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WATER INFILTRATION, CONDUCTIVITY AND RUNOFF UNDER FALLOW AGROFORESTRY ON SLOPING TERRACES

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ABSTRACT

Appropriate management of available water supplies is essential to prolong the growing season and optimise the effectiveness with which rainfall is used for agricultural production. The present study examined the impact of planting tree fallows (*Alnus acuminata, Calliandra calothyrsus and Sesbania sesban*) on the degraded upper sections of sloping terraces on water infiltration and subsequent runoff on a Haplic ferralsol in southwestern Uganda. Infiltration measurements, done by a tension infiltrometer, were conducted under 3-year old tree canopies, under maize stands grown adjacent to trees, and under sole maize *(Zea mays)*. Runoff from confined plots of agroforestry (trees on upper and crops on lower terrace sections) and sole crop systems were measured by the tipping bucket method mounted with counters. Measurements of runoff was done during the long rains of 2003 and short rains of 2004. Infiltration was invariably higher under agroforestry systems ($P<0.001$) than sole cropping, particularly under *Alnus* and *Calliandra* systems. A similar pattern was observed for saturated hydraulic conductivity (Ksat), which was greater in all tree-based systems except *Sesbania* than in the sole crop ($P<0.01$). The Ksat values were 1.3, 2.2, 1.0, and 0.8 cm h^{-1} respectively under *Alnus, Calliandra, Sesbania* and sole crop systems. Of even greater significance is the ability of trees to reverse the typical gradient in soil hydraulic properties observed on sloping terraces. Saturated hydraulic conductivity was consistently higher on the upper terrace than the lower terrace in the tree-based systems ($P<0.01$), whereas the reverse was true for the sole cropping system. During rainfall events of <10 mm, runoff accounted for only <4% of total rainfall in all treatments. The reduction in runoff relative to the sole crop control was 64, 84, and 96 in the *Alnus, Calliandra,* and *Sesbania,* respectively. During high rainfall events (>10mm) the effect of agroforestry was more dramatic, reducing runoff relative to the sole crop by 92, 76, and 91, respectively under *Alnus, Calliandra*, and *Sesbania* systems. Results demonstrate the ability of trees to break loose the hard compacted soils on the upper terrace part so as to increase infiltration. The resultant increase in infiltration coupled with physical barriers of ground litter combine to reduce runoff under agroforestry systems.

Key Words: *Alnus acuminata, Calliandra calothyrsus, Sesbania sesban*, southwestern Uganda

RÉSUMÉ

Une gestion appropriée des sources d'eau disponibles est essentielle en vue de prolonger la saison de croissance et optimiser l'efficacité avec laquelle l'eau de pluie est utilisée pour la production agricole. Cette étude a examiné l'impact de la pratique consistant à cultiver sur des jachères de bois au niveau des sections supérieures dégradées des terrasses en pentes sur infiltration d'eau et ruissellement subséquent sur un sol 'Haplic ferrasol' dans le Nord de l'Ouganda. Des mesures de l'infiltration faites à l'infiltromètre à tension on été effectuées sous couvertures d'arbres âgés de trois ans, sous des futaies de maïs cultivés à côté d'arbres et sous des cultures de mais non-mélangées *(Zea mays)* le ruissellement en provenance de parcelles confinées d'agroforesterie (Arbres dans les sections supérieures et cultures dans les sections plus basses des terrasses) et des systèmes de cultures non-mélangés étaient mesurés à l'aide de la méthode du seau monté de compteurs (Tipping bucket). Les mesures de ruissellement étaient conduites durant les longues pluies de 2003 et les courtes pluies de 2004. L'infiltration était invariablement plus élevée sous les systèmes d'agroforesterie (P<0.001) que sous les cultures non-mélangées en particulier sous les systèmes *Alnus* et *Calliandra*. Un motif particulier de tendance a été observé pour la conductivité hydraulique saturée (Ksat) qui était plus élevée dans tous les systèmes centrés sur les arbres à l'exception de Sesbania plus que dans les cultures non-melangées (P<0.01). Les valeurs Ksat étaient 1.3, 2.2, 1.0 et 0.8 respectivement sous *Alnus, Calliandra, Sesbania* et les systèmes de cultures non-mélangés. La capacité arbres inverser le gradient typique dans les propriétés hydrauliques du sol observées sur terrasses en pentes est même d'une plus grande signification. La conductivité hydraulique sature tait plus élevée de manière stable sur les hautes terrasses que sur les terrasses plus basses dans les systèmes à arbres (P<0.01) tandis que l'inverse était vrai pour les cultures non-mélangées. Au cours de précipitations inférieures à 10 mm, le ruissellement s'élevait à seulement 4% de pluie tombée au total dans tous les traitements. La réduction en ruissellement en rapport avec le contrôle monocultural était de 64.84696 dans les systèmes *Alnus, Calliandra* et *Sesbania*. Les résultats démontrent la possibilité que présentent les arbres à percer les sols durs et compacts des parties supérieures des terrasses en vue d'accroître l'infiltration. L'augmentation qui se produit en conséquence est couplée à la barrière ses déchets au sol et s'allie pour réduire le ruissellement sous les systèmes d'agroforesterie.

