or in an agroforestry system containing eucalyptus trees (*Eucalyptus globulus*) were evaluated. Trees were planted at stand densities of 625, 833 and 1225 stems ha^{-1} on 20.4 x 14 m erosion plots with 2 % slope in July 2000. Crop rotations were: wheat-chickpea-tef (WCT), chickpea-tef-wheat (CTW) and tef-wheat-chickpea (TWC) for 3 consecutive years commencing July 2000. The tree densities and cropping sequences were arranged in a split plot design with three replications. Runoff, soil loss, seasonal water use and soil profile water depletion were compared over the 3 years rotation period.

Runoff and soil loss varied significantly among crop species in 2000 and among crop species and tree densities in the 2001 and 2002 cropping seasons. Under sole chickpea produced significantly lower runoff and soil loss as compared to the two cereals. The soil loss from sole wheat and tef were comparable and ranged between 12 to 26 Mg ha^{-1} y^{-1}. Over the years, average runoff from sole crops was 22 %, 16 %, 10 % of season's rainfall in wheat, tef and chickpea, respectively. In the agroforestry system the annual runoff declined to 7 to 14 % in 2001 and to less than 2.5 % in the 2002 cropping season. Similarly, soil loss in the agroforestry system reduced to 0.5 Mg ha^{-1} irrespective of crop species in 2002. The seasonal water use in the agroforestry system was significantly higher than under sole cropping and increased with increasing tree densities. The water use in the agroforestry system is linked with runoff reduction and profile moisture extraction efficiency. Sole crops exploit 1m of the soil profile whereas the tree-crop mixture used soil water down to 2.5 m. *Eucalyptus* trees capture runoff and soil, which would otherwise had been lost from sole cropping. This justifies their integration thereby compensating for the extra resource required for their growth. Water conserved due to tree intervention in agroforestry land use is utilised to meet increased evapotranspiration demand, and hence ground water recharge in appreciable quantities is unlikely, particularly in dry years.

Keywords: Ethiopia, Eucalyptus, Vertisols, highland, soil loss, runoff

Introduction

Natural resource degradation in terms of soil fertility decline, soil erosion, deforestation and disturbance of the hydrological cycle through land mismanagement are testimony that current land use systems in the East African highlands are often far from sustainable. In the Ethiopian highlands, land degradation has reached a point where the prevailing land use systems cannot meet their food and feed targets (FAO, 1983). Smallholder farmers' conditions in the Ethiopian highlands will worsen further as per capita land holdings are expected to decline from 1.8 ha in 1985 to 0. 7 in 2015 (IUCN, 1990). On the other hand, around 85 % of the 64 million Ethiopians derive livelihood directly from the land resources; and this population is currently growing at the rate of about 2.7 % per annum, requiring a food production increase of at least the same rate (Sonneveled, 2002).

As the result of the productivity decline under the traditional land management, vast forest and woodland areas have been converted to arable agriculture at considerable cost to the environment (FAO, 1986). Although application of mineral fertiliser increases yields in arable farming, mineral fertiliser alone cannot sustain crop yields in the long run. Retention of crop residues in agricultural fields plays an important role in nutrient cycling, erosion control and the maintenance of appropriate soil physical and chemical properties. However, retention of crop residues in the Ethiopian highland farming system for the purpose of recycling nutrients and an improvement of soil organic matter is unthinkable in the current status of unbalanced demand and supply of livestock fodder. It is equally unthinkable to bring dung into the farming system without having a substitute for its domestic fuel use. The important contribution of soil organic matter to sustainability lies predominantly in those circumstances where management based on fossil-fuel sources is either impossible or undesirable, which is the case in many tropical farming systems (Swift and Woomer 1993). In today's Ethiopia, the potential of the forest resources to supply fuel-wood on a sustainable yield basis is estimated to be 12.5 million $m^3 y^{-1}$ while the demand is 45 million $m^3 y^{-1}$ (EFAP 1994). In the same document the projected demand for the year 2014 is about 90 million $m^3 y^{-1}$ and the supply on a sustainable yield basis is 9 million $m^3 y^{-1}$. Therefore, high potential and more resilient land needs intensification in their use to sustain human needs both in food and wood.

Over the recent years, *Eucalyptus globulus* trees planted along the borders of cropland has come to dominate the highland Vertisols landscape. These border plantings are expanding at faster rate. Although environmental concerns are frequently taken into concern at policy and planning level, they are rarely quantified and evaluated from the sustainable resource utilisation point of view relevant to Ethiopian climatic, soil and land-use conditions. In his resent study Selamyihun et al, (2001; 2003) evaluated *Eucalyptus globulus* boundary plantings and short rotational *Eucalyptus globulus* based agroforestry system on seasonally waterlogged highland Vertisols. The results of these studies showed that both systems produce a large biomass within a short period of time without inducing a major land use shift. In addition, for the smallholder farmer the role of *Eucalyptus globulus* boundary planting is far reaching when it is evaluated in its potential contribution to the farming system through substitution of dung fuel. Each kg of N, P and K in stem wood would bring back 20 kg N, 26 kg P and 10 kg K to the farming system in the form of organic fertilizer. Currently dung fuel counts for 81 % of the total annual biomass fuel consumption in rural households.

Cannell et al. (1996) argued that agroforestry may increase productivity provided the trees capture resources which are underutilised by crops. On the average, highland Vertisols receive 1000 mm rainfall per annum of which 70 % occurs between June and September. Nevertheless, the effective rainfall for crop production is appreciably lower than these annual amounts. During the early part of the growing season, most of the 8 million hectares of highland Vertisols are left bare, as there are no crops well adapted to waterlogged conditions. As a result 30-50 % of the seasonal rainfall is lost as runoff with considerable risk of soil erosion (Teklu et al., 1999). The scope for improving water use is, therefore, considerable in the seasonally waterlogged highland Vertisols crop production environment. However, scattered acacia trees among agricultural crops, a common feature of the traditional agroforestry system in the Ethiopian highlands shed their leaves during much of the cropping season and have virtually no ecological interaction. Identification and promotion of multi-purpose tree species that can be used for soil and water conservation on

Vertisols is difficult. It is thought that the damage to the roots during the seasonal cracking of Vertisols limits the number of tree species that can grow on Vertisols. Apart from its fast growth eucalyptus is among the few tree species that can tolerate seasonally variable conditions of Vertisols (Probert et al., 1987).

Fast growing eucalyptus trees are vivacious consumers of water, particularly when the supply is adequate (Malik and Sharma, 1990). *Eucalyptus* trees that use the seasonal excess moisture may maximise the fraction of the rainwater that is used for biomass production and mitigate soil, water and nutrients erosion problems associated with the traditional rainy season fallow practices. However, the high demand for water imposed by fast growing exotic trees may be a cause for concern to farmers in many tropical countries, particularly in semi-arid regions. For instance, Calder et al. (1997) reported that eucalyptus plantations in southern India not only used all of the rainfall which infiltrated into the soil but also extracted a further 100 mm of water for each 1 m depth of soil penetrated by the root. It is therefore essential to consider the implications of increased water use in eucalyptus based agroforestry system for medium and long-term water budgets. Particularly with respect to the source of water used by trees, the rate of water depletion below the crop rooting zone, and prospects for deep recharge during periods of high rainfall.

This research was designed to complement previous studies and come up with facts and figures that indicate water resource utilisation of eucalyptus in agroforestry system from a sustainability point of view. As it is demand driven and need oriented, its applicability and contribution is expected to be high in the present discussion on issues that revolve around *Eucalyptus* plantations. It is also expected to enable decision-makers to make informed and unbiased decisions in the area of agricultural and forestry development policies and to give due considerations on farmers' choice of species. The study compares three crops in sole and in eucalyptus rotational agroforestry system having different stand densities with regard to their runoff, soil loss, soil water depletion and seasonal water use in seasonally waterlogged highland Vertisols.

Materials and methods

Site description

The study was conducted from 2000 to 20003 at Ginchi Research Farm located in the central highlands of Ethiopia at 38 ^{0}E and 9 ^{0}N and at an elevation of 2200 masl. The site has a subhumid climate with an average annual rainfall of 1200 mm of which 30 % occurs before the onset of the main rainy season, between February and April. Runoff, which accounts for 30-50 % of the seasonal rainfall, only occurs between July and September. Mean monthly maximum and minimum temperatures range between 26 ^{0}C and 9 ^{0}C and the annual PET is 1400 mm. The study was conducted on deep Pellic Vertisols (Soil Survey Staff, 1974). The field capacity of the profile ranged from 0.55 to 0.6 kg kg $^{-1}$ and saturated hydraulic conductivity is about 2.5 mm h^{-1}.

Experimental setting

Eucalyptus globulus, the most common tree species in the Ethiopian highlands, were raised in a nursery and transplanted as six-month-old seedlings in 20 x 30 x 60 cm pits in July 2000. Each pit was filled with 2 kg farmyard manure after being thoroughly mixed with the dugout soil. Seedlings were planted at a spacing of 2.83 x 2.83 m, 3.5 x 3.5 m and 4 x 4 m, which is equivalent to stand densities of 1250, 833 and 625 trees ha^{-1}, respectively, in three replications. To maintain constant stand density through the experimental period tree seedlings lost before the age of six months were replaced by the ball planting method in June 2001. Three traditional Vertisol crops, durum wheat, tef and chickpea, were grown as sole and intercrop between *E. globulus* trees for three consecutive seasons (2000/2001, 2001/2002 and 2002/2003). Plots planted with tef, chickpea and wheat in the 2000/ 20001 cropping season were followed by wheat-chickpea, tef-wheat and chickpea-tef cropping sequences in the 2001/2002 and 2002/2003 cropping seasons, respectively. The treatments were arranged in a split plot design where the four tree spacings (including the control sole crop with zero tree density) constitute the main plot factor while the three cropping sequences (chickpea-tef-wheat (CTW), tef-wheat-chickpea (TWC) and wheat-chickpea–tef (WCT) represent the sub plot factor. Trees were planted on 286 m^2 (20.4 X 14 m) hydrologically isolated erosion plots with a 2 % slope.

Wheat (CV kilintto) was sown each season in the first week of July on broadbed and furrow (BBF) seedbeds with a basal dose of 60 kg N and 20 kg P per hectare and harvested towards the first week of November. Tef (CV DZ-354) was sown each season around mid August on flat seedbed tilled several times during the rainy season and with the same amount of fertilizer as wheat and was harvested towards the end of November. Waterlogging sensitive chickpea (CV Maryie) was planted in the first week of September and harvested in December-February.

