Do Species Mixtures Increase Above- and Belowground Resource Capture in Woody and Herbaceous Tropical Legumes?

Stanley M. Gathumbi,* James K. Ndufa, Ken E. Giller, and Georg Cadisch

ABSTRACT

The rotation of crops with planted, N_2-fixing legumes is a promising agroforestry innovation for replenishing soil fertility in the tropics. We postulated that woody and herbaceous legumes with different growth and rooting patterns could be mixed to optimize above- and belowground resource capture. The objective of this study was to evaluate the effect of species interactions on resource utilization by legumes grown in mixtures on a Kandiudalfic Eutrudox in western Kenya. Four woody legume shrubs—pigeonpea [*Cajanus cajan* (L.) Millsp.], sesbania [*Sesbania sesban* (L.) Merr.], crotalaria (*Crotalaria grahamiana* Wight and Arn.), and tephrosia (*Tephrosia vogelii* Hook F.)—grown in monoculture and mixed stands were evaluated for light interception, soil N and water uptake, and biomass production. Siratro [*Macroptilium atropurpureum* (DC.) Urb.] and groundnut (*Arachis hypogaea* L.) were undersown in woody legume stands. Total aboveground biomass production ranged from 9 to 13 Mg ha^{-1} for monoculture and 8 to 15 Mg ha^{-1} for mixtures of woody legumes. Total N in woody-legume stands ranged from 100 to 178 kg N ha^{-1}. Biomass and plant N were not significantly different among woody-legume treatments. However, undersowing siratro as a supplement increased stand productivity and recycled biomass N. Species complementarity in topsoil and subsoil utilization of mineral N was observed in crotalaria + sesbania and pigeonpea + tephrosia mixed stands. Dense soil cover created by siratro led to better conservation of soil water. Results indicated that the tested mixtures provide a better risk management strategy through compensatory growth potential. Greatest opportunities for intensifying resource utilization appear to exist through undersowing a creeping legume with an open-canopy woody legume.

THE DELIBERATE PLANTING of fast-growing tree, shrub, and herbaceous legume species (referred to as improved fallow) in rotation with crops for the improvement of soil fertility has become a central agroforestry technology for soil fertility management in Africa (Buresh and Tian, 1997). These technologies have a high potential for adoption by smallholder farmers in western Kenya (Niang et al., 1996) and southern Africa (Kwesiga et al., 1999). Improved fallows can replace traditional fallows, which normally consist of a combination of broad-leaved weeds and grasses and must be of longer duration to achieve similar recoveries in soil fertility (Bartholomew, 1977). Maize (*Zea mays* L.) yields are increased tremendously after improved fallows compared with continuous maize or natural fallows (Jama et al., 1998; Nyakanda et al., 1998). Sesbania has been the main focus for recent research on improved fallows in eastern and southern Africa due to its traditional use by smallholder farmers, its compatibility for intercropping with crops during establishment, and the supply of wood for stakes and fuel (Swinkels et al., 1997). Other species are being evaluated with a view to diversifying the range of options available to farmers and reducing overdependence on a single species that may be prone to disease and pest attack. For instance, sesbania is susceptible to root-knot nematodes (*Meloidogyne* spp.) (Desaeger and Rao, 1999) and a devastating beetle pest (*Mesoplatys* spp.). Extensive monocultures of single species may also lead to buildup of new pests and diseases as found with crotalaria (from Mararano, Madagascar)—a shrubby legume recently introduced in western Kenya—which has been extensively attacked by a caterpillar (*Catochrysops* sp.). There is thus an urgent need to evaluate several potential fallow species for each target region.

Mixing species with compatible and complementary rooting and/or shoot growth patterns in fallows may have multiple advantages. Undersowing herbaceous or shrubby legume species under the tall, open canopy of sesbania may improve light capture and lead to gains in net primary productivity of the fallow. Planting shallow-rooted species together with species that are able to root to depth may enhance uptake of water and nutrients from the soil profile, preventing losses of nutrients by leaching into the subsoil. Mixing species may also increase fallow residual benefits for the next crop by improving the synchrony of nutrient supply and crop demand if the species grown in mixtures differ in their residue quality (Handayanto et al., 1997; Palm, 1995; Swift et al., 1979).

Fallows comprised of species mixtures may therefore be superior in their potential to replenish soil fertility and can provide a wider range of fodder and wood products than pure-species fallows (Kerr, 1999; Rao et al., 1997). Mixing fallow species may also reduce the risk of failure in establishment or productivity due to constraints such as drought, disease, or pest attack.

The objectives of this study were to assess growth compatibility and productivity, soil water and N uptake, and aboveground plant N for a range of promising shrubby legumes in both pure and mixed fallows. The feasibility of undersowing groundnut or the creeping forage legume siratro as understories between the rows of the woody fallow legumes was also explored as this may be an attractive option for farmers. Three hypotheses were tested: (i) Mixing species in fallows can increase aboveground resource capture, (ii) mixing species in

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Published in Agron. J. 94:518–526 (2002).

Abbreviations: LAI, leaf area index; PAR, photosynthetically active radiation.

fallows can increase belowground resource capture, and (iii) mixing species in fallows can provide a wider variety of useful products for farmers.

MATERIALS AND METHODS

This study was conducted on farmers' fields in western Kenya (0°06′ N, 34°34′ E; 1330 m above sea level) from 20 Oct. 1997 to 11 Apr. 1998, with treatment blocks set up at two adjacent farms. Rainfall in the study area is distributed in two crop-growing seasons per year, with an annual mean of 1800 mm. The growing season during the long rains extends from March to August, and the growing season during the short rains extends from September to January. The rainfall pattern during the short-rains season when the experiment was established is shown in Fig. 1.