Mots Clés: *Alnus acuninata, Calliandra calothyrsus, Sesbania sesban*, sud-Ouest de l'Ouganda

INTRODUCTION

The rate of infiltration of water into the soil, its subsequent movement in the soil matrix and surface runoff are important considerations in developing soil management practices which increase rainfall use efficiency and maintain a favorable soil water status that is crucial for plant and soil health. Land use systems may alter infiltration and runoff through their effect on soil structure and micro-topographical modifications, as well as by providing physical barriers to runoff (Young, 1997). Appropriate land use systems may greatly enhance *in situ* conservation of water by increasing infiltration and reducing runoff (Lal, 1996). Infiltration and runoff interact to determine the quantity of water stored in the soil matrix as any rainfall, which exceeds the infiltration capacity, or prevailing soil moisture deficit is usually lost as runoff. Thus, on the steeply sloping hillsides of southwestern (SW) Uganda, arable farming is often constrained by runoff of rainfall, which cannot infiltrate into the soil sufficiently rapidly, causing erosion and reducing the quantity of water and fertile topsoil available for crop production (Bagoora, 1993). In such environments, where erosion has been reported to range from 10 to 500 t ha^{-1} yr^{-1} (Bagoora, 1993), agroforestry technologies such as contour hedgerows of *Calliandra calothyrsus, Leucaena diversifolia* and *Alnus acuminata* have been showed to be effective in controlling runoff by over 65% (AFRENA, unpublished data). However, the current understanding of the importance of agroforestry in increasing infiltration and reducing runoff is limited primarily to contour-planted hedgerows (Kiepe, 1995) yet many other systems are practiced on hillslopes, including improved fallows and rotational woodlots. A sound understanding of the hydrological functioning of these agroforestry systems is key in developing management interventions that increase water use efficiency, yield and sustainability. The work reported in this paper aimed to establish:

(i) the impact of short-duration woodlot land use systems on infiltration and soil hydraulic conductivity on terrace benches in SW Uganda

(ii) whether incorporating trees on the upper terrace sections reduces runoff and increases infiltration, thereby increasing the supply of water to support tree and crop growth.

MATERIALS AND METHODS

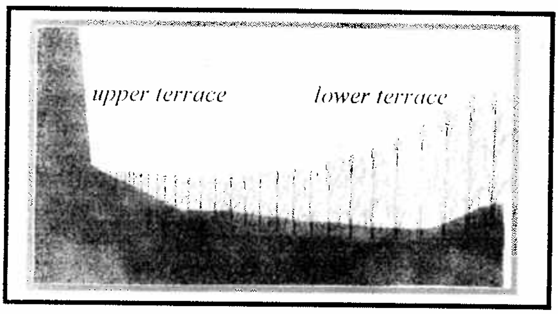
Study location and design. The study was conducted in Kabale district, southwestern Uganda on gently sloping (10 % gradient) terraced farmland (latitude 1°15" S, longitude 29° 55" E, altitude 1850 m above sea level). The soil was a Haplorthox (Haplic ferralsol) with a sandy clay loam texture. The area receives a bimodal annual rainfall of *c*. 1000 mm. Mean maximum and minimum temperatures are 23 and 10 °C, respectively. Measurements of infiltration and runoff were made on a 3-year old trial originally designed to examine the role of tree fallows and woodlots in the rehabilitation of the degraded upper terrace sections. The terrace benches exhibit systematic variation in crop production, with yields being low on the upper section and much higher on the lower terrace (Fig. 1a). In the present study, trees were grown on the upper terrace for three years (Fig. 1b) before being harvested, while cropping continued on the lower terrace. The tree species used were *Alnus acuminata*, *Calliandra calothyrsus* and *Sesbania sesban*; a mixture of the three species was also examined. A sole cropping treatment was included as a control for comparison purposes. The experiment was an unbalanced split plot design containing three blocks.

Measurement of infiltration. In recent years, tension infiltrometers have become the standard approach for *in situ* measurements of infiltration and hydraulic conductivity in agricultural soils and assessments of water movement through macropores and the soil matrix (Reynolds *et al.*, 2000). This approach has several advantages over the double ring method: (i) soil pore structure is not disturbed by driving rings into the soil to determine one-dimensional flow; (ii) only steady-state infiltration measurements are needed and no knowledge of antecedent moisture regimes is required; and (iii) measurements are more rapid and less water is required.

Tension infiltrometers measure infiltration rates induced by pressures below atmospheric, i.e., negative pressures or tensions. This design feature permits measurement of water flow properties in soil by excluding macropores with diameters of 0.1 cm or larger, which may otherwise dominate infiltration (Watson and Luxmoore, 1986), as water only flows within the soil matrix and pores up to 0.1 cm in diameter. The contribution of macropores to infiltration and hydraulic conductivity may be assessed by varying the negative pressure head at the soil surface (Holden *et al.*, 2001).