Runoff and soil loss measurement

Erosion plots (20.4 m long and 14 m wide) were aligned next to each other across the main slope (Figure 1). The minimum distance between monocrop and tree-crop plots was 12 m. Each plot was enclosed by a 50 cm galvanized metal sheet of which 20 cm was inserted into the ground and 30 cm remained above the surface. To measure runoff and soil loss each plot had an installation containing a metal gutter at the lower end of the plots, a sediment box and a collection tank. The metal gutter intercepted runoff and directed it to the collection tank. The sedimentation box also acted as a multi-pipe divisor with 7 pipes. Only the middle pipe was connected to the runoff-collecting tank through a 12.5 mm diameter plastic hose, thus allowing only (in theory) 1/7 of the runoff to be collected during each rainfall events. The actual amount going into the tank was determined using a calibration curve. The box and tank were shielded from direct rainfall. Each plot was kept clear of up-slope runoff by a runon barrier and an interceptor drain at the upper end of the plots.

Sediment and water samples were collected when available once every 24 hours. Representative samples were collected from the sedimentation box and from the overflow tank after stirring the mixture vigorously. Concentration of the suspended material was determined using the filtration method (Hudson, 1993). In this method a known volume of soil suspension was filtered through a filter paper (of known weight) that retained particles >1.2 μm, dried at 105 ^{0}C for 24 hours and weighed. Then sediment concentration was converted to sediment yield (Mg ha^{-1}) taking into account the total runoff volume (Hudson, 1993). Runoff and soil loss data were analyzed per year to evaluate the treatment effects using MSTATC-91 statistical package.

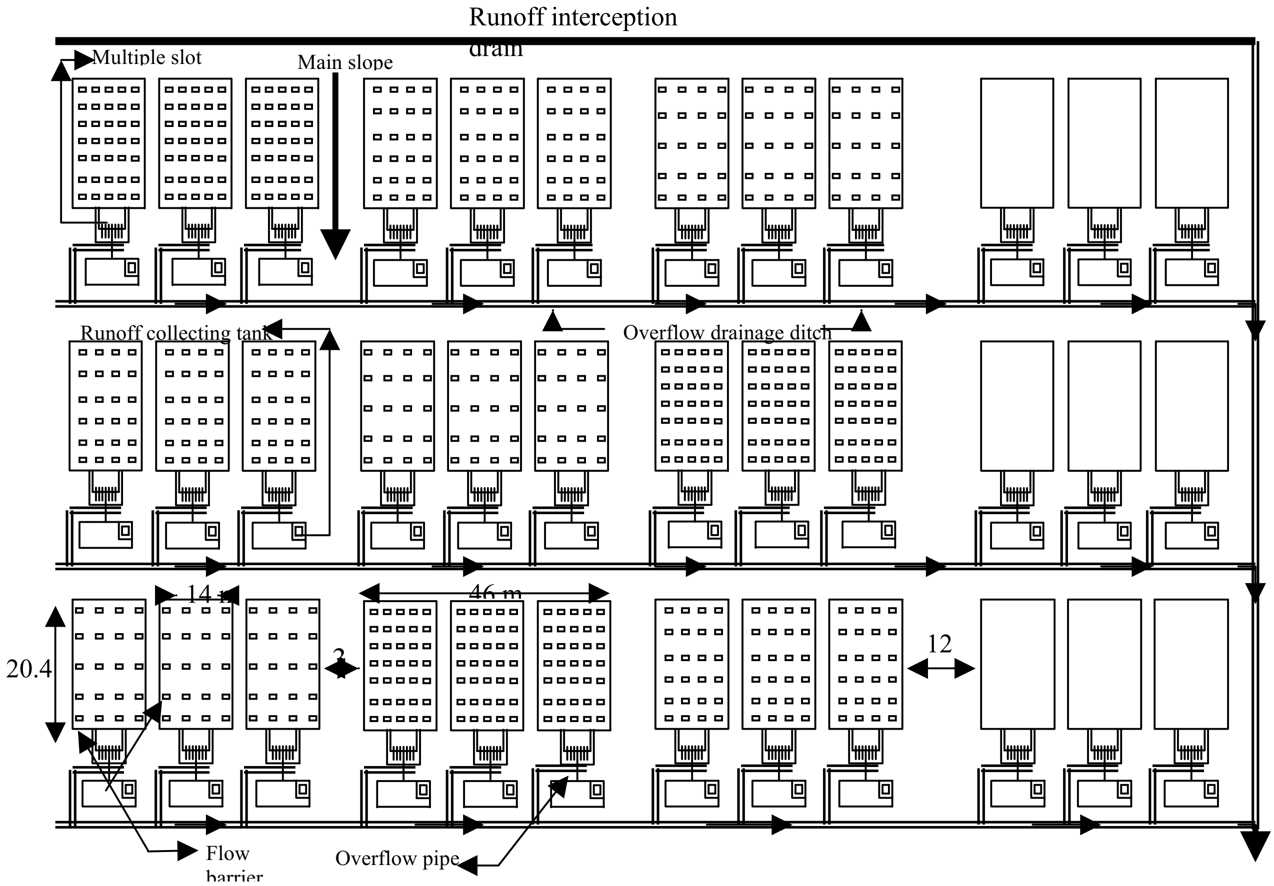

Figure 1. Layout of erosion plots. Small squares (□) shows the tree rows and the their number represent the tree density per plot. Empty boxesat the right corner represent the control sole crops.

Soil moisture measurement

The soil moisture profile was monitored by means of a neutron probe (Wallingfored Soil Moisture Probe Type I.H.III). Aluminum access tubes were installed in the experimental plots in March 2000 at least five months before the start of the measurements. The arrangement and number of the tubes per plots differed between treatments. The simplified approach of Wallace and Jackson (1994) with two-dimensional grid sampling was followed: One tube was placed in the center between the tree rows (tree row position). One in the center between the tree alleys (central position) parallel to tree row position and the third one (after the total area enclosed by four trees was divided into four equal small blocks) was placed in the center of the small block opposite to tube in central position (Figure 2). In the monocrop plots two tubes were placed at 4 m distance in the upper and lower direction from the center of the plot in downslope direction. Measurements were taken at 10 cm intervals, starting at a depth of 10 cm, down to a depth of 2.5 m from July 2000 to June 2003 at 10 days intervals. The neutron probe was calibrated against data obtained from destructive sampling. For this calibration bulk density values used to convert gravimetric to volumetric soil water content (θ) were derived from Fox's three-dimensional normal shrinkage analytical expression (Fox, 1964).

Water use

Seasonal water use (WU) during the crop growing periods i.e. from July to October, Mid July to mid December and September to December for treatments involving wheat, tef and chickpea, respectively in 2000, 2001 and 2002 was computed as:

$$WU = R + Ru \pm \Delta S \quad (1)$$

where R and Ru and ±ΔS are rainfall, runoff and change in water content (0-2.5 m soil depth) over 10- day intervals from planting to harvesting. ΔS values were averaged over the plots from tubes in different positions. Due to the nature of soil matrices we assumed that drainage losses were negligible below a soil depth of 2.5 m. Ru was obtained from soil erosion plots. 10-day water use data were aggregated to monthly data before statistical analysis. Analysis of variance was done and LSD compared using MSTATC statistical package.

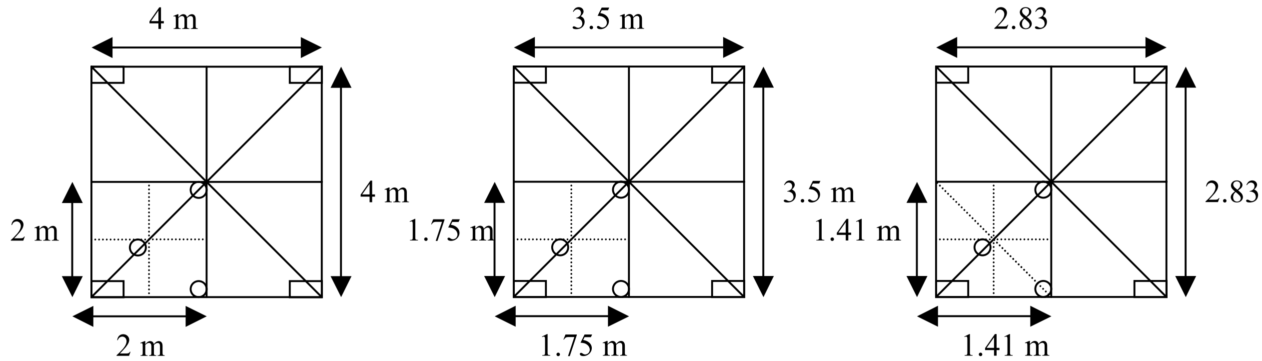

Figure 2. Schematic presentation of access tubes (●) positions relative to the trees (■). One tube was placed in the center between the tree rows (tree row position). One in the center between the tree alleys (central position) parallel to tree row position and a third one was placed at the center of the small block between the tree and tube in central position. Drawings are not onto scale.

Soil water depletion during the dry period was computed from ΔS data over a soil depth of 2.5 m. Deep drainage was assumed to be negligible and the measured depletion of water was therefore due to the evaporation from bare soil in case of monocropping and from soil evaporation plus tree water use in the tree-crop systems.

Pant available water (PAW) for each soil layer was determined using the formula:

$$PAW = AW - PWP \qquad (2)$$

where AW is the amount of water (mm) in the given soil depth, PWP is the calculated amount of water that will not be variable for plants (-1.5 MPa); PAW is the plant- available water at that depth (Astatke et al., 1995). The moisture content at PWP (-1.5 MPa) was determined for each soil depth using the pressure plate technique and the bulk density at PWP is calculated from the three-dimensional, normal volume change analytical expression given by Fox (1964). Because soil water measurements during the dry season in the field were taken under conditions of extensive surface cracks, this made representative bulk density sampling almost impossible with conventional methods. Soil water data were analysed after being aggregated per year, month and depth, keeping treatments as a fixed effect. Analysis of variance was done and LSD compared using MSTATC statistical package.

Results

Rainfall

During the whole experimental period rainfall followed the expected long-term rainfall distribution pattern with most of the rains being received during the summer months of June to September (Figure 3). The annual rainfall during the experimental period, however, was consistently lower than the long term annual average for the experimental site. For instance the long term average rainfall exceeds the rainfall in the year 2002 by about 40 %. Nevertheless, the rainfall distribution within the growing season (i.e. June to September) was fairly uniform across the three seasons. Except in 2001 cropping season's rainfall peaked during July and August and leveled off towards September.

Runoff and soil loss

Annual runoff and soil loss are given in Table 1. The results revealed that the annual runoff and soil loss from different plots under the same crop were fairly uniform during the crop establishment year (2000) indicating that runoff and soil loss variations between replications were not significant. During this period, the annual runoff from wheat plots varied between 144 to 111 mm which is equivalent to 19 to 16 % of the seasonal rainfall (June to September).