The soils are highly weathered and are generally classified as very fine, kaolinitic, isohyperthermic Kandiudalfic Eutrudox (Table 1). The methods of soil analysis were pH in a 1:2.5 soil/water suspension; organic C by wet oxidation with heated acidified dichromate, followed by colorimetric determination of Cr^{3+} (Anderson and Ingram, 1993); extractable P and exchangeable K by extraction with 0.5 *M* sodium bicarbonate ($NaHCO_3$) + 0.01 *M* ethylenediaminetetraacetic acid (pH 8.5); and exchangeable Ca, Mg, and exchangeable acidity after extraction in 1 *M* KCl.

Experimental Design

The four main fallow shrub and/or tree legumes tested and their sources were medium-duration pigeonpea ICP13211 from ICRISAT, Hyderabad, India; crotalaria from Mararano, Madagascar; sesbania from Yala, Kenya; and tephrosia from Yaounde, Cameroon. As the main objective of this experiment was to evaluate the performance of the legume species in pure stands and mixtures, all possible combinations of the four main test species were included. The feasibility of intercropping the fallow species with a local variety of groundnut and an herbaceous forage legume siratro—accession GBK12102 from International Livestock Research Institute (ILRI), Addis Ababa, Ethiopia—was also evaluated. Continuous maize (hybrid HB511), natural fallow, and calliandra (*Calliandra calothyrsus* Meissn.) (from Kakamega, Kenya) were used as control plots. Calliandra was included as an agronomic control, being a well-adapted, slow-growing legume species in the study area commonly used in hedgerow intercropping systems. The experiment was laid out in a randomized complete block design consisting of 24 treatments replicated four times. Due the large number of treatments, two blocks were located in one farm and the remaining two on another farm situated about 0.5 km away. Soil characteristics were similar at each farm (Table 1).

Plant Establishment

One-month-old plant seedlings grown in a nursery were transplanted to the field on 20 Oct. 1997. Plot size was 6 by 5.25 m (31.5 m^2). Tree and shrubby legumes were planted at a spacing of 0.75 by 0.75 m in both pure- and mixed-species fallows, with species in mixed stands planted in alternate rows. Siratro and groundnut in pure-stand treatments were planted at a spacing of 0.375 by 0.75 m for siratro and 0.20 by 0.375 m for groundnut. In mixed fallows, these species were planted in between rows of tree and/or shrub legumes at the same interrow spacing as in pure-stand treatments.

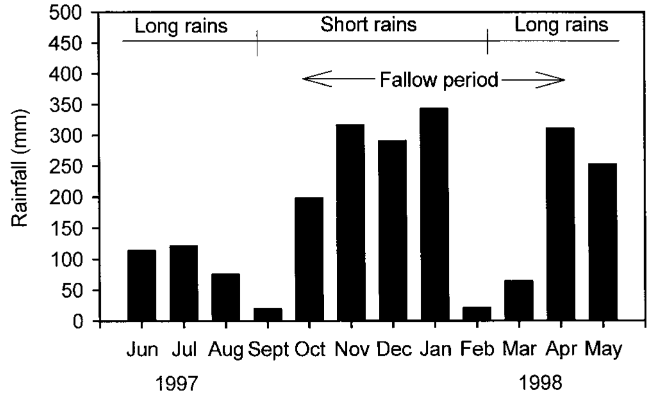

Fig. 1. Total monthly rainfall (mm) received between June 1997 and May 1998 at Nyabeda, western Kenya.

Measurements during Establishment

Root collar diameter and plant height were monitored on a monthly basis after transplanting. Photosynthetically active radiation (PAR) was measured 2 and 3 mo after transplanting using a portable ceptometer consisting of a narrow, 80-cm-long probe with 80 sensors. Canopy transmittance and the total incoming PAR in open areas were used to calculate the leaf area index (LAI) using the Beer–Lambert equation where Q_1 = canopy PAR transmittance, Q_0 = total incoming PAR, and k = canopy light extinction coefficient (Vose and Swank, 1990). In this method, the calculation is based on the assumption that the foliage and individual leaves are randomly distributed. Five ceptometer readings were taken for both above and below the canopy at five locations within the treatment plots, i.e., four measurement points at 1 m from each corner of the plots and one at the center.

Fallow Harvesting Procedures

Fallow harvesting was carried out between 6 and 8 Apr. 1998 on a block basis, except for groundnut, which had been harvested on 20 Feb. 1998. For trees and shrubby fallow species, and for siratro, the net harvest area was 2.25 by 3 m (6.75 m^2). Net harvest area for groundnut was 3.75 by 3.75 m (14 m^2). Plants were cut at ground level and separated into stems, branches (>5 mm), and foliage (leaves and pods). Fresh weight was immediately determined in the field for each plant component in the harvest area. Subsamples of each plant component were taken and fresh weight determined. Subsamples were then placed in plastic bags, packed in a cool box, and transported back to the laboratory where they were oven-dried at 70°C for 48 h, weighed for dry matter determination, and then finely ground using a micro hammer mill. Groundnut

Table 1. Initial soil physical and chemical characteristics (0–15 cm) of the two field experiment sites at Nyabeda, western Kenya.

Farm	pH (H_2O) (1:2.5)	Organic C	Total N	Exchangeable P	Exchangeable cations Ca	Mg	K	Acidity	Sand	Silt	Clay	Bulk density
		g kg^{-1}		mg kg^{-1}	cmol$_c$ kg^{-1}				%			g cm^{-3}
1	5.8	14.0	1.3	1.0	6.0	1.7	0.3	0.5	21	23	56	1.3
2	5.4	14.0	1.6	1.6	4.7	1.7	0.3	0.4	33	20	47	1.3

plants were separated into pods (grains and husks), foliage, and roots. All the pods in the harvest area were weighed fresh in the field, sun-dried, and subsequently shelled.

Dry plant samples were analyzed for total N using the Kjeldahl procedure (Anderson and Ingram, 1993), and NH_4 was then determined colorimetrically using an SFA-2 Burkard scientific autoanalyser (Bukard Sci., Uxbridge, Middlesex, UK).