Infiltration measurements were conducted between March and April 2004, a period that provided the wetting front needed for reliable infiltration measurements, especially at higher pressure heads. Infiltration was measured on both the upper and lower terrace sections; in the agroforestry systems, this involved making measurements under the trees on the upper terrace

(a). Sole crop showing gradient on terrace



(b). Tree fallows on upper terrace

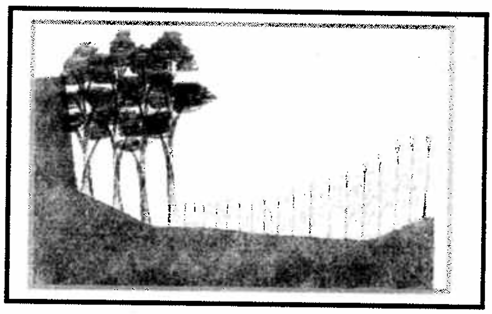


Figure 1. Variation in crop yield on terrace benches: (a) sole crop; (b) trees integrated on the upper terrace while cropping continues on the lower terrace.

and on the cropping area on the lower terrace. Infiltration was measured at two randomly selected locations on both the upper and lower terrace sections in all replicate plots of the three treatments examined. The need for replicated infiltration measurements was demonstrated by previous observations that soil hydraulic properties on terrace benches are highly variable, exhibiting coefficients of variation ranging from 30% to over 200% (Siriri, 1997).

Before commencing measurements, surface vegetation and loose large soil aggregates were removed from the soil surface to provide a level surface on which to place the infiltrometers. A 10 mm thick layer of moist fine sand with the same diameter as the circular base of the infiltrometer was applied at each location to eliminate surface irregularities and ensure good contact between the soil and the base of the infiltrometer. Porous disk infiltrometers were placed on the sand at each measurement location and infiltration was measured using pressure heads of –6 and –3 cm. Measurements were made using the -6 cm pressure head first avoid hysteresis (Reynolds and Elrick, 1991). Infiltration measurements continued until a steady state was achieved, defined as when the water level in the infiltrometer reservoir remained constant for at least 10 minutes. Infiltration rate was recorded as the depth of water entering the soil per unit time (cm min^{-1}).

The objectives of using two supply heads were twofold: (i) to enable hydraulic conductivity to be calculated using the method developed by Reynolds and Elrick (1991), which produces two unknown parameters which can only be solved using Eq. 5 and 6 below; and (ii) to estimate the contribution of small pores to the infiltration process relative to flow in the soil matrix based on observations that, according to capillary theory, water flows through small pores with diameters of up to 0.1 cm when a pressure head of -3 cm is applied, whereas flow is predominantly through the soil matrix when a -6 cm pressure head is used (Baird, 1997). The results may be used to assess the influence of the different land use systems on the distribution and connectivity of small pores in the soil.

Deriving saturated hydraulic conductivity (K_{sat}). Saturated hydraulic conductivity was calculated from the steady-state infiltrometer data using the method described by Reynolds and Elrick (1991) in which Wooding's solution for infiltration from a shallow pond (Wooding, 1968) is combined with Gardner's (1958) unsaturated hydraulic conductivity function. Wooding proposed Eq. 1 to estimate steady-state unconfined infiltration rates into soil from a circular source of radius r:

$$Q = \pi r^2 K \left(\frac{1 + 4}{\pi r \alpha}\right) \quad (1)$$

where Q denotes the volume of water entering the soil per unit time ($cm^3\ h^{-1}$), K represents its hydraulic conductivity ($cm\ h^{-1}$) and α is a constant for the soil at a specified tension, h (cm). In the present study, a disk with a radius of 9.875 cm was used as a water source. According to Gardner (1958), K at a specified tension, h, is related to the saturated hydraulic conductivity (K_{sat}) of the soil by the relation:

$$K(h) = (K_{sat}) exp(\alpha h) \quad (2)$$

The measured infiltration values were converted to Q values ($cm^3\ h^{-1}$) as follows:

$$Q(h) = \pi r_i^2 INFIL * 60 \quad (3)$$

where r_i is the internal radius of the water tube (2.25 cm in the present study).

K from Eq. 1 was substituted with $K_{sat}exp(\alpha h)$ from Eq. 2 for each of two Q values, Q_1 and Q_2, corresponding to the two tensions applied, h_1 and h_2, respectively to provide Eq. 4 and 5:

$$Q_2 = \pi r^2 (K_{sat} Exp(\alpha h_2)) \left(\frac{1+4}{\pi r \alpha}\right) \quad (4)$$

$$Q_1 = \pi r^2 (K_{sat} Exp(\alpha h_1)) \left(\frac{1+4}{\pi r \alpha}\right) \quad (5)$$