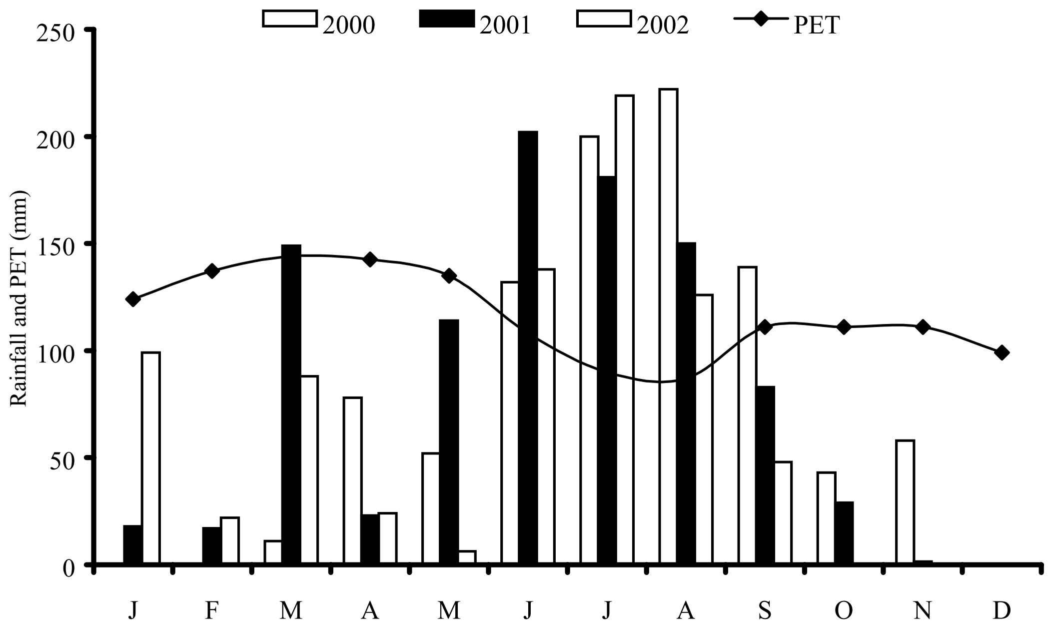

Figure 3. Annual rainfall distribution and mean PET between 2000-2003 at Ginchi, Ethiopia.

On the average plots under tef and chickpea transformed 16 % and 10 % of the seasonal rainfall into runoff respectively. In the 2001 and 2002 cropping seasons both tree density and crop species and their interactions significantly influenced the annual runoff and soil loss (Table 1). In the 2001 cropping seasons, the runoff from sole wheat was 22 % of season's rainfall, which reduced to 14, 10 and 7 % under agroforstry systems with low, intermediate and high tree stand density respectively. A similar trend was observed with tef where the inclusion of eucalyptus at stand densities of 625, 833 and 1225 stems ha^{-1} reduced the runoff to 13, 9 and 8 % of the season's rainfall, respectively compared to 18 % under sole cropping. Unlike the two crops, however, the runoff losses under chickpea were more or less similar irrespective of the tree stand densities in the 2001 cropping season. In the 2002 cropping season, irrespective of the crop species inclusion of eucalyptus into the agricultural system brought down runoff losses to less than 2.5 % of the seasonal rainfall compared to 5 to 10 % under sole crops.

Monthly runoff distribution in the 2001 and 2002 cropping seasons followed the rainfall distribution pattern with the maximum monthly runoff occurring in August irrespective of crops (Figure 4). Apparently, the runoff from sole and agroforestry systems was initiated after 250 to 260 and 285-300 mm of rainfall respectively and continues to the end of the rainy season. With the exception of wheat, which was planted early with a provision for surface drainage, about 50 to 70 % of the annual runoff from sole crops occurs under bare soil conditions where the potential for soil particle detachment and their subsequent transport is high. In contrast, runoff during the early part

Table 1. Runoff and soil loss from sole and agroforestry system between 2000-2003 cropping season at Ginchi Ethiopia.

Crops	Tree density	Runoff (mm)			Soil loss (Mg ha^{-1})		
	(stems ha^{-1})	2000	2001	2002	2000	2001	2002
Wheat	0	144a	133a	62a	23a	26a	17a
	625	127ab	85b	17b	18a	19ab	0.6b
	833	111b	61bc	15b	21a	12b	0.2b
	1225	114ab	40c	13c	28a	14b	0.1b
	Mean	**124a**	**79a**	**26a**	**23 a**	**19 a**	**0.7**
Tef	0	110ab	112a	51a	24a	22a	12a
	625	85b	75b	11b	17ab	14b	0.3b
	833	108ab	55c	8b	22a	15b	0.1b
	1225	125a	48c	10b	14b	11c	0.1b
	Mean	**105a**	**54ab**	**20b**	**19b**	**16 a**	**0.5b**
Chickpea	0	70a	57a	26a	0.9a	0.9a	0.5a
	625	85a	40ab	6b	13a	0.7ab	0.1a
	833	65a	35b	4b	11a	0.5 b	0.1a
	1225	75a	37ab	8b	0.6a	0.6b	0.1a
	Mean	**74b**	**40b**	**9c**	**1.1c**	**0.6 b**	**0.2b**

Means within the same column without common letters differ significantly at $P < 0.05$.
Values within the same crop and column without common letters differ significantly at $P < 0.05$

of the rainy season, particularly in wheat and tef was considerably reduced in the agroforestry systems. This may suggests that part of the water used by eucalyptus was water unused by the crops and the reduction in runoff volume might reduce the risk of soil and nutrient erosion associated with the practice of late planting crops on highland Vertisols in Ethiopia.

The mean annual soil loss from wheat was comparable with the mean annual soil loss from tef (23 Mg vs. 19 Mg ha^{-1}) and these values were significantly higher than the soil loss observed under chickpea (11 Mg ha^{-1}) in the 2000 cropping season. In the following season, the soil loss from sole wheat, which was 26 Mg ha^{-1} declined by 27 to 54 % in the agroforestry system when the tree density varied from 625 to 1225 stems ha^{-1}. The soil loss from sole wheat was significantly higher than from wheat intercropped between 833 and 1225 trees ha^{-1}. Wheat intercropped between 833 and 1225 trees ha^{-1} had slightly lower soil loss than wheat between 625 trees ha^{-1} but the differences were not large enough to be statistically significant. In the third season the soil loss in the agroforestry system was less than 0.3 Mg compared to 17 Mg ha^{-1} from sole wheat and the differences were significant. In both seasons the soil loss from tef showed a similar trend where the soil loss in the agroforestry system was declined by 34 to 50 % compared to what it was in sole tef cropping condition in the 2001 cropping season. While in the following season the soil loss in the agroforestry system was less than 0.3 Mg ha^{-1} compared to 1.2 Mg ha^{-1} in sole tef. Though the differences were modest, the soil loss from sole chickpea was higher than the soil loss from chickpea-tree system.

Crop water use

Under sole cropping, the water use of chickpea was significantly higher than that of wheat and tef across the three seasons (Table 2). With a few exceptions in case of chickpea, the water use of tree-crop systems was significantly higher than under sole cropping and increased with increasing tree density though this increase was modest in the 2002 cropping season.

The water use in sole and in tree-crop system slightly decreased in the third season compared to what it was in the second season and this decrease was relatively higher in the chickpea-tree system than in the tef-tree and wheat-tree systems. In rainfed agriculture, crop water use comes from the growing season precipitation and from soil water stored before planting. However, the relative contribution between the two (calculated as percentage of the average change in soil water storage between planting and harvesting to the total water consumed) varied significantly among crops and between sole and tree-crop systems. The average change in soil water content (ΔS) between planting and harvest showed that water used in sole wheat came entirely from precipitation and consequently soil water storage increased by 224, 49, and 69 mm in 2000, 2001, 2002 respectively. In wheat-tree system, while still growing season precipitation was the sole source of consumed water, the increase in soil water storage at harvest declined by about 50 % compared to sole wheat in the last two cropping seasons. In contrast, some 135 mm (53 %) and 100 mm (42 %) of the total available water consumed in the second and third seasons in sole tef were derived from growing season precipitation, whereas the remaining water used was derived from soil water stored at planting. In the tef-tree system the contribution of growing season precipitation to the total water consumed ranged between 172 to 201 mm (53 %) in the second and about 126 mm (40 %) in the third season. In case of chickpea, 76 to 78 % of the total water consumed under both systems was derived from soil water stored at planting in the second and third seasons. Thus, tree- crop systems show a marked increase in water use not only because of better utilization of seasonal precipitation but also due to increased soil water abstraction. In the latter case increased water use may result in intense water competition between the crop and the tree, particularly in late-planted crops where the sole source of water is soil water stored at planting. Hence it necessary to assess the water use pattern during the growing period in the two systems.

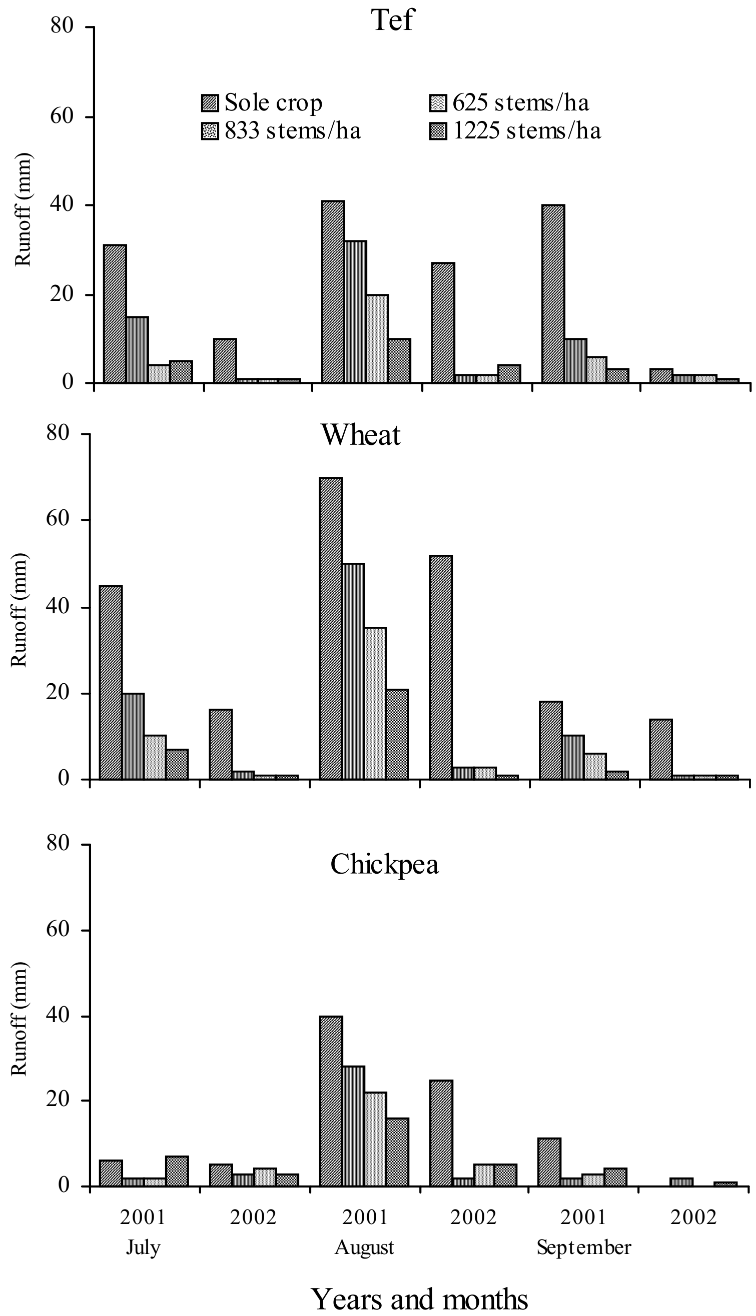

Figure 4. Distribution of annual runoff from tef, wheat and chickpea plots under sole and agroforestry system in 2001and 2002 cropping season at Ginchi Ethiopia