Plant mixtures show the result of interspecies competition compared with intraspecies competition in sole stands. We determined the effect of interspecies competition by comparing aboveground plant N for individual species in sole and mixed stands. We calculated plant N differences based on same plant density. The effect of competition on changes in plant N (PN_{diff}, expressed in kg N ha^{-1}) for a given species when mixed with other woody species grown at 50:50 plant populations was calculated using the equation:

$$PN_{diff} = PN_{mix} - PN_{sole}/2$$

where PN_{mix} is the plant N (kg ha^{-1}) of species grown in mixture with another species and PN_{sole} is the plant N (kg ha^{-1}) of the same species grown in sole stand. Siratro and groundnut, unlike woody species, were added as understory plant populations without decreasing the population of the woody species. Hence, we used the following equation to determine the effect of competition on changes in plant N for a given species when mixed with siratro and groundnut:

$$PN_{diff} = PN_{mix} - PN_{sole}$$

Soil Sampling and Analysis for Mineral Nitrogen Determination

Initial soil sampling was carried out in September 1997 just before the fallow establishment, and the final soil sampling was done between 26 March and 4 April 1998. Using an Edelman auger with a diameter of 7 cm, soils were sampled to 200-cm depth at the following six depths: 0 to 15, 15 to 30, 30 to 50, 50 to 100, 100 to 150, and 150 to 200 cm. On both sampling times, all of the treatment plots were sampled individually. Soil augering was done at six spots per plot and samples bulked for layers above 100 cm and four spots for layers below 100 cm. Soil samples were analyzed for gravimetric soil water content and for mineral N (NH_4–N and NO_3–N), with two subsamples for each sample, after extraction of 20 g of field moist soil with 2 *M* KCl. The resulting extract was analyzed for NH_4–N by a colorimetric method following the procedure of Anderson and Ingram (1993) and for NO_3–N and NO_2–N by Cd reduction (Dorich and Nelson, 1984), with subsequent colorimetric determination of NO_2 (Hilsheimer and Harwig, 1976). Cores were taken at each selected depth to determine bulk density, which was later used to convert N values from mg kg^{-1} into kg ha^{-1} and gravimetric water content to m^{3}m^{-3}.

Data Analysis

All data on growth parameters, biomass, and plant N were subjected to one-way analysis of variance (ANOVA) using Genstat statistical software (Payne et al., 1987). Wherever appropriate, data were grouped according to species and their respective mixtures. Mineral N data were not normally distributed, and hence were square root–transformed before conducting the ANOVA using the procedures of Gomez and Gomez (1984). Tests of significance between treatment means were performed using the Tukey test at $P = 0.05$. Standard errors of the difference are reported to enable comparison of treatment means.

RESULTS

Aboveground Characteristics of the Improved Fallows

All of the test fallow tree and/or shrub species were fast growing except for calliandra. Crotalaria established rapidly but remained short (≈1.5 m tall) and 3 mo after fallow establishment, already had a completely closed canopy so that light penetration was minimal (Fig. 2). Sesbania, which grew slowly initially, was the tallest tree at the end of the experiment, reaching almost 3 m. However, sesbania and pigeonpea fallows had a less dense aboveground canopy at the early fallow growth phase compared with tephrosia and crotalaria (Fig. 2). Fallows consisting of crotalaria, tephrosia, and siratro completely smothered the undergrowth of weeds because of reduced light penetration due to their dense canopies.

Among the legume monoculture fallow species, crotalaria had the highest LAI (1.3) 3 mo after planting (Fig. 2). Mixing fallow species did not significantly increase LAI compared with the LAI of the more dense species at this early stage of establishment. In plots where groundnut was undersown, LAI measured above the groundnut plants was slightly smaller with pigeonpea and sesbania plots compared with crotalaria and tephrosia plots at 2 mo after planting (Fig. 2). At this stage, the groundnut crop was at the critical growth stage of pod filling. After 3 mo, the LAI was smallest in pigeonpea + groundnut plots compared with the other groundnut mixtures.

Sole groundnut yielded 1.02 Mg ha^{-1}, which was significantly ($P < 0.05$) more than in the intercrop treatments. Groundnut yielded significantly less grain (0.2–0.3 Mg ha^{-1}) in crotalaria and tephrosia intercrops than in sesbania and pigeonpea intercrops (≈0.4 Mg ha^{-1}).

Fallow Aboveground Biomass Production

Total aboveground dry matter production in the improved fallows ranged between 8.7 and 13.2 Mg ha^{-1} in woody single-species treatments and between 8.2 and

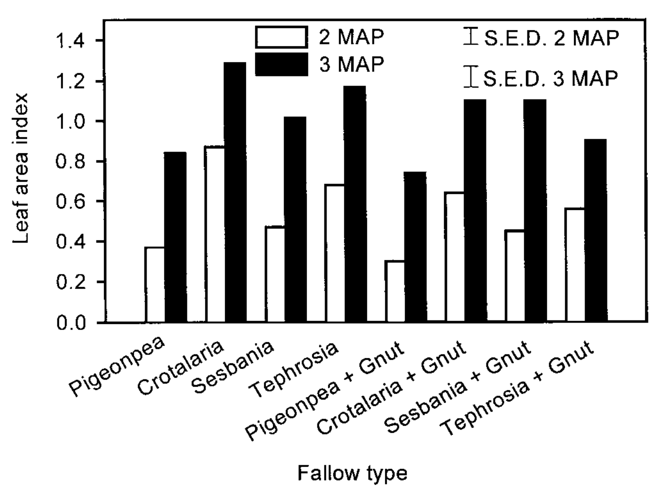

Fig. 2. Leaf area index (LAI) for single species and groundnut (Gnut) mixtures at 2 and 3 mo after planting (MAP) at Nyabeda, western Kenya, in 1997–1998.

15.2 Mg ha^{-1} in mixed-species treatments (Fig. 3a). In most cases, there were no significant differences in the aboveground biomass production between pure- and mixed-species plots.