Dividing Eq. 5 by Eq. 4 and solving for α provides Eq. 6:

$$\alpha = \frac{1n\ (Q2 \div Q1)}{h_2 - h_1} \quad (6)$$

The value of α for each infiltration measurement was calculated using Eq. 6 and then used to compute K_{sat} by solving Eq. 4 and 5 for this parameter; these were respectively re-written as Eq. 7 and 8:

$$K_{sat} = \frac{Q_1}{\pi r^2 \alpha * b_1 * c} \quad \text{.......} (7)$$

where $b_1 = Exp(\alpha h_1)$ and $c = 1 + \frac{4}{\pi r \alpha}$

$$K_{sat} = \frac{Q_2}{\pi r^2 \alpha * b_1 * c} \quad \text{.......} (8)$$

where $b_2 = Exp(\alpha h_2)$

Measurement of runoff. Measurements of runoff were made between October 2003 and May 2004, a period which included rainfall events within the 2003/4 long (September to February) and 2004 short rains (March to June), corresponding to the two cropping seasons in Kabale District. Runoff was measured for 12 rainfall events (Table 1) using the runoff plots (5 m long by 12 m wide) that were enclosed within 15 cm wide galvanized iron sheeting retained by pegs. Enclosure of the run-off plots prevented run-on from uphill areas and ensured that runoff was measured only for the treatment plots. Runoff was channeled through gutters to tipping buckets fitted with counters, which were calibrated to measure 3 liters of runoff per tip. The counters recorded the number of tips and any remaining runoff in the buckets was measured manually using a measuring cylinder. To avoid spillover of runoff to neighboring downhill plots, runoff from tipping buckets was drained into pits dug at the lower end of the terraces. Runoff was recorded for all day-time rainfall events and some night-time events. Runoff was calculated as a proportion of rainfall recorded by the automatic weather station as follows.

TABLE 1. Dates of runoff measurement and total rainfall (mm) received

Date	Total rainfall [mm]
6 Nov. 2003	2.8
26 Nov. 2003	9.1
27 Jan. 2004	4.5
29 Feb. 2004	5.5
8 Mar. 2004	2.7
13 Mar. 2004	20.2
31 Mar. 2004	14.4
4 Apr. 2004	21.6
12 Apr. 2004	18.8
24 Apr. 2004	14.0
2 May 2004	35.9
5 May 2004	22.8

$$\text{Runoff coefficient} = [R_{off}/P_g]100 \quad \text{.......} (9)$$

where R_{off} denotes runoff (mm) and P_g represents gross rainfall (mm).

During each event, rainfall was recorded by the weather station installed at the experimental site and also at the government weather station located less than 2 km from the site. The volume of runoff recorded during each rainfall event was recalculated as runoff per unit land area (l m^{-2}). To elucidate the relationship between the quantity of rainfall and runoff, runoff was also recalculated as the corresponding depth of water (mm) to match the units used for rainfall, based on the assumption that 1 l m^{-2} corresponds to a standing depth of water of 1 mm.

Statistical analysis. The results obtained for infiltration, hydraulic conductivity and runoff were analysed using the Genstat 8.11 statistical package. Due to the unbalanced nature of the experimental design, the analysis involved linear modelling using the REML (residual maximum likelihood) approach (Patterson and Thompson, 1971). The study site was also characterized by inherent variability within blocks which, if not accounted for, would constitute a source of variation influencing treatment effects. In addition to blocking, site variability was assessed by growing an initial cover crop before establishing the treatments. Local variability in the performance of the cover crop was used as a covariate to remove any confounding effect on the actual variation between the treatments examined. Covariance analysis was carried out under the REML schedule for all parameters assessed. Two types of covariate were used. During analysis of infiltration and hydraulic conductivity, the initial crop yield data were used, as productivity is strongly related to soil water storage capacity, which in turn depends on infiltration and hydraulic conductivity. For analysis of runoff, the slope of individual plots was used as a covariate due to its strong direct linear influence on runoff.

RESULTS

Effect of land use systems on infiltration and hydraulic conductivity. Table 2 shows the mean values for infiltration rate and hydraulic conductivity on the upper and lower terrace sections. Infiltration was invariably substantially greater when a pressure head of -3 cm rather than -6 cm was used (P<0.001). In both cases, infiltration differed between treatments (P<0.001), with the highest and lowest values being found in the Alnus and sole crop systems. There was no significant difference in infiltration between the Alnus, Calliandra and tree mixture systems at a pressure head of -3 cm, although the values were greater than in the sole crop treatment (P<0.001). Infiltration in the Sesbania system did not differ significantly from the sole crop treatment. At a pressure head of -6 cm, infiltration rates were greater in the Alnus and tree mixture systems than in the sole crop (P<0.001).

A similar pattern was apparent for saturated hydraulic conductivity (K_{sat}), which was greater in all tree-based systems except Sesbania than in the sole crop (P<0.01). However, variability between replicate values was high, averaging 91%, which may have masked genuine treatment differences.

Figure 2 shows treatment effects on infiltration on the upper and lower terrace sections, corresponding to the areas where the trees and crops were grown in the agroforestry systems. Comparison of the two terrace positions should provide information on the extent to which the land use systems examined modified these gradients.