Special and temporal variation in water stress

It is commonly accepted that the upper limit of the optimum soil water content for plant growth is the field capacity (FC), and lower limit equals about 70 % of FC. When the soil water content is below 60 % of the FC, water stress may hinder the growth and development of crops. The FC of the experimental field ranges between 0.55 and 0.6 kg kg^{-1}. The PWP ranges between 0.35-0.39 kg kg^{-1}. Available water is about 0.20. Critical soil water content was assumed at 60 % of this available water, i.e. when 0.12 of 0.20 is used. The corresponding water content is of 0.48-0.43 kg kg^{-1}. On the bases of this critical value, the duration of the water stress period in the different soil layers for the above three crops in sole and agroforstry system was determined for the 2001 and 2002 cropping seasons. To characterize the severity of water stress, the extent of water deficit was divided into four levels: slight deficit (with soil water content ranging from 50 to 59 % the of FC), moderate (with soil water content ranging from 40 to 49 % of FC), severe (with soil water content ranging from 30 to 39 % FC) and extreme deficit (with a soil water below 30 % of FC).

Results show that crops in a tree-crop system suffered more from various degrees of water stress than crops in sole cropping and that the duration of water stress increased with increasing tree density (Figure 5). For chickpea, water tress was observed in both 2001 and 2002 cropping seasons. In the 2001 cropping season, water stress in the 0-0.5, 0.5-1.0 and 1-2 m layers emerged respectively on 29 October, 10 and 25 November, lasting for 60, 30-45 and 20-30 days with tree densities of 833 and 1225 stems ha^{-1}. In 2002 cropping season water stress occurred from 10 October to the beginning of January (harvest) in all soil layers, which lasted for about 85-90 days when the tree density varied from 625 to 1225 stems ha^{-1}. In the tef-tree system the water stress occurred between 1 November until crop harvest in 2001, lasting for 30 to 45, 20 to 30 and 10 to 20 days across the three tree densities in the 0-0.5, 0.5-1.0 and 1-2 m layers respectively. In contrast in the 2002 cropping season the onset of the water stress period was started one month earlier and lasted for 60 to 75, 65 to 80 and 30 to 60 days until the crop harvest in the 0-0.5, 0.5-1.0 and 1-2 m layers respectively. In the wheat-tree system significant water stress was observed only in the 2002 cropping season particularly with the two highest tree densities and lasted for 30 to 70, 35 to 60 and 10 to 45 days in the 0-0.5, 0.5-1.0 and 1-2 m layers respectively. In sole crops water stress lasting for 30 days in wheat, 30 to 45 in tef and 65 to 10 days in chickpea occurred in the 0-0.5, 0.5-1.0 layers respectively in the 2002 cropping season. Onset of the water stress period overlapped with later stage of crop developments towards the end rainy season and continued until crop harvest. Therefore, among the three crops, chickpea experienced the most severe water stress in the tree-crop system. At sowing, soil water content in all three layers remained above 60 % of FC for any crop in either sole or tree-crop system. Minimum soil water contents, in the 0-0.5, 0.5-1.0 and 1-2 m layers were at extreme, moderate and slight deficit in 2001 and at extreme, moderate and moderate deficit in 2002 respectively in chickpea-tree systems. At the same time in the tef-tree system soil water contents were at extreme, moderate and slight deficit in the 0-0.5, 0.5-1.0 and 1-2 m layers respectively in 2002 and at extreme in the first and slight deficit in the other two layers in 2001. In the wheat-tree system the soil water was at moderate deficit in the 0-0.5 m layer and slight deficit in the other layers in 2001 cropping season while it was at extreme and at slight deficit in 2002 cropping season except under highest tree density respectively. In sole cropping though there were few exceptions soil water in 0-0.5, 0.5-1.0 and 1-2 m layers were at extreme to moderate, moderate and slight deficit respectively which are more or less comparable to water stress levels experienced in tef-tree systems in 2001 and wheat-tree systems in 2001 and 2002.

.

Table 2. Rainfall between planting and harvesting, seasonal soil moisture recharge (ΔS), water use (WU) and runoff (all in mm) sole crop and agroforestry systems for three cropping seasons (2000-2002) at Ginchi, Ethiopia.

Crop	Tree density	2000			2001			2002		
	(stems ha^{-1})	runoff	WU	ΔS	runoff	WU	ΔS	runoff	WU	ΔS
Wheat	0	144a	256bc	+224a	133a	260d	+49a	82a	242d	+69a
	625	127a	264b	+263a	75b	346b	+21a	6c	353a	+34b
	833	111b	268b	+275a	71b	362b	+29a	6c	358a	+39b
	1225	114a	279b	+260a	30c	394a	+18b	3c	357a	+33b
	Rainfall*	**653**			**442**			**399**		
Tef	0	90ab	246c	+87b	79b	253d	-118c	30b	234d	-134c
	625	75c	246c	+95b	40c	334b	-160d	4c	312bc	-186d
	833	90abc	246c	+52b	16c	373a	-177de	4c	326b	-200d
	1225	80bc	246c	+87b	13cd	384a	-183e	4c	315bc	-189d
	Rainfall*	**417**			**214**			**130**		
Chickpea	0	37d	305a	-70c	11cd	294c	-189e	5c	292c	-244e
	625	40cd	294a	-62c	2c	328b	-214f	2c	349ab	-302f
	833	26d	294a	-48c	3c	322b	-209e	0c	321b	-273f
	1225	25d	291ab	-44c	4c	341b	-229f	0c	319b	-271f
	Rainfall*	**272**			**116**			**48**		

Values within the same column without common letters differ significantly at $P< 0.05$

*received between planting and harvesting

Table 3. Plant available water within 2.5 m soil depth during the dry season (no annual crops) under sole and agroforestry system at Ginchi, Ethiopia.

Months	2000				2001				2002			
	0	625	833	1225	0	625	833	1225	0	625	833	1225
	Wheat											
November	358	371	387	363	368	317	292	301	277	202	177	134
December	307	310	308	300	323	252	236	250	245	201	166	121
January	293	284	274	287	340	241	250	238	220	179	169	106
February	273	264	246	276	295	205	206	199	214	158	155	98
March	285	240	237	250	288	191	196	190	207	131	135	90
April	239	235	208	230	246	186	189	176	196	121	130	90
May	226	206	186	233	241	186	171	141	197	104	114	90
Change	**132c**	**165b**	**201a**	**130c**	**127b**	**131a**	**121b**	**160a**	**80a**	**32b**	**63a**	**44b**
	Tef											
January	322	322	294	309	321	272	255	274	181	129	170	120
February	314	275	261	250	251	248	226	206	170	112	140	126
March	320	293	270	268	275	228	242	208	173	98	125	112
April	287	232	224	226	230	208	203	185	150	91	116	107
May	275	232	221	231	222	171	165	171	149	82	93	103
Change	**47fg**	**96c**	**83c**	**78de**	**99c**	**101c**	**90c**	**103c**	**32b**	**47b**	**77a**	**17c**
	Chickpea											
January	254	261	218	247	268	253	268	247	182	107	172	109
February	211	217	201	207	226	206	226	207	166	118	155	104
March	224	229	212	218	223	190	223	218	159	98	135	99
April	180	186	166	174	194	179	194	174	149	78	125	90
May	193	201	180	187	183	159	178	187	135	75	112	90
Change	**61ef**	**60ef**	**38g**	**60e**	**85cd**	**75d**	**90c**	**60d**	**47b**	**32bc**	**60ab**	**19c**

Means within the same year without common letters differ significantly at $P < 0.05$.