Foliage production of improved fallows ranged between 2.2 and 6.2 Mg ha^{-1}, with sesbania monocrop as the poorest and tephrosia + siratro mixture plots as the best (Fig. 3b). Among the shrubby leguminous species in pure stands, crotalaria yielded most foliage and sesbania the least. Among the mixed-species treatments, total foliage production was least in crotalaria + sesbania plots but not significantly different from other fallow combinations, except for tephrosia + siratro, crotalaria + siratro, and pigeonpea + siratro. The natural fallow had a higher (6 Mg ha^{-1}) foliage biomass compared with the legume treatments as it consisted of natural broad-leaved weeds and grasses {mainly African couchgrass [*Digitaria scalarum* (Schweinf.) Chiov.]}. By contrast, the plant N of the natural fallow was small (76 kg N ha^{-1}) due to the

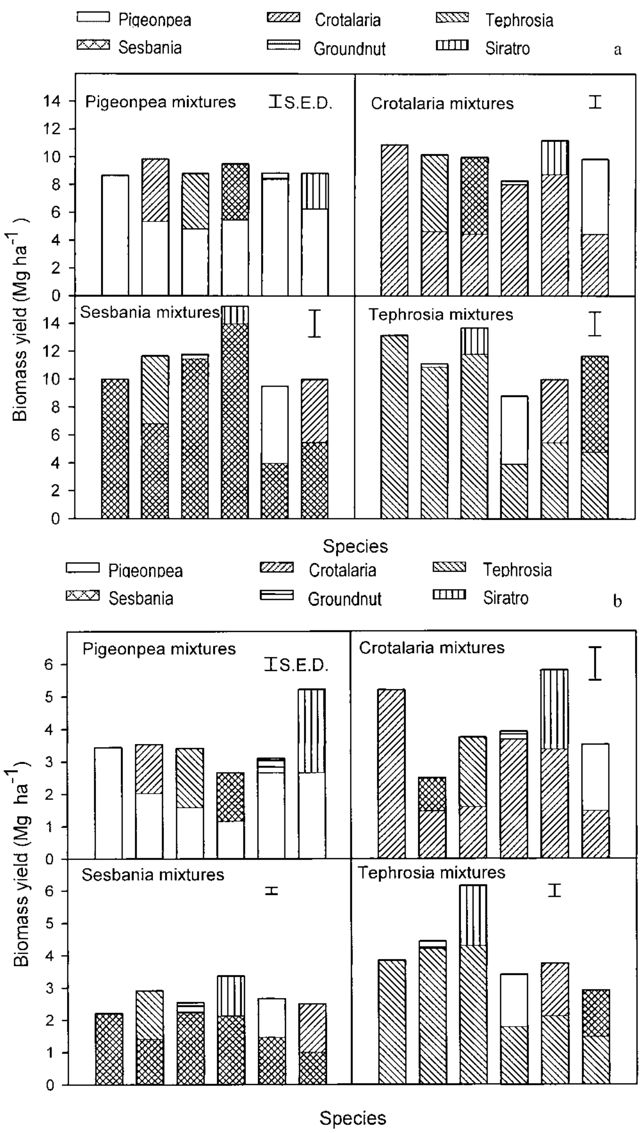

Fig. 3. (a) Total aboveground biomass (Mg ha^{-1}) and (b) total foliage biomass (Mg ha^{-1}) for species grown in mixtures at Nyabeda, western Kenya, in 1997–1998.

low N content (12 g kg^{-1}) of the grasses. For control plots, maize yielded 2.5 Mg ha^{-1} total aboveground biomass, calliandra 2.3, and siratro 5.1.

Wood dry matter production (the difference between total biomass and foliage biomass) varied strongly among the species: Tephrosia yielded the largest amount of wood (9.3 Mg ha^{-1}) compared with sesbania (7.8), crotalaria (5.7), and pigeonpea (5.2). Among the mixtures, pigeonpea + siratro (3.0 Mg ha^{-1}) and sesbania + siratro (11.8 Mg ha^{-1}) gave the smallest and the largest wood yields, respectively. Pigeonpea yielded more wood in mixtures, except when combined with siratro. By contrast, wood yield decreased from 4.6 Mg ha^{-1} to 2 to 3.5 Mg ha^{-1} with tephrosia mixtures, whereas wood production of crotalaria and sesbania was little affected by mixing.

The high wood/foliage ratio could explain the relatively small foliage yields in both sole sesbania stands and in its mixtures compared with other fallow species. A low wood/foliage ratio and relatively high N content in shoots (≈30 g kg^{-1}) led to the large biomass and plant N of crotalaria. All fallow mixtures that included siratro had a greater foliage component (22–59%) of the total biomass production as the density of the companion species was not altered when siratro was included as an understory. Siratro produced substantially more biomass in pure stands (5 Mg ha^{-1}) than when intercropped with the shrubby species (1.2–2.5 Mg ha^{-1}) but is an attractive option for inclusion in fallows for soil fertility management by farmers due to its added value as forage.

Fallow Aboveground Plant Nitrogen

Among the improved fallow tree and/or shrub monocultures, sesbania accumulated the least aboveground N and crotalaria the most (Table 2). Among the mixtures, total aboveground plant N was largest in the tephrosia + siratro mixture (224 kg N ha^{-1}) and least in the sesbania + groundnut mixture (98 kg N ha^{-1}). No significant differences were observed in total plant N among the crotalaria and pigeonpea mixtures.

In sole-species treatments, the foliage N ranged between 18 and 150 kg N ha^{-1}, with groundnut and crotalaria having the lowest and the highest plant N yields, respectively (Table 2). Among the woody legumes, foliage N was >60 kg N ha^{-1}, except for calliandra, which produced only 45 kg N ha^{-1}. In mixtures of woody legumes, the largest foliage N was recorded in tephrosia + siratro mixtures and the smallest in crotalaria + sesbania mixtures. Generally, mixed-species fallows of woody species undersown with siratro resulted in the greatest amounts of N in foliage, ranging between 110 and 168 kg N ha^{-1}.