No significant interaction between land use and terrace position was detected, perhaps due to the highly variable hydraulic properties within individual plots. However, important differences between treatments were nevertheless apparent (Fig. 2). At a pressure head of -3 cm, infiltration rate on the upper terrace was invariably greater in the agroforestry treatments than in the sole crop (P<0.05), with the highest value being recorded under *Alnus*. As infiltration at a pressure head of -3 cm reflects the contribution of small pores (Baird, 1997), the agroforestry treatments apparently increased pore-driven infiltration relative to the sole cropping system. The increase in infiltration rate on the upper terrace relative to the sole crop was 97, 55, 49 and 45%, respectively, in the *Alnus*, tree mixture, *Calliandra* and *Sesbania* systems.

Although infiltration rates might be expected to be similar on the lower terrace section as this was under continuous cropping in all treatments, infiltration rate on the lower terrace was again

TABLE 2. Effect of land use systems on mean infiltration rate and saturated hydraulic conductivity on the upper and lower terrace sections

Land use system	Infiltration rate [cm h^{-1}] Pressure head		Saturated hydraulic conductivity K_{sat} [cm h^{-1}]
	-3 cm	-6 cm	
Alnus acuminata	21.4	12.6	1.3
Calliandra calothyrsus	19.4	8.0	2.2
Sesbania sesban	15.6	9.2	0.9
Tree mixture	18.6	10.7	1.2
Sole crop	12.7	7.3	0.8
SED	2.0***	1.3***	0.4**
CV (%)	23	38	91

** and *** respectively denote P<0.01 and P<0.001

greater in all agroforestry systems than in the sole crop treatment at –3 cm pressure head ($P<0.001$; Fig. 2a), demonstrating the substantial spatial influence of trees planted on the upper terrace. Of the agroforestry systems examined, Calliandra exhibited the greatest infiltration rate relative to the sole crop ($P<0.001$). The relative increase in infiltration rate relative to the sole crop was 53, 46, 64 and 22% respectively in the Alnus, tree mixture, Calliandra and Sesbania systems.

At pressure head of -6 cm, flow is predominantly through the soil matrix. Treatment differences and the absolute values for infiltration rate were much smaller at a pressure head of -6 cm than at -3 cm (Fig. 2b), and the increase in infiltration rate in the agroforestry systems relative to sole crop was also smaller (Fig. 2a, b). Infiltration rates on the upper and lower terrace sections were again greatest in the Alnus system, although the values were not significantly greater than in the tree mixture; the values for both treatments were greater than in the sole crop ($P<0.001$). Infiltration rates in the Calliandra and Sesbania systems did not differ significantly from the sole crop control.

Influence of land use system on hydraulic conductivity. Figure 3 shows saturated hydraulic conductivity (K_{sat}) in the surface soil horizon for

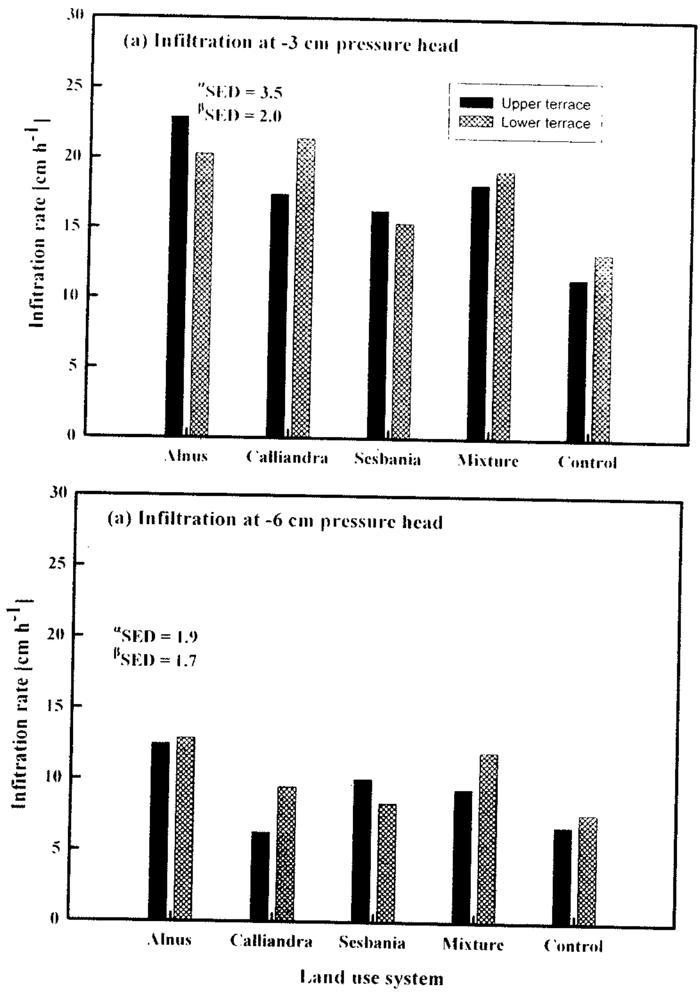


Figure 2. Effect of position on the terrace on infiltration at pressure heads of -3 and -6 cm. – and – represent standard errors of the difference between treatment means (SED) for the upper and lower terrace sections.

both terrace locations in all treatments. As for infiltration, there was no significant interaction between treatment and terrace position, perhaps because of the extensive variability in K_{sat}. The coefficient of variation for K_{sat} was much larger on the upper terrace (106%) than on the lower terrace (60%), perhaps reflecting the influence of trees. K_{sat} values were greater on the upper terrace in all agroforestry treatments ($P<0.01$), whereas the reverse applied in the sole cropping system. K_{sat} was greater in all tree-based systems except Sesbania than in the sole crop control ($P<0.01$). K_{sat} was also greater under *Calliandra* than in the tree mixture and Sesbania treatments ($P<0.01$), but not the *Alnus* system. The influence of the land use system on K_{sat} on the upper terrace was closely related to the observed infiltration responses, particularly with a -3 cm pressure head.