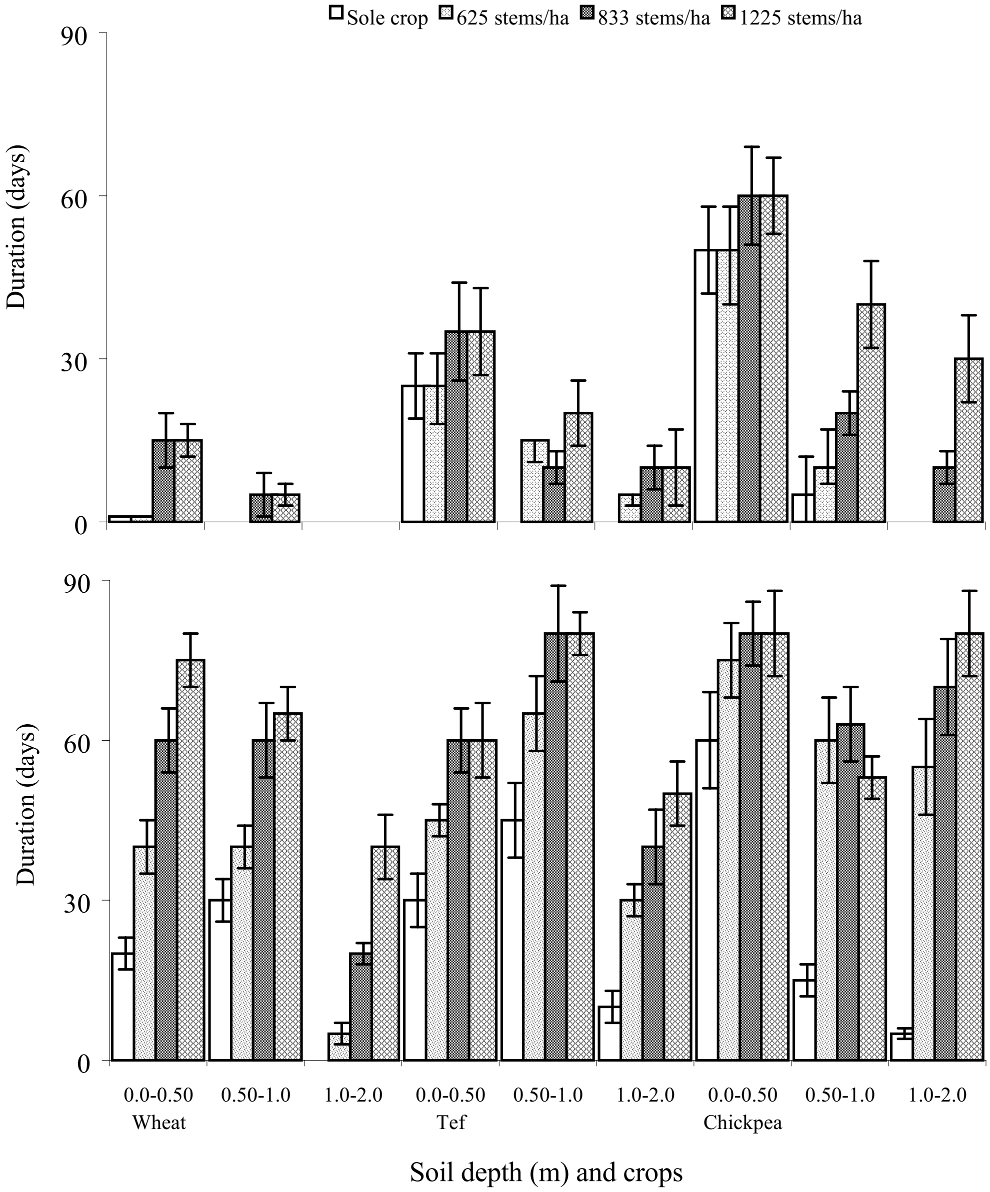

Figure 5. Duration of water stress period in different soil layers for wheat, tef and Chickpea under sole and agroforestry system in 2001 (upper) and 2002 (lower) cropping seasons. Bars at indicate the standard error.

Plant available water in dry season

Plant available soil water within 2.5 m soil depth during the dry seasons (from crop harvest to beginning of next growing season) are presented in Table 3. The amounts of PAW at the beginning of the dry season corresponded to the trends observed for water use in the preceding growing season. Irrespective of crop species, less water remained in the soil in the tree-crop system than in sole cropping. PAW was higher for low tree density than for high tree density indicating that trees at high density exploit the soil water more than trees at low density. PAW was higher in 2001 compared to in 2002. Across all three seasons PAW was depleted to the lowest level measured in all plots at the end of the dry season (May). However, the actual amount varied significantly across crop species and tree densities. In treatments involving wheat and trees PAW in May was 85 to 105 mm lower than in plots under monocrop, both in 2001 and 2002 and these differences were significant. In tef monocrop plots had significantly higher PAW and the differences were 52 to 58 mm in 2001 and 45 to 67 mm in 2002 when the tree density varied from 625 to 1225 stems ha^{-1}. Similarly, in treatment involving chickpea PAW in monocrop plots exceeded the amount in crop-tree plots by about 25 mm in 20001 and 60 mm in 2002 but the differences were significant only in 2002 season. Nevertheless, the total amount of PAW lost during the dry period seemed little affected by the presence of the trees (Table 3). This may suggest that the large proportion of the water used by the trees was the water that otherwise would have been lost through evaporation under monocropoing. Thus the observed differences in PAW between the two land use systems at the end of the dry season may be attributed to differences in PAW at harvest rather than increased water abstraction during the dry season by trees.

Discussion

Runoff and soil loss

Runoff measurements are the most accurate way to estimate removal of substances from a site, as well as a very useful parameter for indirect measurement of infiltration. The differences in runoff and erosion between the sole and tree-crop systems were not significant in the 2000 cropping season since both have a period of establishment during which soil exposure is similar. However, in the subsequent two seasons both runoff and soil erosion rates varied considerably among seasons, crops and land use (sole and tree-crop). Differences between years are ascribed to variations in the amount and distribution of the rainfall. Under sole cropping condition, plots grown with chickpea gave considerably less runoff in comparison to plots grown with wheat and tef. In most cases the differences in runoff between wheat and tef were not substantial. Runoff differences among crop species are largely ascribed to the differences in seedbed preparation methods. Wheat was planted on 80 cm wide and 20 cm high beds sandwiched between two 20 cm wide drainage furrows through which excess water drains from the field. On the other hand, at beginning of the season chickpea plots were shaped into ridge and furrows at intervals of 30 to 40 cm perpendicular to the downslope direction so as to trap the excess water which otherwise is lost as runoff. Tef plots were ploughed several times during the rainy period to prepare a fine seedbed on which tef seeds were broadcasted on top as late as mid August. Compared to ridge and furrows, tef seedbeds have only minor depressions, which get closed during the first rain and the absence of any obstruction to overland flow resulted in excessive runoff during much of the rainy season.

Inclusion of eucalyptus at different stand densities into the two cereals significantly reduced runoff and associated soil loss in both seasons. However, in the chickpea plots the presence of surface depressions masked the tree effect, yielding similar runoff irrespective of tree canopy. Wiersum (1991) suggested that runoff reduction under trees is attributed to increased interception and infiltration. The high moisture buildup in the tree-crop system and the open canopy architecture of eucalyptus suggests that interception losses may contribute little to explain the runoff reduction observed in the present study. However, it is more likely that as the tree-crop system tends to exhaustively deplete soil profile water, this makes the land more water receptive. Thus increased water intake results in lower runoff losses. Similar results are reported by Narain et al. (1999) where inclusion of paired rows of eucalyptus at 10 m interval in maize plots cut down the runoff losses from 28 % of the season's rainfall (1037 mm) in sole maize to 13 %.

Under sole cropping, chickpea had significantly lower soil loss than wheat and tef. In the current study, in spite of early vegetative cover under wheat no significant difference in soil loss from sole wheat and late-planted tef was found; unlike Teklu et al. (1999) who reported that wheat on BBF significantly reduces soil erosion rates compared to late planted crops. Vegetative cover reduces the direct impact of raindrop on the soil and reduces the flow velocity. This reduces the amount of soil detached by rain and by flowing water and the capacity to transport sediments provided. However, under BBF system this is not the case as runoff water concentrates in dead furrows between the beds before of leaving the field. Under rainfall conditions of the experimental site a high volume of concentrated water flows occasionally in the dead furrows which can erode considerable soil material from the bed walls. Soil materials eroded in this way might contribute for a significant proportion to the total soil loss in our case as witnessed from an increase in width and depth of drainage furrows at the end of each rainy season. Dead furrows are free of vegetative cover and accounts about 20 % of the total area under the BBF system and the soil on bed walls is very loose and easily detachable under wet soil conditions.

In the current study, the soil loss from the tree-crop systems was significantly lower than the soil loss from sole cropping conditions. Studies from Gouyi (2002), however, indicated that the single-layer eucalyptus plantation gives little soil cover and accelerate soil erosion. In the current study, significant differences in the kinetic energies between throughfall and atmospheric rainfall would not be expected since trees did not attain the maximum terminal velocity height in either of the two seasons. Thus soil erosion at the initial phase (splash and detachment) due to direct rainfall impact (Quansah, 1981) under both land uses is about the same. However, the transport, the second phase of soil erosion is higher under sole crops, which indeed experienced the highest runoff as compared to tree-crop system.

The annual rates of soil erosion from sole crops are comparable to the rates estimated by Hellden (1987) using the universal soil loss equation (USLE) adapted for Ethiopian highlands. The soil loss tolerance limit (TL) in the Ethiopian highlands is estimated at 10 Mg ha^{-1} (Hellden, 1987), which is likely to vary with slope gradient and land use. If this value of TL is assumed to apply on highland Vertisols across all land uses, soil loss rates from small cereal cultivation clearly indicate unsustainable conditions. However, as expected from the scale effect on soil loss estimates, our estimate could be somewhat higher than the watershed scale estimates on soil erosion from highland Vertisols. It is noted that sediment yield of the region could be higher than or lower than, depending on the sedimentation and mass failures processes at the watershed scale. No matter what, our the results show that integration of eucalyptus into agricultural crops cut down soil erosion rates at least to the tolerable limits in seasonally waterlogged highland Vertisols. Eucalyptus trees capture part of the runoff and soil, which would otherwise be lost from sole cropping and this may justify their integration, thereby compensating for the extra resource required for their growth.

Water use

The water use in the tree-crop systems in the current study reaffirms the hypothesis that agroforestry offers an appropriate technology for improving the management of available water supplies and maximizing the proportion of rainfall utilized by crops (Cannel, et al., 1996; Stroosnijder, 2003). Wallace (1996) proposed that combining trees and annual crop directly improves water use in semiarid regions mainly because of a higher efficiency in rainfall utilization by reducing evaporation losses from bare soil. In the current study, tree-crop systems with an effective runoff reduction mechanism recorded higher seasonal water use. Water use as well depended on tree densities. Similarly, a higher water use for trees planted at high density (2150 trees ha^{-1}) compared to lower densities (304 and 82 trees ha^{-1}) was reported by Eastham et al. (1990) in a tree pasture agroforestry system. Increased water use in tree-crop systems during a relatively wet year (2001) is in accordance with the suggestion that eucalyptus can substantially increase transpiration through stomatal regulation under abundant water supply (Calder, 1994).

Under the current study, PAW lost from sole and tree-crop systems during dry seasons was comparable. Morris et al. (1990) showed that, after harvest of wet paddy rice (a situation where soil water content is high as in our case), the same amount of water can be lost from the soil profile by evaporation or drainage as would be used by crops during the following dry season. PAW lost during the dry period was higher under wheat than under tef or chickpea probably because of a difference in length of the dry season. Early crop harvest of wheat initiated early surface crack development. Surface cracks enhance deep soil drying in Vertisols. Available water resources were not exploited in the same way and the same extent in the different treatments. Tree-crop systems generally used more water and took up water from deeper soil layers than their sole counter parts in 2001. Higher water extraction in the surface layers by monocrops and from subsurface layers by crop-trees is explainable through the difference in the rooting patterns of crops and trees. The root system of most annual crops is confide within 1 m depth, whereas more than one third of the total tree root length at 90 months age was found to extend beyond 1 m depth and could potentially utilize sub-soil moisture which is unexploitable by agricultural crops (Singh et al, 1998 as cited by Narain et al., 1998). However, as the trees increasingly dominated water use and deep reserves were depleted, competition for available water in the surface horizons with associated crops resulted in water stress periods of various intensities, particularly with chickpea and to a lesser extent in tef and wheat. In a situation like this, trees by virtue of their perennial root infrastructure are likely to be stronger competitors for water than the crops (Ong et al, 1999). The shift in moisture extraction pattern from deeper to surface horizons indicate that tree growth became progressively dependant on current rainfall, thus, the low rainfall in year 2002 was also partly contributed to the water stress levels observed in that season. This suggest that water stress in tree-crop systems is dependent on crop species, tree density and prevailing environmental conditions, particularly seasonal rainfall.

