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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.

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 y^{-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., 38º E, 9º 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 × 1 m in area and divided into a 5 × 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 (D) as:

$$Freshmass = 0.0887 * D^{1.868} * H^{0.8423}$$

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.

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.

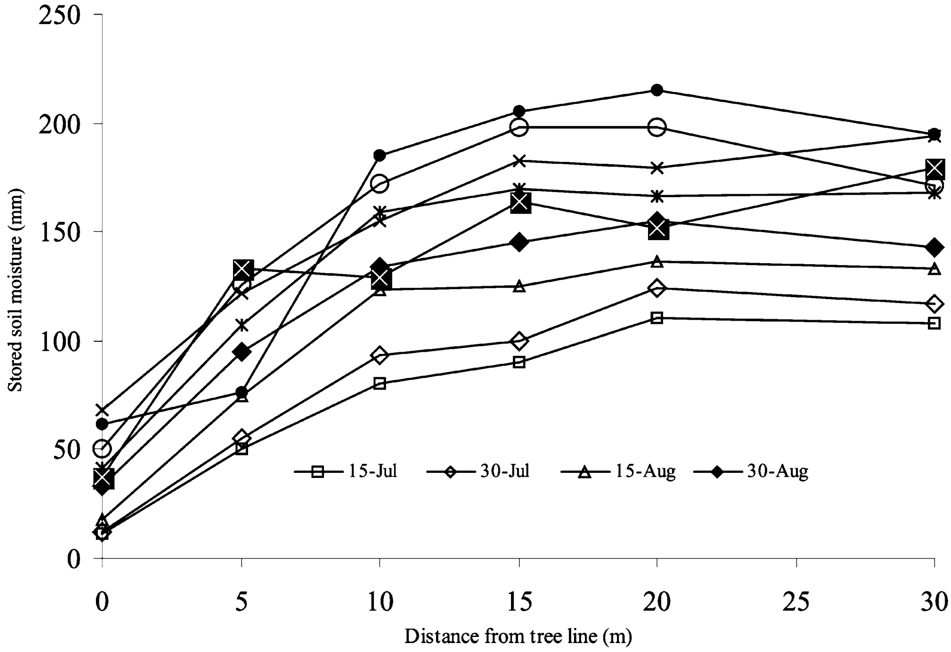

Figure 1. Available soil moisture in the top 1 m of wheat fields during the 2000 growing season as a function of the distance from eucalypt boundaries in Ginchi, Ethiopia.

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

Soil moisture use

The total precipitation received in year 2000 was 266 mm less than the long-term average (1200 mm). Nevertheless, precipitation during crop growing season (i.e., June to September), was followed the expected long-term rainfall pattern; peaked in August and leveled off during September. 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

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	Distance from tree line											
(cm)	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			

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 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 (Table 3, Table 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.

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 ($P \leq 0.05$).

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 (Table 3, Table 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 (Table 3, Table 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 (Table 3, Table 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 fac-

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	Stand age (years)					
	4		8		12	
(m)	N/S*	E/W	N/S	E/W	N/S	E/W
Tef						
24	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.

ing 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.

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).

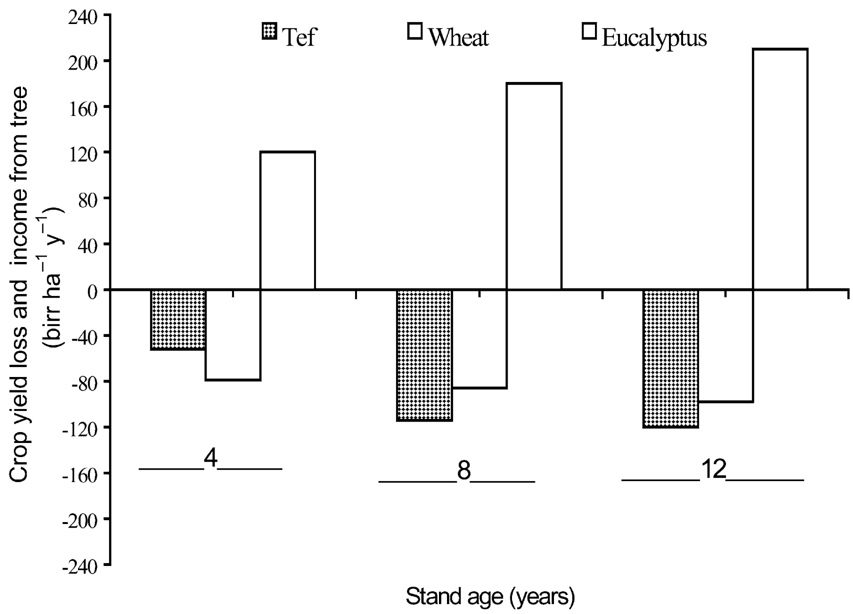

Figure 2. Crop yield losses incurred due to eucalypt boundaries versus additional income generated through the sales of wood and wood products at Ginchi, Ethiopia. (1 US \$ = 8 Ethiopian birr in 2000)

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 the adjacent cropped area they occur in a hexagonal pattern. This affirms the results of Eswaran and Cook (1988) who speculated that the orientation and pattern of surface cracks development in Vertisols is 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 results 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.