On the lower terrace, K_{sat} was greater under Calliandra than in any other treatment (Fig. 3); K_{sat} values for all other tree-based systems did not differ significantly from the sole crop control. These observations suggest that only Calliandra was able to influence K_{sat} on the lower terrace section. This difference may be attributable to variation between tree species in rooting structure and function within the surface soil horizons. K_{sat} values on the lower terrace were consistent with the observed pattern for infiltration rates across all treatments examined.

Effect of land use systems on runoff. Table 3 shows the effect of land use on runoff and the percentage of rainfall lost as runoff. Runoff was greatly reduced in all tree-based systems relative to the sole cropping system ($P<0.001$), although no significant difference was detected between the various tree-based treatments. The loss of rainfall resulting from runoff ranged between 1.6 and 4.1% in the tree-based systems, compared to 17.4% in the sole cropping treatment. The reduction in runoff resulting from the presence of trees was 90, 78, 91 and 87% respectively in the *Alnus, Calliandra, Sesbania* and tree mixture systems.

As the quantity and intensity of rainfall are important factors in determining runoff, a sound understanding of the relationships between these parameters is vital. In the present study, only the quantity of rainfall during each rainfall event was recorded, and not rainfall intensity. Table 4

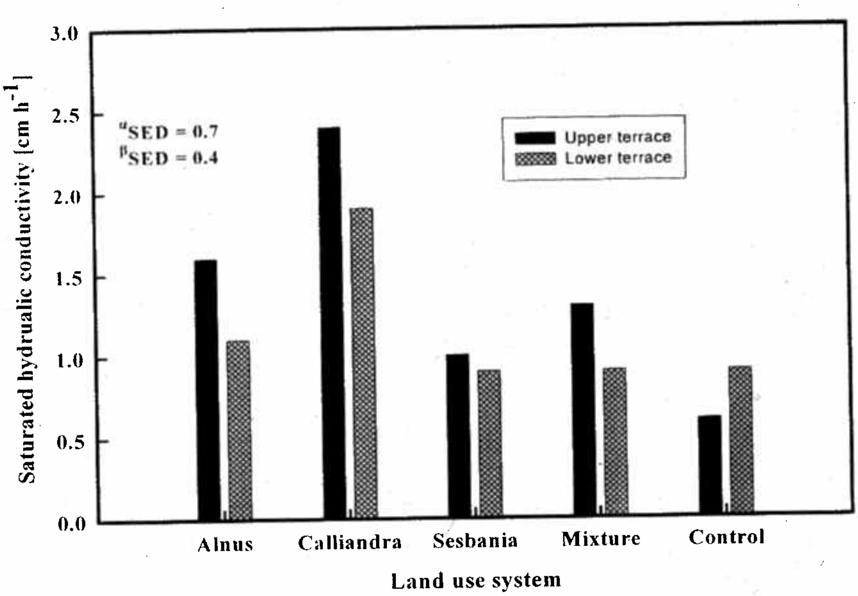


Figure 3. Effect of position on the terrace on saturated hydraulic conductivity. – and – represent standard errors of the difference between treatment means (SED) for the upper and lower terrace sections. The interaction between treatment and location on the terrace was not significant.

summarizes the influence of the quantity of rainfall on runoff. Precipitation was categorised into small (=10 mm) or large rainfall events (>10 mm); the first category comprised five events, while the second comprised seven events. Fewer low rainfall events were recorded because these, especially those <5 mm, often caused too little runoff to be detectable using tipping buckets.

During rainfall events =10 mm, runoff accounted for <4% of total rainfall in all treatments. The reduction in runoff relative to the sole crop control was 64, 84, 96 and 96% in the *Alnus, Calliandra, Sesbania* and tree mixture systems; these reductions were significant for all except Alnus ($P<0.05$), despite a 64% reduction in the latter treatment compared to the sole cropping system. This observation may be related to inter-specific differences in crown architecture and its effect on the partitioning of rainfall. Alnus has a relatively dense canopy with simple broad leaves, whereas *Calliandra* and *Sesbania* have small bi-pinnate compound leaves. Such differences in crown and leaf architecture are likely to affect rainfall interception, throughfall and stemflow as Alnus is likely to intercept a greater proportion of rainfall than Calliandra and Sesbania during small rainfall events; the intercepted rainfall may then be channeled as stemflow to the ground, increasing runoff. By contrast, the more open crowns of Sesbania and Calliandra allow greater throughfall, consequently reducing stemflow.