Mixing pigeonpea with crotalaria resulted in 11 kg ha^{-1} more plant N for pigeonpea than when pigeonpea was grown in monoculture at equal plant density (Fig. 4). Wood N changes for pigeonpea grown in mixtures ranged between 24 and −12 kg N ha^{-1} when grown with sesbania and with siratro, respectively. Crotalaria was most strongly negatively affected by competition from other species in absolute terms (Fig. 4), resulting in

Table 2. Foliage, wood, and total aboveground plant N of the single- or mixed-species fallows and controls at Nyabeda, western Kenya, after the 1997–1998 short rains.

Species	Foliage Species 1	Foliage Species 2	Total foliage N	Wood Species 1	Wood Species 2	Total wood N	Total N yield
	kg N ha^{-1}						
Pigeonpea	110	–	110	38	–	38	148
Pigeonpea + crotalaria	68	44	112	17	23	40	152
Pigeonpea + tephrosia	55	66	121	25	12	37	158
Pigeonpea + sesbania	44	41	85	42	11	53	138
Pigeonpea + groundnut	71	9	80	36	–	36	116
Pigeonpea + siratro	87	62	149	26	–	26	175
SED†	18.2**	6.0***	19.1**	18.7 NS	2.8***	8.2 NS	23.6 NS
Crotalaria	150	–	150	28	–	28	178
Crotalaria + pigeonpea	44	68	112	23	17	40	152
Crotalaria + tephrosia	50	63	113	19	28	47	160
Crotalaria + sesbania	41	28	69	9	52	61	130
Crotalaria + groundnut	79	5	84	24	–	24	108
Crotalaria + siratro	97	63	160	31	–	31	191
SED	29.0**	10.7***	30.2*	5.5*	4.8***	6.4***	30.8 NS
Sesbania	64	–	64	36	–	36	100
Sesbania + pigeonpea	41	44	85	11	42	53	138
Sesbania + crotalaria	28	41	69	52	9	61	130
Sesbania + tephrosia	47	44	91	24	19	43	134
Sesbania + groundnut	54	6	60	38	–	38	98
Sesbania + siratro	79	32	111	59	–	59	170
SED	13.3	3.6***	11.9***	11.8*	5.3***	11.6 NS	21.7**
Tephrosia	117	–	117	33	–	33	150
Tephrosia + pigeonpea	66	55	121	12	25	37	158
Tephrosia + crotalaria	63	50	113	28	19	47	160
Tephrosia + sesbania	44	47	91	19	24	43	134
Tephrosia + groundnut	93	4	97	29	–	29	126
Tephrosia + siratro	122	46	168	56	–	56	224
SED	19.9***	2.9***	20.1*	9.1*	2.9***	9.4 NS	25.7*
Pigeonpea	110	–	110	38	–	38	148
Crotalaria	150	–	150	28	–	28	178
Sesbania	64	–	64	36	–	36	100
Tephrosia	117	–	117	33	–	33	150
Siratro	145	–	145	–	–	–	145
Groundnut	18	–	18	–	–	–	18
Natural fallow (control)	76	–	76	–	–	–	76
Galliandra (control)	45	–	45	9		9	45
SED	23.6***		23.6***	4.6***		4.6***	23.2***

* Significant at the 0.05 level.
** Significant at the 0.01 level.
*** Significant at the 0.001 level.
† SED, standard error of the difference between treatment means.

total N reductions of 20 to 71 kg ha^{-1} when mixed with tephrosia and groundnut, respectively. However, crotalaria wood N, unlike foliage N, was not strongly affected by competition. Mixing sesbania with pigeonpea, tephrosia, and siratro resulted in increased sesbania foliage N compared with the monoculture. Similarly, sesbania wood N increased in most of the mixtures, except with pigeonpea where it was reduced by about 8 kg ha^{-1}.

Tree and/or shrubby legume species in monoculture fallows, with the exception of calliandra, yielded ≥28 kg N ha^{-1} in wood (Table 2). In fallow mixtures, the smallest amount of wood N was found in crotalaria + groundnut plots and the largest amounts in crotalaria + sesbania. Wood N in mixtures was not significantly different from that of respective single-species wood, except for the crotalaria + sesbania mixture, which contained significantly more N in the wood than crotalaria alone.

Effect of Fallows on Mineral Nitrogen and Water Storage in the Soil

Initial mineral N content for the soil profile to a depth of 200 cm totaled 152 kg N ha^{-1}. The surface 15 cm had similar amounts of mineral N as the deepest layer sampled (150–200 cm), and less NO_3–N and total mineral N were present at 30 to 50 cm than in both the upper and deeper layers.

After 6 mo, there was less mineral N in the surface 50 cm with all treatments, except in the calliandra and groundnut plots (Fig. 5). The amount of mineral N had increased at depths between 30 and 100 cm in most of the fallow systems but was often depleted in the deepest layers sampled. Subsoil N (150–200 cm) was decreased by 8.1 kg ha^{-1} in sole sesbania fallows compared with a decrease of 4.1 kg ha^{-1} in the sole crotalaria plots and a net increase in pigeonpea fallows. Conversely, topsoil (0–15 cm) mineral N was decreased more strongly in sole pigeonpea, crotalaria, and siratro plots compared with sole sesbania. The crotalaria + sesbania mixture resulted in relatively more decreases in both topsoil and subsoil N compared with sole crotalaria and in topsoil compared with sole sesbania. Combinations of tephrosia and pigeonpea also resulted in slightly more topsoil and subsoil N extraction compared with their respective monocultures. Results also suggested slightly less topsoil N present after sole pigeonpea than after tephrosia but more subsoil N after pigeonpea than tephrosia.