Clearly, from a conservation viewpoint, integration of eucalyptus into agricultural crops is of paramount importance. The problem with this is, however, that crop yields may fluctuate markedly due to a poor match between water supply and demand, particularly at the later stage of the agroforestry system. However it seems still possible to improve this match between demand and supply so that the system satisfies both productive and protective functions through proper crop selection, tree density adjustment or pruning. For instance chickpea, which suffered most from water stress in the second and third season, can be considered only during the tree establishment year when tree water requirement is still low and stored soil moisture is enough to support both crop and tree. Since water stress in tef was only critical in the third season, it can be grown in the second season following chickpea and then wheat can be advised for the third season. This suggestion was supported by the work of Selamyihun (under preparation) who found that wide difference in land equivalent ratio values (1.2-1.68) depending on how these three crops were intercropped between eucalyptus trees in the sequence following each other for three years in seasonally waterlogged highland Vertisols. Land equivalent ration (LER) indicates the land area required under sole cropping to produce the yield achieved in the agroforestry system. While ELR values of greater than one signifies that there is a niche differentiation between the system components or green area duration is extended (Loomis and Conner, 1992), and provides evidence of complementarity and that complementarity changes with cropping sequences used.

Conclusions

Available soil profile water and evaporative climatic demand seem to be the controlling factors for water use of the two land uses. While crops intensively utilize water from shallow depth, trees have the potential to extract water from deeper layers and continue to be productive during non-cropping periods. The adoption of agroforestry as a preferred land-use system will only be achieved by demonstrating that it is either more productive (i.e. higher combined yield of tree and crop products), and/or that it is more sustainable than current practices of growing trees and crops separately. Integration of eucalyptus into the agricultural system substantially increased the seasonal water use and cut down soil erosion rates to tolerable limits. However, the hydrological effect of growing eucalyptus on agricultural land would be reduced catchment runoff particularly in dry years. The highlands are headwaters of the major drainage systems, which extend to the lowlands. Thus any activity that affect the hydrology of the highlands have significant impact on water resources for the lowlands. It is logical, therefore, to expect that some compromises must be made. For example, reducing tree density, in some cases, results in only a slight increase in soil losses and reduces the direct economic benefit accrued from the tree component but may be necessary from a stand point of sustainable ecological functioning at higher scale.

Traditional Vertisol management practices are far from sustainable. Sediments produced from the highlands are likely to pollute streams and lakes and pile up on bottomlands, in stream channels and in reservoirs. The rainfall has a strongly seasonal character, which is associated with high intensity, high volume storms. Vertisols, under such climatic conditions, are susceptible to severe erosion. Any improved farming system suggested to replace the traditional Vertisol management system must incorporate some elements of soil conservation. The natural environment is suitable to intensify annual cropping. In this regard technically known agroforestry practices form important elements for improved land use. However, further research is required to evaluate the rotational agroforestry system over time and also to identify other potential tree species that can serve both productive and protective functions in this environment.

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Chapter 11

Conclusive summary

Conclusive summary

This study explores productive and protective functions of *Eucalyptus globulus* based agroforestry systems in the Ethiopian highland Vertisols. Ginchi watershed, a typical Vertisol watershed in terms of environmental setting and production systems in the central highlands of Ethiopia was used as the study site. The major findings from this study are briefly presented here.

In Ginchi experimental watershed, land use/ cover changes have occurred over the last three and half decades. The major change is an increase of cultivated area at the expense of grassland. Though less dramatic, woodland and riverine trees have also declined over the years in the expense of the grassland. The driving force behind the land use changes was obviously the need to produce more food and fiber to support the ever-increasing population. Over the years, the gullied area under cropland declined by 36 % while that under grassland, particularly in the upper part of the watershed increased tenfold. Once developed, gully channels enhances the export of sediment by increasing the connectivity in the landscape, which leads to an increased risk of sediment deposition down slope in addition to their significant drying out effect in the intergully area. This, therefore, calls for alternative grazing management in order to release the pressure on upper slopes where the risks of environmental degradation and detrimental impact down the slope remain highest.

Analysis of measured runoff and rainfall data revealed that traditional tef based cropping system on highland Vertisols transforms 23-40 % of the seasonal rainfall into runoff, which is equivalent to 102 to 307 mm runoff ha^{-1} $annum^{-1}$. These amounts are enough to raise a second crop on a hectare of land and can be harvested in small farm ponds at household level. Small farm ponds are efficient means to control runoff and may reduce the risk of sediment deposition in large–scale reservoirs.

In recent years, boundary planting on croplands forms the most important tree-growing niche in Ginchi watershed. Eucalyptus trees are the single dominant tree species in this system and are planted in a line with one-meter interrow spacing. Tree densities in this unilateral alley system range between 90 and 120 trees ha^{-1}. The second most important tree-growing niche is the homestead where livestock browsing and trembling susceptible tree species dominate. Here, trees are valued for shade, aesthetics and production of fuelwood and fodder. Farmyard manure application at the time of planting and mulching are the two standard practices used in farm tree planting. Most farmers believe that mulches are very effective in conserving soil moisture while manure and in situ decomposed plant residues are seen as an important source of nutrients for the young eucalyptus trees. Farmers utilize a pattern of gradual establishment to spread risk and cost of establishment over several years.

Farmers plant trees for the purpose of timber production, fuelwood, fencing, boundary demarcation and a cash crop. Ecological objectives are secondary for most farmers in their adoption decision. Most farmers in Ginchi watershed prefer to plant mainly eucalyptus. Attributes such as seedling availability, pole quality and growing experience makes *Eucalyptus globulus* the most preferred species. Farming experience, education, agroecological factors (slope, soil type and drainage) were found to influence the adoption decision.

The annual wood production of eucalypt boundaries on Vertisols ranges between 168 kg ha^{-1} y^{-1} at the age of four years to 2900 kg ha^{-1} y^{-1} at the age of twelve years. On Nitosols where farmers utilize short rotation cycles (four years) annual wood production was 903 kg $ha^{-1}y^{-1}$ in the first cycle and this increased by two fold in the second and third rotation cycles. The wood production rates of eucalypt boundaries were three to four times higher than the maximum wood production rare of *E. globulus* woodlot plantations in the Ethiopian highlands. With this productivity, eight to twelve years year-old eucalypt boundaries on a hectare of land (100-110 trees) can produce a biomass that could meet 50-75 % of the biomass energy requirement of a rural household of five people for eight to 12 years. Thus eucalypt boundaries can produce large volumes of timber and wood products within a short period of time without requiring a major shift in land use. This is an advantage for land-constrained smallholder farmers who cannot spare land for block plantations.

The wood harvest from 8-year-old eucalypt boundaries planted on a hectare of land would have a potential to replace 12 ton of caw dung, which could bring back 176 kg N, 156 kg P and 60 kg K as organic fertilizer to the farming system. This means that 1 kg of nitrogen removed with harvested wood (stem and branches) enables to bring back 20 kg N as organic fertilizer. In case of P, every kg removed with wood biomass enables to bring 26 kg of P as organic fertilizer. Likewise every kg of K removed with wood biomass enables to bring back 10 kg K as organic fertilizer. On the other hand, if natural woodlands have to supply the same amount of fuelwood as eucalypt boundaries on a hectare of land, each household needs about 1.22 ha of woodland every year. Boundary plantings thus help to preserve woodland and biodiversity by providing substitutes for forest products. This would be achieved by allowing households to practice intensive forest farming along farm boundaries thereby considering an optimal rotation period.

However, the tree component affects the yield of adjacent agricultural crops by altering the availability of growth resources such as light, water and possibly soil nutrients. The effective lateral range of root competition was 10 m and 20 m on Vertisols and Nitosols respectively. Where the productivity of wheat and tef were influenced by the presence of trees (near the tree line), yields were reduced by about 25-93 %, which is equivalent to a yield loss of 4.5-26 % per ha. These yield reduction levels are lower than those reported for unilateral eucalyptus alley system in other semi-arid regions. In spite of the low tree density and the long payoff period, tree-wheat production systems' net present values are 1.3 and 1.7 times higher than for sole wheat cropping on Vertisols and Nitosols respectively. In addition risks, associated with weather and price are higher for sole cropping than for mixed tree–cropping. Thus *Eucalyptus* boundaries would help the smallholder farmers to increase income and achieve food security, which leads to stabilizing the livelihood of resource poor farmers.

We evaluated the allelopathic potential of eucalyptus under field and controlled laboratory conditions. The results revealed that the litterfall, which is the source of bioactivity compounds in the soil system, followed the annual cycle of rainfall pattern. This causes litterfall to be well separated in space and time from the cropping period. The presumed environmental impact, as demonstrated for litter extract, has little ecological relevance to the current eucalyptus-crop production system. Because the bioactive chemicals released from eucalyptus either do not accumulate in sufficient concentration to affect seed germination and root growth of agricultural crops or are oxidized fast enough in the soil to be harmful. However, nutrient immobilization as a result of litter decomposition can persist over several months after litter incorporation. This will then overlap with early crop establishment where nitrogen deficiency can limit crop growth and hence crop yield across the tree-crop interface. Allelochemicals, aside from playing an important role in plant-plant interference do play an important role in influencing soil microbial ecology and nutrient dynamics. Thus further research should be conducted to assess a possible shift in microbial populations and the extent to which nutrient dynamics, particularly N, is influenced by eucalypt boundaries.

Our observation from a short (3 years) rotational eucalyptus based agroforestry system further revealed that highland Vertisols could support this intensive tree-crop production system. At the end of the three years rotation eucalyptus trees at stand densities of 1225, 833 and 625 stems ha^{-1} had produced 5, 3.6 and 2.7 Mg oven dry aboveground biomass per hectare with a cumulative crop yield losses of 6 to 21 %, respectively. Land equivalent ratios (LER) in the agroforestry system ranged between 1.21 to 1.69 depending on cropping sequence and tree density. In the three years period, sole crops removed 3 to 4 times more N and 5 to 10 times P compared with three-year-old eucalyptus stands. The mean annual accumulation rates in the standing tree biomass ranged between 8 to 13 kg N and 1.5 to 2.5 kg P ha^{-1} with the tree densities from 625 to 1225 stems ha^{-1}. However, provided that the leaf fraction, which accounts for 20 % of the total tree biomass, is recycled back into the soil system the total amount of N and P removed in the agroforestry system can be reduced 32 to 45 %. Thus a short rotation eucalyptus based agroforestry system can be utilized to meet wood demand without inducing significant nutrient depletion and crop yield loss in seasonally waterlogged highland Vertisols.

Soil erosion is a threat to agricultural production in Ginchi watershed. This was revealed from a large erosion plot study that evaluated the soil conservation efficiency of short rotational eucalyptus based agroforestry system. Our results show that integration of eucalyptus into agricultural crops cuts down soil erosion rates to the tolerable limits in seasonally waterlogged highland Vertisols. Although farmers in the studied watersheds are aware of erosion, and can pinpoint erosion indicators, adoption of soil and water conservation (SWC) practices is low. Factors like farming experience, the source of the land, and severity of erosion are of greater influence on the adoption of SWC measures than land security.