TABLE 3. Influence of land use system on mean runoff following 12 rainfall events between November 2003 and May 2004

Land use system	Runoff [mm]	Runoff as proportion of rainfall [%]
Alnus acuminata	0.34	2.1
Calliandra calothyrsus	0.79	4.1
Sesbania sesban	0.31	1.6
Tree mixture	0.43	2.4
Sole crop	3.43	17.4
SED	0.79	4.2

Absolute runoff and the proportion of rainfall lost as runoff were much greater during large rainfall events (>10 mm), accounting 23% of total rainfall in the sole cropping system. The reduction in runoff relative to the sole crop control was 92, 76, 91 and 88% in the *Alnus, Calliandra, Sesbania* and tree mixture systems. Runoff from all tree-based systems was lower than in the sole crop control ($P<0.001$). Although runoff was lowest in the Alnus system, the differences between the tree-based systems were not significant.

Further analysis reveals that the relationship between the quantities of rainfall received and runoff varied between treatments. An increase in rainfall from <10 mm to >10 mm increased runoff in the *Calliandra, Sesbania*, tree mixture and sole cropping systems by up to 1500%, whereas an equivalent increase in rainfall caused a more moderate 344% increase in the Alnus land use system.

DISCUSSION

Infiltration. Infiltration at a pressure head of –3 cm reflects the contribution of small pores to

TABLE 4. Runoff under different land use systems following low (n=5) and high rainfall events (n=7) between November 2003 and May 2004

Land use system	Runoff [mm]		Runoff as proportion of rainfall [%]	
	Rainfall category			
	≤10 mm	>10 mm	≤10 mm	>10 mm
Alnus acuminata	0.09	0.40	1.59	2.34
Calliandra calothyrsus	0.04	1.14	0.86	5.30
Sesbania sesban	0.01	0.43	0.02	2.26
Tree mixture	0.01	0.57	0.05	3.25
Sole crop	0.25	4.77	3.42	22.95
SED	0.09	1.01	1.14	5.57
SED (interaction)	1.10	6.0		

infiltration, while measurements made using a pressure head of –6 cm focus on infiltration through the soil matrix (Baird, 1997). The observation that infiltration rates determined using a -3 cm pressure head were substantially greater than those obtained using a -6 cm head (P<0.001, Table 5) shows that water movement through smallpores was more important in determining infiltration than flow through the soil matrix. The extent to which trees enhance the formation, distribution and continuity of macro- and micropores is therefore likely to be critical in determining water storage in agroforestry systems. Pore-driven infiltration rates were greater in the Calliandra, Alnus and tree mixture treatments than in the sole cropping system (P<0.001, Table 2). Several factors may contribute to the greater pore-driven infiltration in these systems, including enhanced soil aggregation resulting from an increase in organic matter content, facilitation of percolation resulting from the action of tree roots as channels for by-pass flow (van Noordwijk *et al.*, 1991), and an increased number of flow paths resulting from increased soil fauna populations (Bouma *et al.*, 1982). Previous studies suggest that the populations of soil fauna are generally greater in agroforestry than in sole cropping systems, perhaps because of litter fall or microclimatic improvements (Brussard *et al.*, 1993). Substantial litter fall was observed in all tree-based systems in the present study. By contrast, continuous cropping is associated with a deterioration of soil structure, accompanied by increased compaction and reduced soil porosity (Lal, 1989).

Infiltration on the lower terrace might not be expected to differ between treatments as this area was continuously cropped. However, the presence of trees on the upper terrace appears to have influenced soil structure on the lower terrace as infiltration measured using a pressure head of -3 cm was greater in all tree-based systems except Sesbania than in the sole crop control (P<0.001). This observation implies that trees affected soil pore size distribution on the lower terrace, perhaps as a result of root extension into the adjacent cropping area or microclimatic modifications. This may be particularly true for Calliandra, whose above- and below-ground influence may extend for up to 4 m from the tree line (Siriri *et al.* in press). As a result of their influence on the lower terrace, the trees helped to reverse the gradient in soil hydraulic properties typically observed on terrace benches in SW Uganda.

The greatly increased infiltration observed under Calliandra deserves further consideration as the trees in this treatment not only provided the highest pore-driven infiltration (P<0.001) but also exhibited a significant spatial influence on infiltration, which extended beyond the area in which the trees were grown (P<0.05, Fig. 2). As a shrub, *Calliandra* has a highly versatile rooting system capable not only of producing substantial numbers of superficial fine lateral roots extending over considerable distances, but also of exploring the soil profile to considerable depths (Hairiah *et al.*, 1992). Also unlike Alnus, which is classified as a tree because of its straight growth form and life span, Calliandra extends its crown laterally, affecting adjacent cropping areas through litter fall and microclimatic modifications. These factors may all have contributed to the spatial influence of this species on infiltration. These observations substantiate the arguments presented Siriri *et al.* (in press) regarding the extension of Calliandra roots into the adjacent cropping area.