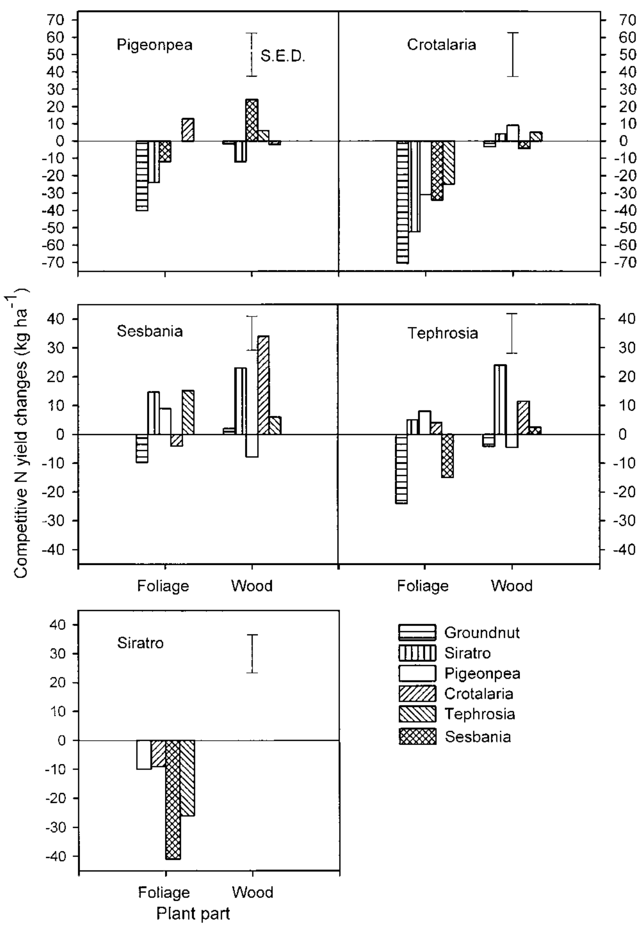

Fig. 4. Effect of competition on changes in plant N for a given species when mixed with other species at Nyabeda, western Kenya, in 1998. Standard error of the difference in means (SED) bars are for comparison of total plant N differences for a respective species in mixtures and in sole stand.

At the end of the fallow period, tephrosia + pigeonpea, crotalaria + sesbania, and crotalaria + siratro fallows led to a net depletion of whole-profile soil mineral N by 30, 15, and 30 kg ha^{-1}, respectively, compared with the amount present at the start of the experiment while the other fallows resulted in accumulation of mineral N. Net changes in profile mineral N in sole pigeonpea, crotalaria, and sesbania fallows and their respective mixtures were not significantly different ($P >$ 0.05). However, there was a significantly greater net accumulation of mineral N (106 kg ha^{-1}) after calliandra compared with all of the other species. Total profile mineral N content at end of the fallow was 259 kg ha^{-1} after calliandra compared with 123 to 170 kg ha^{-1} for the other fallows.

In April 1998, 6 mo after fallow establishment, the soil water content at lower soil depths was less in fallow treatments than under maize or natural fallow treatments or than the initial soil water content (Fig. 6). The difference increased with soil depth, particularly with respect to maize, which showed the lowest soil water uptake below 100 cm. Sesbania fallows depleted soil water content in the subsoil most strongly while the highest soil water content among the improved fallow treatments was found under the sole siratro plots.

DISCUSSION

Effect of Species Interactions on Fallow Performance

Substituting woody legume species in mixtures at a 50:50 planting density did not result in increased dry matter yield or N accumulation compared with the sole-species stands of the same species. Nyakanda et al. (1998) found similar results with mixtures of sesbania and pigeonpea in Zimbabwe. However, undersowing siratro led to a greater production of total foliage biomass in all siratro-mixed fallows. This was mainly due to the fact that the density of the companion species was not changed when siratro was included as an understory species and siratro was able to efficiently utilize the light penetrating to the soil surface.

The differences observed in total aboveground biomass and plant N for the specific species in mixtures can be attributed to the degree of complementarity and competitive ability compared with the companion species. For instance, inclusion of sesbania in mixtures resulted in reduction in total biomass yield of crotalaria (14%), tephrosia (20%), and siratro (50%) compared with monocultures at equal plant densities. On the other hand, sesbania profited from being associated with the other species; the increases in wood biomass and plant N (Fig. 4) and changes in soil mineral N profiles suggest that this was achieved through a better exploitation of the upper soil layers by the mixtures. Thus, in most cases, reduction in biomass and plant N in the less competitive species was compensated for by increased yield of the more competitive species in the mixture. This largely explains the lack of significant differences in the overall fallow biomass and N performance between sole-species fallows and their respective mixtures in the majority of cases.

The lower-growing species, such as siratro (a creeping legume) and crotalaria (a short shrub), suffered most from competition as could be expected. However, other results suggest that the balance of competition and complementarity is often fragile. For example, in this study, sesbania was very competitive, but it has been observed that when the fallows were established by direct seeding, sesbania develops slowly and suffers from competition by the associated species.

Complementarity in Belowground Resource Capture

Accumulation of mineral N for the entire profile to 200 cm-depth at the end of the fallow period showed that the different systems either depleted or spared N present in the soil mineral N pool. Amounts of mineral N were decreased in the surface and deepest soil layers after 6 mo under the different improved fallow systems, i.e., there was a depletion in mineral N at depths of 0 to 30 cm and 150 to 200 cm for most of the improved fallow systems (Fig. 6). The depletion of the soil mineral N could be attributed to the net active N uptake by plant roots and/or downward movement (leaching) although the latter is thought to be small in unfertilized fallow systems where plants are actively absorbing N