References

Bojo J. and Cassels D. 1995. Land degradation and rehabilitation in Ethiopia: A reassessment. AFTES Working Paper No. 7. The World Bank, Washington, DC.

EFAP 1993. Ethiopian forestry action program: Final report. Ministry of Natural Resource Development and Environmental Protection. Addis Ababa, Ethiopia, pp 63.

Eswaran H. and Cook T. 1988. Classification and management related properties of Vertisols. In Jutzi S.C., Haque H., Mclntire J. and Stares J.E.S. (eds), Management of Vertisols in sub-Saharan Africa. Proceedings of a conference held at ILCA, Addis Ababa, Ethiopia 31 August- 4 September 1987. 64–84 pp

FAO (Food and Agriculture Organization of the United Nations) 1985. The ecological effects of Eucalyptus. FAO Forestry Paper No. 59, Rome, pp 85.

Gezahegn A. and Tekalign M. 1995. Determinants of demand for fertilizer in Vertisol cropping systems of Ethiopia. Tropical Agriculture (Trinidad) 72: 165–169.

IUCN 1990. Workshop Report on Human Population Dynamics and Resource Demand; 30 Nov. to 1 Dec., 1990; The World Conservation Union 18th General Assembly, Perth, Australia.

Khybri M.L., Gupta R.K., Sewa R. and Tomar H.P.S. 1992. Crop yields of rice and wheat grown in rotation as intercrops with tree species in the outer hills of Western Himalayas. Agroforestry Systems 17: 193–204.

Lisanework N. and Michelsen A. 1993. Allelopathy in agroforestry systems: the effects of leaf extracts of *Cupressus lustanica* and three *Eucalyptus* spps. on four Ethiopian crops. Agroforestry Systems 21: 63–74.

Malik R.S. and Sharma S.K. 1990. Moisture extraction and crop yield as a function of distance from a row of *Eucalyptus tereticornis*. Agroforestry Systems 12: 87–128.

Michelsen A., Lisanework N. and Friis I. 1993. Impacts of tree plantation in the Ethiopian highland on soil fertility, shoot and root growth, nutrient utilization and mycorrhizal colonization. Forest Ecology and Management 61: 299–324.

MSTAT- C 1991. A microcomputer program for the design, management and analysis of agronomic research experiments. Michigan State University, East Lansing, Michigan, USA.

Ong C.K., Black C.R., Marshall F.M. and Corlett J.E. 1996. Principles of resource capture and utilization of light and water. In: Ong C.K. and Huxley P. (eds), Tree-crop interactions. A Physiological approach. CAB International, Wallingford, UK. 73–158.

Onyewotu L.O.Z., Ogigirigi M.A. and Stigter C.J. 1994. A study of the competitive effects between a *Eucalyptus camaldulensis* shelterbelt and adjacent millet (*Pennisetum typhoides*) crop. Agriculture, Ecosystems and Environment 51: 281–286.

Peter D.B. 1965. Water availability.. In: CA Black (eds), Methods of soil analysis. Part I. Physical and mineralogical methods. Agronomy Monograph No. 9, Madison, Wisconsin, pp 279–285

Pohjonen V. and Pukkala T. 1990. *Eucalyptus globulus* in Ethiopian Forestry. Forest Ecology and Management 36: 19–31.

Pukkala T. and Pohjonen V. 1989. Forest inventory and management planning in the fuelwood plantations of Ethiopia. Faculty of Forestry, Joensuu University, Finland, pp 110.

Rao M.R. and Coe R.D. 1991. Measuring crop yields in on-farm agroforestry studies. Agroforestry Systems 15: 275–289.

Striling C.M., Williams J.H., Black C.R. and Ong C.K. 1990. The effect of timing of shade on developments dry matter production and light use efficiency in ground net (*Arachis hypogaea*) under field condition. Australian Journal of Agricultural Research 41: 633–644.

Teklu E., Selamyihun K., Tekalign M. and Mesfin A. 1999. Effects of land preparation methods on runoff and soil loss on Vertisols at Ginchi (Ethiopia). Ethiopian Journal of Natural Resources 2: 1–15.

Van Noordwijk M., Lawson G., Soumare A., Groot J.J.R. and Hairiah K. 1996. Root distribution of trees and crops: Competition and/or complementary.. In: Ong C.K. and Huxley P. (eds), Tree-crop interactions. A Physiological approach. CAB International, Wallingford, UK, pp 319–364.

Verinumbe I. 1987. Crop production on soil under some forest plantations in the Sahel. Agroforestry Systems 5: 185–188.

Zohar Y. 1985. Root distribution of a Eucalyptus shelterbelt. Forest Ecology and Management 12: 305–307.