The effects of trees on infiltration observed in the present study are generally comparable to previous studies of similar agroforestry systems. For example, Kiepe *et al.* (1995) reported that an increase in soil porosity under *Cassia siamea* contour hedgerows in semi-arid central Kenya increased infiltration by up to 94% compared to alleys, while Lal (1989) also observed an increase in infiltration under hedgerows as compared to alleys.

TABLE 5. Guidelines for interpreting hydraulic conductivity data

Conductivity class	Hydraulic conductivity [cm h^{-1}]
Very slow	<0.8
Slow	0.8-2.0
Moderate	2.0-6.0
Moderately rapid	6.0-8.0
Rapid	8.0-12.5
Very rapid	>12.5

Source: Landon (1984)

Hydraulic conductivity. The K_{sat} values recorded in the present study are generally low when evaluated using the classification guidelines developed by Landon (1984; Table 5). A similar study by Raussen *et al.* (1999) provided slightly higher values, although the trends among treatments were similar.

K_{sat} values in the present study may, at best, be classified as moderate for Calliandra, but fall into the slow category for all other land use systems; the low K_{sat} values obtained emphasise the severity of soil degradation, whereas the study reported by Raussen *et al.* (1999) was conducted at 10 on-farm sites with different levels of degradation. The poor crop performance reported in Siriri *et al.* (in press) supports the evidence presented here that the soil at the present experimental site was severely degraded. The observed treatment differences are consistent with those described by Raussen *et al.* (1999), who found that K_{sat} values in treatments containing Alnus or Calliandra were more than double those obtained under sole cropping. In both studies, K_{sat} was significantly higher under Calliandra than in any other land use system, an effect attributed to its versatile rooting system and high rate of litter decomposition, which would increase soil organic matter content, increasing the stability of soil aggregates.

A potential concern with the K_{sat} values obtained in the present study is the high coefficient of variation (CV) for measurements in the same treatment. Many studies have reported high spatial micro-variability of K_{sat} values in the field (Baker, 1978; Siriri, 1997), and in the present study CV values of up to 200% were recorded, increasing the difficulty of identifying significant treatment effects. CV may be reduced by increasing the number of measurements made for individual treatments; in the present study, the duplicate measurements made in individual plots appeared to be insufficient to cope with the prevailing extensive micro-variation.

Runoff. The striking difference in runoff between the tree-based and sole crop systems emphasises the importance of agroforestry in conserving water for productive use, particularly as the protective influence of agroforestry in controlling runoff appears to increase as the quantity of rainfall received during specific rainfall events increases, a phenomenon also reported for hedgerow intercropping systems in central Kenya (Kiepe and Rao, 1994). Comparable, but less dramatic results were also reported by Ndayizigiye (1993), who compared runoff from two year old Calliandra and Leucaena hedgerow systems with that from traditional cropping systems. Average runoff was respectively 12, 9 and 2% of rainfall under bare soil, sole cropping and hedgerow intercropping conditions; however, under very high rainfall intensities, runoff increased to 68, 35 and 20% of rainfall in the same treatments.

While infiltration and soil hydraulic conductivity are vital in reducing runoff in agroforestry systems, changes in soil surface characteristics are also important. Alnus produces substantial quantities of litter, estimated to be 2-4 t ha^{-1} over a period of two to three years (Siriri, unpublished data); this may have had significant effects on soil surface roughness and water storage in the litter, both of which are important in determining runoff. The bushy undergrowth in the sole Sesbania treatment impeded runoff despite the seemingly low infiltration and hydraulic conductivity values in this treatment. Runoff under Calliandra was slightly, but not significantly, higher than in the other tree-based systems, perhaps because the lack of undergrowth and rapid decomposition of its litter left the soil surface exposed. The influence of canopy structure on raindrop size and velocity and net incident rainfall after taking account of canopy interception losses may also be important in explaining the observed differences between treatments.

CONCLUSIONS

This study has demonstrated the potential of agroforestry systems to increase infiltration rate and hydraulic conductivity and thereby reduce runoff. Infiltration in particular is greatly enhanced when there is a well-developed network of soil pores. The agroforestry treatments appeared to increase pore-driven infiltration, particularly in the Alnus and Calliandra systems, perhaps as a result of their vigorous rooting systems and associated microbial activity. Despite the high coefficient of variation for hydraulic conductivity, the effects of trees in increasing hydraulic conductivity relative to the sole crop were noticeable, especially under Calliandra. Perhaps of even greater significance is the ability of trees to reverse the typical gradient in soil hydraulic properties observed on sloping terraces in Kabale District. Saturated hydraulic conductivity was consistently higher on the upper terrace than the lower terrace in the tree-based systems, whereas the reverse was true for the sole cropping system. This observation demonstrates the ability of trees to loosen the hard compacted soils on the upper part of terrace and thereby enhance water movement into the soil profile. The influence of the agroforestry systems was dramatic in terms of the reduction in runoff, particularly during high rainfall events when the reduction relative to the sole crop was 92, 76, 91 and 88% respectively in the Alnus, Calliandra, Sesbania and tree mixture systems. These reductions are of major significance in a region where erosion and runoff have been blamed for land degradation and loss of productivity.

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