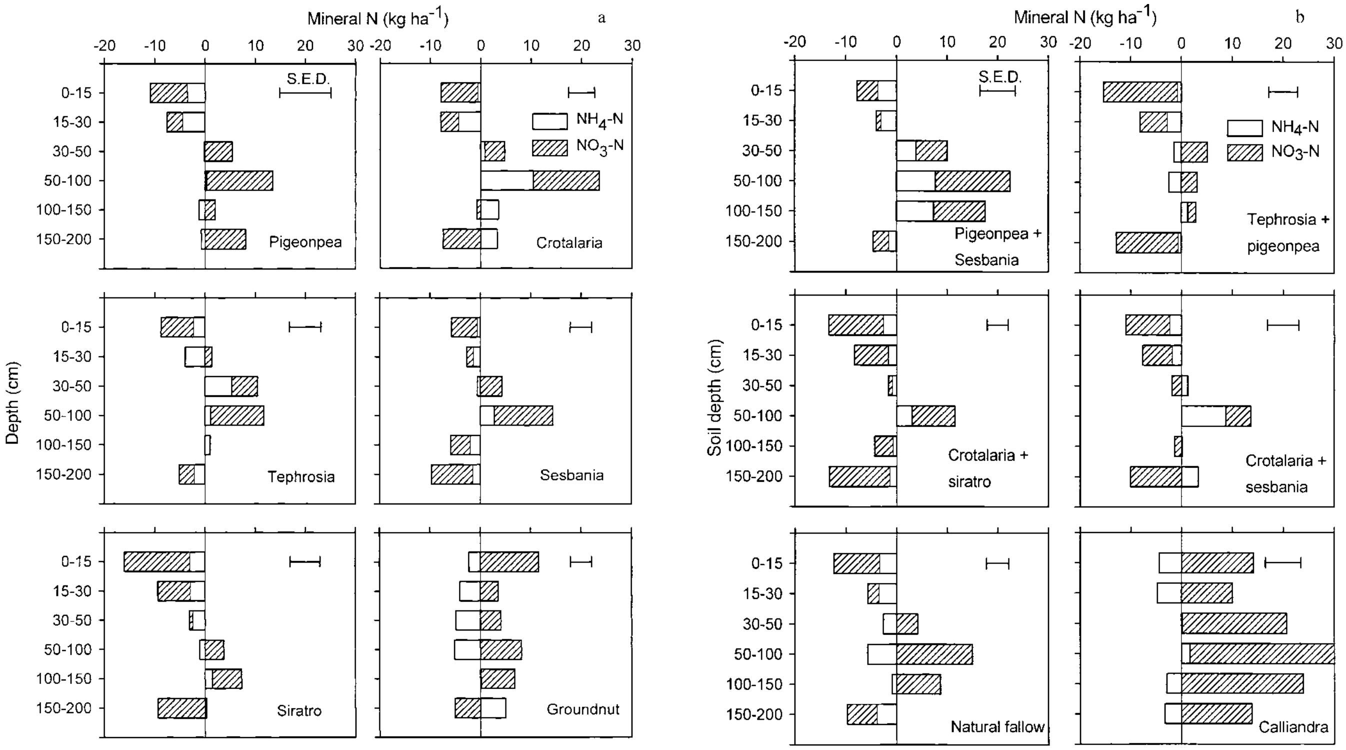

Fig. 5. Changes in mineral N (NH_4–N plus NO_3–N, kg ha^{-1}) at fallow harvest compared with mineral N at planting in different soil layers as affected by (a) monocrop fallows and crop systems and (b) mixed fallows, natural fallow, and calliandra monocrop fallows at Nyabeda, western Kenya. Standard error of the difference in means (SED) bars are for comparison of total mineral N values between treatments means.

from the soil solution. The resulting net effect on soil mineral N could be attributed to the total soil N uptake by the plants; continuous mineralization of the N from the soil N pool; and some mineralization of the roots, nodules, and fallen litter that may occur during the fallow (although litter fall in these short-term fallows was neglible). For example, groundnut plots in which the harvested biomass was returned to the plot after harvesting 2 mo before the final soil sampling showed a net positive mineral N accumulation in sole and intercropped stands in improved fallows. In contrast, the large accumulation of soil mineral N after the calliandra fallow (256 kg N ha^{-1} total profile mineral at harvest) resulted from its slow growth, and hence limited plant N uptake (45 kg N ha^{-1}), demonstrating the considerable potential of these soils to supply mineral N.

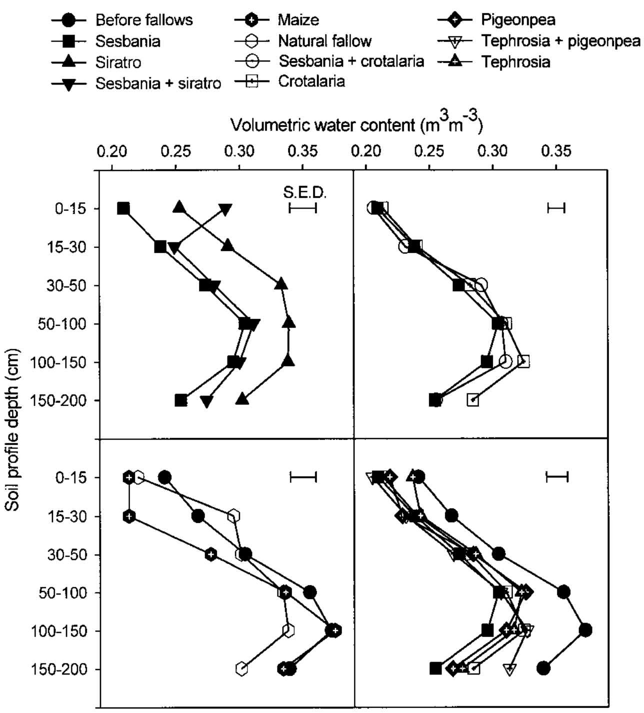

Fig. 6. Effect of different types of fallows on soil water content 6 mo after fallow establishment in the field experiment at Nyaeda, western Kenya, in 1998. Standard error of the difference in means (SED) bars are for comparison of volumetric water content values between fallow treatment means.

A similar degree of complementarity in belowground resource capture was observed as for aboveground resource utilization. Mixing sesbania and crotalaria resulted in increased topsoil and subsoil N uptake compared with sole crotalaria. The two species in monocrop fallows already exhibited potential for complementarity in soil mineral uptake at different soil depths. Sesbania reduced subsoil N at 100 to 200 cm twice as much as crotalaria while the latter extracted more of the topsoil N (0–15 cm). The increased mineral N uptake from both topsoil and subsoil by sesbania + crotalaria mixture contributed to a larger total N in aboveground biomass compared with sole sesbania fallow. A similar phenomenon was observed for pigeonpea and tephrosia in sole-species fallows where pigeonpea extracted less subsoil N than tephrosia and the reverse was true for the topsoil N. Mixing pigeonpea + tephrosia resulted in increased exploitation of subsoil N compared with their respective monocultures.