In summary, the empirical studies revealed that the environment in seasonally waterlogged highland Vertisols is suitable to intensify the present day annual sole cropping. In the near future it is inconceivable to get other species, be it indigenous or exotic, that can substitute *Eucalyptus* in a full range of benefits it provides in the highland Vertisols where identification and promotion of multipurpose trees for soil and water conservation is remain a challenge. Therefore, there must be a step by step strategy to reach a judicious resource utilisation that increases sustainable production in the farming systems. For highland Vertisols the role of *Eucalyptus* boundary plantings is far reaching when it is evaluated in its potential contribution to the farming system through its substitution of dung. Under appropriate management practices dung is a renewable and sustainable soil improvement resource because of its role in the maintenance of physical and chemical soil properties. Consequently it leads to a higher productivity of the farming systems. Boundary plantings are economically viable and fits very well in mixed smallholder farming systems on highland Vertisols. Likewise, the proposed short rotational eucalyptus based agroforestry system cuts down soil erosion to tolerable limits, reduces runoff and increases the total amount of available water for biomass production. Since *Eucalyptus* trees capture the runoff and soil, which would otherwise had lost from sole cropping. These effects justify its integration of eucalyptus in traditional sole cropping system there by compensating for part of the extra resource required for their growth. Therefore, the farmers' choice to plant *Eucalyptus* species on seasonally waterlogged highland Vertisols must be acknowledged by policy makers.

We may now answer the research *question* as outlined in Chapter 1.

1. Why do farmers plant competitive eucalyptus trees on their farmlands?

With a rising demand and a reduced natural supply of tree products, eucalypt boundary plantings provide returns to the household factors of production and consumption.

2. Is the resource base enough to support an intensified tree-crop system on a sustainable basis?

The natural environment is suitable to intensify annual sole cropping and a tree-crop system does not induce significant nutrient depletion provided the leaf fraction is recycled back into the soil system.

3. Is the allelopathic potential of eucalyptus a real treat to the environment?

The peak litterfall season is well separated from the cropping period and the litter losses its phytotoxicity long before crops are planted due to subsequent abiotic and biotic soil processes.

4. Does the alternative resource utilization efficiency of eucalyptus justifies its integration into the prevailing agricultural system on highland Vertisols?

Growing eucalyptus for firewood as an alternative to dung fuel brings back 10 to 26 times more NPK into the farming system as organic fertilizer for every kg of NPK removed with wood harvest (stem and branches).

5. Are there opportunities to optimize resource use complementarity in an eucalyptus based agroforestry system?

Proper cropping sequence (chickpea-tef- wheat), tree row orientation (north-south) and response farming (pruning trees in dry years) increase complementarity in eucalyptus based agroforestry system.

6. Can productive and protective functions in an eucalyptus based agroforestry system compliment each other?

An eucalyptus based agroforestry system can be more productive (combined yield of tree and crop products) and more sustainable than the traditional sole cropping practice.

Samenvatting

Deze studie onderzoekt de productieve- en beschermende functies van *Eucalyptus globulus* op bos-landbouw systemen op vertisolen in de hooglanden van Ethiopië. Het Ginchi stroomgebied is qua omgevingsfactoren een representatief stroomgebied in de Centrale Hooglanden van Ethiopië, met productie systemen op vertisolen. Het stroomgebeid werd voor deze studie gekozen als proefgebied. De belangrijkste uitkomsten van de studie worden hieronder samengevat.

In de laatste drie decennia hebben in het Ginchi onderzoeksstroomgebied, veranderingen in landgebruik en in bodembedekking plaats gevonden. De belangrijkste verandering is een toename in gecultiveerd gebied ten koste van grasland. Alhoewel minder dramatisch, bossen en bomen langs de rivieroever zijn ook in oppervlak en aantal achteruitgegaan. De drijvende kracht achter de veranderingen in landgebruik was blijkbaar de behoefte om meer voedsel en vezelproducten te produceren, om de altijd maar toenemende bevolking te onderhouden. Door de jaren heen nam het met geulen doorsneden akkerland met 36% af, terwijl het op het grasland areaal, en met name het bovenstrooms gedeelte van het stroomgebied vertienvoudigde. Eenmaal gevormd, wordt de afvoer van sediment door de geulen vergroot door een toename van de versnijding van het landschap, hetgeen weer leidt tot een toenemend gevaar van sediment depositie hellingafwaarts en daarenboven tot een significante uitdroging van het landbouwareaal tussen de geulen. Dit vraagt daarom om een alternatief begrazingsbeheer met tot doel de druk op de hellingen boven in het stroomgebied, het risico van degradatie van het milieu en het kwalijke effect beneden aan de helling, te verminderen.

Een analyse van de gemeten bovengrondse afstroming en de regenval data wees uit dat er bij het traditioneel op tef gebaseerde gewassensysteem op vertisolen in de hooglanden 23 – 40 % van de seizoensgebonden neerslag wordt omgezet in afstroming, hetgeen equivalent is aan 102 – 307 mm afstroming per hectare per jaar. Deze hoeveelheden, opgevangen in kleine bedrijfsstuwmeertjes, zijn genoeg om een tweede gewas te telen. De kleine bedrijfsstuwmeertjes zijn effectieve maatregelen om de afstroming te beheersen en het kan tegelijkertijd het risico van sediment depositie in grote waterreservoirs verminderen.

In het nabije verleden vormde perceelscheidingsbeplanting op akkerbouwpercelen de belangrijkste niche voor boomteelt in het Ginchi stroomgebied. De Eucalyptus boom is de dominante boomsoort in dit systeem. De bomen worden geplant als lijnvormige elementen met een onderlinge afstand van 1 m. Boomdichtheden in dit eenzijdige systeem variëren tussen de 90 en 120 bomen per hectare.. De op een na belangrijkste boomteelt niche is het woonerf. Hier hebben de bomen waarde vanwege de schaduw die ze geven, de esthetiek en de productie van brandhout en veevoeder. Het aanwenden van mest ten tijdens het zaaien c.q. poten van gewassen en het met strooisel of gewasresten bedekken, zijn de twee standaard werkwijzen, die gebruikt worden bij boomaanplant op boerenbedrijven. De meeste boeren geloven dat vegetatie resten erg effectief zijn bij het conserveren van bodemvocht, terwijl mest en ter plaatse afbrekende plantenrestengezien kunnen worden als een belangrijke bron van voedingsstoffen voor de jonge eucalyptus bomen. Om de kosten en het risico te spreiden gebruiken boeren een schema waarbij geleidelijke aanleg over een aantal jaren wordt geprefereerd.

Boeren planten bomen voor de productie van constructie hout, brandhout, afrasteringpalen, het afbakenen van eigendom en als handelsgewas. Bij de besluitvorming zijn voor de meeste boeren de ecologische doelen van secondair belang. De meest boeren in het Ginchi stroomgebied geven er de voorkeur aan om voornamelijk eucalyptus te planten. Bijkomende zaken zoals de

beschikbaarheid van plantmateriaal, de kwaliteit van het (rond)hout en de ervaring maakt *Eucalyptus globulus* tot de meest geprefereerde soort. Ervaring met de teelt, opleiding, agro-ecologische factoren (helling, bodemtype en drainage) werden beschouwd als zijnde van invloed op de beslissing tot aanplant.

De houtproductie van eucalyptus perceelscheidingsbeplanting op vertisolen varieert tussen 168 kg per hectare per jaar met een vierjarige houtopstand, tot 2900 kg per hectare per jaar voor een opstand van 12 jaar oud. Op nitisolen waar boeren korte rotatie perioden van 4 jaar gebruiken, was de houtproductie 903 kg per hectare per jaar in de eerste cyclus en verdubbelde in de tweede en derde rotatie cyclus. De hoeveelheid houtproductie van een eucalyptus randbeplanting in de Ethiopische hooglanden was drie tot vier keer hoger dan de maximale houtproductie van perceelsgewijze aangeplante *Eucalyptus globulus*. Met deze productiviteit, kunnen acht tot twaalf jaar oude eucalyptus randbeplantingen met per hectare 100 – 110 bomen een productie genereren, die voor 50 – 75 % tegemoet komt aan de biomassa behoefte van een locale boeren gemeenschap van 5 personen. Bijgevolg, kunnen eucalyptus randbeplantingen in een kort tijdsbestek een groot volume aan constructiehout en andere houtproducten produceren, zonder dat er een grote verandering in het landgebruik noodzakelijk is. Dit is een voordeel voor de kleine boeren die beperkt over land kunnen beschikken en die geen mogelijkheid hebben om bomen perceelsgewijs aan te planten.

De houtoogst van een hectare 8 jaar oude eucalyptus randbeplanting zou het potentieel hebben om 12 t koeienmest te vervangen, hetgeen op zijn beurt 176 kg N, 156 kg P en 60 kg K door organisch bemesting in het landbouw systeem brengt. Dit betekent, dat 1 kg stikstof verwijderd met geoogst hout (stammen en takken) het mogelijk maakt om 20 kg N als organische bemesting terug te brengen. In het geval van fosfor, brengt iedere kg verwijderd hout 26 kg P als organisch bemesting terug. Op een zelfde manier brengt iedere met hout verwijderde kg kalium 10 kg K als organisch bemesting terug. Aan de ander kant, als natuurlijk houtopstanden per hectare dezelfde hoeveelheid aan brandhout moeten opbrengen als eucalyptus randbeplanting dan heeft ieder boerenbedrijf 1.22 hectare per jaar nodig. Randbeplantingen helpen dus mee aan de bescherming van natuurlijke houtopstanden en behouden de biodiversiteit door vervangende producten voor de bosproducten te produceren. Dit kan ondermeer volbracht worden door boerenbedrijven toe te staan om intensive bosaanplant langs perceelsgrenzen toe te passen en daarbij te zorgen voor een optimale rotatie periode.

Echter, de boomcomponent beïnvloedt de opbrengst van de aangrenzende landbouwgewassen door een verandering van de voor de groei benodigde hulpmiddelen, zoals licht, water en mogelijk ook voedingsstoffen. De effectieve laterale wortelontwikkeling en wortelconcurrentie besloeg 10 – 20 m op vertisolen en nitisolen. Op plaatsen waar de productiviteit van tarwe en tef werd beïnvloed door de aanwezigheid van bomen (dichtbij de bomenrij) werden oogsten gereduceerd met 25 – 93 %, hetgeen equivalent is aan een vochtverlies van 4.5 – 26 % per hectare. Deze oogstreducties zijn lager dan (gerapporteerde gegevens) voor een eenzijdige 'laan'-boom-aanplant van eucalyptus in andere semi-aride regio's. Ondanks de lage boomdichtheid en de lange terugbetaalperiode, vertegenwoordigen boom-tarwe productie systemen een waarde die op vertisolen en nitisolen 1.3 tot 1.7 keer hoger liggen dan voor een eenzijdige rotatie van enkel tarwe. Daarenboven risico's geassocieerd met klimaat- en prijsverhoudingen zijn hoger voor enkelvoudige rotatie dan voor een mengteelt van bomen en gewassen. De eucalyptus randbeplanting zou de kleine boer kunnen helpen zijn inkomen te verhogen en voedselzekerheid te verschaffen, hetgeen leidt tot een stabieler bestaan voor de boeren, die weinig toegang hebben tot externe hulpmiddelen.

Onder veld- en laboratoriumomstandigheden hebben we de grondvergiftigende (allelopatische) eigenschappen van eucalyptus geëvalueerd. De resultaten wezen uit, dat de bladval, hetgeen een bron is voor bio-activiteit in de bodem, het jaarlijks regenpatroon volgde. Dit veroorzaakt een bladval, die in plaats en tijd gescheiden is van de gewasperioden. De aangenomen omgevingsinvloeden, zoals aangetoond voor blad extract, heeft beperkte ecologische relevantie in het gangbare eucalyptus-gewas productie systeem. Omdat de bio-actieve chemicaliën, die bij eucalyptus vrijkomen, of in een niet voldoende hoge mate accumuleren om het kiemen van zaad en de wortelgroei van gewassen te beïnvloeden of ze zijn snel genoeg geoxideerd om geen schade te berokkenen. De vastlegging van nutriënten kan echter enkele maanden na inwerking van bladstrooisel voortduren. Dit overlapt met een vroege zaai van de gewassen, waarbij stikstofgebrek de gewasgroei kan beperken en daarmee de gewasoogst in het boom-gewas systeem. Allelopatische chemicaliën spelen naast een belangrijke rol in de plant-plant verstoring ook een belangrijke rol in het beïnvloeden van de micro-ecology in de bodem en de nutriënten dynamiek. Nader onderzoek zou uitgevoerd moeten worden om de mogelijke verandering vast te stellen in micro-biologische populaties en de omvang van de nutriënten dynamiek, waar voornamelijk stikstof wordt beïnvloed door eucalyptus randbeplanting.

Onze observatie van een korte (3 jaar) rotatie van eucalyptus gebaseerd op een agro-bosbouw systeem bracht verder aan het licht dat vertisolen in de hooglanden dit intensieve boom-gewas productie systeem konden ondersteunen. Aan het eind van de drie jaar rotatie met eucalyptus bomen, met boomdichtheden van 1225, 833 en 625 stammen per hectare werd respectievelijk 5, 3.6 en 2.7 Mg oven droge bovengrondse bio-massa geproduceerd, gepaard gaand met een cumulatief verlies in oogstproducten van 6 – 21 %. Land Equivalente Ratio's (LER) in agro-bosbouw systemen varieerden tussen 1.21 en 1.69, afhankelijk van het gewas systeem en de boomdichtheid. In de drie jaar periode werd in een systeem met één gewas, 3 à 4 keer meer N opgenomen en 5 tot 10 keer meer P, vergeleken met een drie jaar rotatie van oude eucalyptus opstanden. De gemiddelde jaarlijkse accumulatie van nutriënten in boombiomassa varieerde tussen 8 – 13 kg N en 1.5 – 2.5 kg P per hectare met boomdichtheden van 625 – 1226 stammen per hectare. Echter, aannemende dat de bladfractie, die 20 % van de totale biomassa beslaat, gerecycled wordt en terugkomt in het bodem systeem, waarbij de totale hoeveelheid N en P die onttrokken wordt aan het agro-bosbouw systeem gereduceerd kan worden met 32 - 45 %. Als gevolg van een korte rotatie van eucalyptus in een agro-bosbouw systeem op vertisolen met seizoensgebonden water overlast kan worden gebruikt om de houtbehoefte te dekken zonder significante verliezen aan nutriënten en oogstproducten.

Bodemerosie is een gevaar voor de landbouw productie in het Ginchi stroomgebied. Dit kwam naar voren bij een studie op grote erosie proefvelden, waarbij de bodemconserverende effectiviteit van eucalyptus gebaseerd op een bos-landbouw systeem werd geëvalueerd. Onze resultaten tonen aan, dat integratie van eucalyptus en landbouwgewassen de bodemerosie op vertisolen met seizoensgebonden wateroverlast de bodemerosie kan terugbrengen tot acceptabele hoeveelheden. Ondanks dat boeren in de onderzochte stroomgebieden zich bewust zijn van de erosie en erosie indicatoren herkennen, is de adoptie van bodem en waterconserverende (SWC) maatregelen laag. Factoren, zoals ervaring van de boeren, herkomst van het land en de ernst van de erosie zijn van grotere invloed op de adoptie van SWC maatregelen dan land zekerheid.

Samenvattend bracht dit empirische onderzoek aan het licht, dat het milieu op hoogland vertisolen met seizoensgebonden wateroverlast geschikt is om het huidige landbouwsysteem met allen maar graan in de rotatie, te intensiveren. In de nabije toekomst is het ondenkbaar, dat er op hoogland vertisolen andere soorten, traditioneel of exotisch, die de *Eucalyptus* met het grote scala aan voordelen zou kunnen vervangen, terwijl daarnaast het identificeren en het promoten van bomen met meerdere functies een uitdaging blijft. Daarom, moet er een stapsgewijze strategie ontwikkeld worden om tot oordeelkundig landgebruik te komen, hetgeen de duurzaam productie in landbouwsystemen bevordert. Voor vertisolen in de hooglanden is de rol van Eucalyptus randbeplanting verreikend, tenminste wanneer het geëvalueerd wordt aangaande de potentiële bijdrage, die het levert, denkend aan de vervanging van mest. Bij toepassing van goede beheersmaatregelen is mest hernieuwbaar, daarbij verbetert het duurzaam de bodem, vanwege de rol die het speelt bij het onderhouden van de fysische en chemische bodemeigenschappen. Als gevolg leidt dit tot een hogere productie van de landbouw systemen.

Perceelscheidingsbeplantingen zijn economisch levensvatbaar en passen goed in een gemengd bedrijf van de kleine boer, die op de hoogland vertisolen zijn bedrijf voert. Evenzo brengt het voorgestelde bos-landbouw systeem, gebaseerd is op een korte rotatie met eucalyptus, de erosie terug tot aanvaardbare waarden. Bovendien wordt de bovengrondse afstroming gereduceerd, waardoor de totale hoeveelheid beschikbaar water voor biomassaproductie toeneemt.

Eucalyptus bomen vangen bovengrondse afstroming en bodemdeeltjes in, die bij tarweteelt alleen, verloren zouden gaan. Deze effecten rechtvaardigen de integratie van eucalyptus in traditionele enkelvoudige gewasrotatie systemen, waarbij compensatie plaats vindt van de extra voor de groei van het gewas benodigde hulpmiddelen. Daarom moet de boeren keuze om Eucalyptus soorten op gronden met seizoensgebonden wateroverlast in te zetten door politici erkend c.q. onderkend worden.

We kunnen nu overgaan tot het beantwoorden van de onderzoeksvragen zoals gesteld in hoofdstuk 1.

1. Waarom planten boeren eucalyptus bomen, die concurreren met het gewas, op hun landbouwgrond?

Met de toenemende vraag en de afnemende voorziening van houtproducten uit de natuur, kunnen eucalyptus randbeplantingen opbrengsten opleveren voor de boerenhuishouding.

2. Zijn de natuurlijke hulpbronnen toereikend om een geïntensiveerd boom-gewas systeem op een duurzame manier te ondersteunen.

Het natuurlijk milieu is geschikt om een enkelvoudig gewasrotatie systeem te intensiveren. Een boom-gewas systeem beïnvloedt niet significant de uitputting van nutriënten, er van uitgaande dat de bladfractie gerecycled wordt en terugkomt in het systeem.

3. Is het bodemvergiftigende werking (allelopatische) van eucalyptus een echte bedreiging van het milieu?

De piek in de bladval is gescheiden van het gewasseizoen en het strooisel verliest, dankzij abiotische en biotische processen, zijn bodemvergiftigende werking lang voor de gewassen worden gezaaid.

4. Wordt het effect van het alternatieve gebruik van de hulpbronnen door een geïntensiveerd eucalyptus teelt gerechtvaardigd door het te integreren in het meest voorkomende landbouw systeem op hoogland vertisolen?

Het telen van eucalyptus voor brandhout als een alternatief voor mest brengt als organische bemesting 10 tot 26 keer meer NPK terug in het landbouw systeem voor iedere kg NPK die verwijdert wordt bij de houtoogst (stam en takken).

5. Zijn er mogelijkheden om het gebruik van de hulpbronnen in een op eucalyptus gebaseerd bos-landbouw systeem complementair te optimaliseren.

Complementaire optimalisatie in een op eucalyptus gebaseerd bos-landbouw systeem kan worden gerealiseerd door een aangepaste rotatie (kekererwt-tef-tarwe), een noord-zuid oriëntatie van de bomen en verantwoorde landbouwpraktijken (snoeien van de bomen in droge jaren).

6. Kunnen de productieve en beschermende functies in een op eucalyptus gebaseerd bos-landbouw systeem elkaar aanvullen?

Een op eucalyptus gebaseerd bos-landbouw systeem (een gecombineerde oogst van boom en gewas producten) kan productiever en duurzamer zijn dan een traditioneel gewas systeem gebaseerd op één enkel gewas.

Curriculum Vitae

Selamyihun Kidanu was born in Harar, Ethiopia, on 21 June 1965. He attended elementary and secondary education at Gursum and Harar junior secondary school respectively. In 1988 he obtained a Bachelor of Science (BSc) degree in plant sciences at Alemaya Universality of Agriculture. In September 1988 he joined the Debre Zeit Agricultural Research Center of the Alemaya University. He obtained in February 1992 a Master of Science (MSc) degree in soil physics and chemistry from Ghent State University with distinction. The title of his thesis was 'Hydro-physical characterization and soil-water-air interactions of Ethiopian highland Vertisols'. From March 1992-April 1998; he served the Debre Zeit Agricultural Research Center of the Alemaya University of Agriculture as researcher, lecturer and Head, Crop Science Department of the Center. In this period he coordinated and executed various projects. From May 1998-April 1999 he worked as associate researcher at Debre Zeit Agricultural Research Center of the Ethiopian Agricultural Research Center. In April 1999 he was admitted to the PhD program of Erosion and Soil & Water Conservation Group, Department of Environmental Sciences Wageningen University and Research Center. The fieldwork was carried out from January 2000 to June 2003. The writing of the thesis was started early during this fieldwork and more intensively continued from June 2003-October 2003 in Wageningen.