Cadisch et al. (2002) confirmed the higher subsoil N uptake activity by sesbania compared with crotalaria by injection of ^{15}N into the subsoil in the same experiment. However, subsequent results also revealed that such differences may not always be consistent and indeed may reverse in mixtures if one species establishes poorly or is affected by pests or diseases. Thus, mixing species may also provide a means to reduce risks where adverse conditions affect one species more than the other.

The different fallow systems had varying abilities to extract or conserve soil water, and these results complemented and confirmed observations on mineral N depletion patterns discussed above. For instance, the greater subsoil water extraction by sesbania compared with crotalaria closely reflected the mineral N depletion patterns of the two (more subsoil mineral N was depleted by sesbania), demonstrating that extraction of water and N are closely linked (Fig. 5 and 6).

The soil water stored under sole-siratro plots after 6 mo was substantially greater in the top 50 cm than the initial soil water content and was much greater than in the sole sesbania fallows in the same soil layers. Mixing the two species improved the soil water retention in the top 15 cm compared with the initial soil water content. This can partly be explained by the dense ground cover by siratro, which decreased water losses from the soil surface through reduction of surface runoff and evaporation and enhanced infiltration. On the other hand, sesbania and crotalaria fallows either in sole stands or mixtures extracted more soil water throughout the soil profile. Similarly, Hartemink et al. (1996) concluded that pure sesbania fallows were more efficient in extracting subsoil water than maize and natural weed fallows. In the current study, the topsoil under maize and sole-groundnut treatments was drier than the deeper soil layers, which had not changed much from the initial soil water content (data not presented). This can be attributed to the fact that the two crops were harvested 2 mo before soil water determination and the plots were bare, leading to reduced plant water uptake and increased surface water loss. This results in a higher rainfall requirement to recharge the soil water content and, thus, potentially delayed planting of subsequent crops if rains are scarce.

Complementarity of Uses: Soil Fertility Improvement, Wood, Fodder, and Grain

Among the different tree fallow species and fallow types investigated, the accumulation of woody biomass was, in all cases, greater than foliage production. The wood component of the fallow species is often removed from the plot after fallow harvest, and this contributed substantially to the net nutrient export from the system (e.g., 9–61 kg N ha^{-1}). Sesbania in pure and mixed systems produced the highest proportion of woody biomass (72–78%) (Fig. 3a and 3b). As a secondary product for a fallow intended for soil fertility improvement, the woody component of the fallow can be used as domestic firewood, stakes, and fencing materials. The quality and quantity of wood varies among species, and this can influence a farmer's decision as to which species to adopt. For instance, sesbania wood could be utilized for simple construction and fencing purposes while wood from crotalaria, pigeonpea, and tephrosia could be used as stakes as well as firewood.

Mixtures that included siratro had the highest production of total foliage biomass because including the species as an understory did not alter the density of the companion species. Compared with the pure-siratro plots, siratro in the intercrops had relatively lower biomass production (24–50%). It remains to be tested how the removal of fodder will affect the subsequent impact on soil fertility, but based on the current observations, it appears that the remaining fallow species would provide sufficient inputs for provision of mineralizable N for the next maize crop. Measurements of N_2 fixation of these species have also suggested inputs of 70 to 150 kg N ha^{-1} from the atmosphere, reinforcing their value for soil fertility improvement apart from improved recycling of deep soil N (Gathumbi et al., 2002).

Inclusion of grain legumes as an understory within a fallow system consisting of legume tree and/or shrubby species offers the extra incentive to farmers of an immediate return in cash, food, or both. Groundnut yields were substantially better when intercropped with species with an open canopy structure, such as pigeonpea and sesbania compared with crotalaria and tephrosia, which developed a more dense aboveground canopy within 2 mo after fallow seedling transplanting, as demonstrated by their larger LAI (Fig. 2). Pigeonpea can also produce pods and edible grains in fallows of longer duration than the ones tested here.

CONCLUSIONS

The hypothesis that mixed-species fallows may increase aboveground resource capture was confirmed only for improved fallows where overall planting density was increased by undersowing the creeping legume siratro. Undersowing of siratro also increased total fallow N accumulation. Total aboveground N acquisition by woody legumes at comparable plant populations (in substitutional designs) was increased in the taller legume, e.g., sesbania, which mildly suppressed the lower-growing legume so that the total aboveground fallow N in mixtures was often significantly increased.

The second hypothesis that belowground resource capture can be increased by mixing species was confirmed for selected species with complementarity in root activity patterns. Complementarity was depicted, for example, by differences in soil water depletion at different depth, such as the case of sesbania and crotalaria, which led to an efficient depletion of soil mineral N to depth in the mixed fallow.

The third hypothesis that mixed species could provide a better basket of secondary products while maintaining a high production of foliage biomass for high supply of subsequent soil mineral N was also shown possible with several of the mixtures evaluated: Combining sesbania and crotalaria gave a substantial wood component, undersowing the forage legume siratro provided additional fodder, and groundnut produced a moderate yield of grain.

Based on the results obtained from the different sole species and mixtures, it can be concluded that there is a wide variety of species and fallow types (combined species fallows) from which farmers may choose, depending on their specific needs and preferences. Mixing species requires a good understanding of the early establishment phase as certain species were competitive although sequential timing of planting may alleviate such problems.

ACKNOWLEDGMENTS

We gratefully acknowledge the assistance of both the field and laboratory research teams at the ICRAF/KEFRI/KARI Maseno Agroforestry Research Center and Nyabeda field site. This publication is an output from two projects: Agroforestry Research Network for Africa (AFRENA), funded by the European Union, and NRSP R7056, funded by the UK Department for International Development (DfID) for the benefit of developing countries. The views expressed are not necessarily those of the funding agencies.

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