Published November, 2009

Legumes

Do Mixed-Species Legume Fallows Provide Long-Term Maize Yield Benefit Compared with Monoculture Legume Fallows?

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ABSTRACT

The deliberate planting of fast-growing N_2–fixing legume monoculture species in rotation with cereal crops can be an important source of N for soil fertility replenishment. We hypothesized that mixed-species fallows have a higher potential of giving long-term residual benefits in terms of biomass, nutrients, and quality of residuals leading to long-term nutrient supply to postfallow maize (*Zea mays* L.) crops. To test these hypotheses, two experiments were established in farmers' fields on very fine Kandiudalfic Eutrudox soils with monoculture and mixed-species fallows. Treatments included: sesbania [*Sesbania sesban* (L.) Merr.], crotalaria (*Crotalaria grahamiana* Wight and Arn.), pigeonpea [*Cajanus cajan* (L.) Millsp.], siratro [*Macroptilium atropurpureum* (DC.) Urb.], and calliandra (*Calliandra calothyrsus* Meissn.) as monoculture-species fallow and mixture fallows of sesbania + crotalaria, sesbania + pigeonpea, sesbania + siratro, or sesbania + calliandra compared with continuous maize cropping with or without N fertilizer, and natural weed fallow. Total aboveground biomass ranged from 4.1 to 20.5 Mg ha^{-1} for monoculture and 7.8 to 23.3 Mg ha^{-1} for mixed-species fallows. Recyclable fallow biomass N ranged from 70 to 313 kg ha^{-1} and there was a positive interaction in some mixtures leading to increased N accumulation. Postfallow maize yields for fallows over five cropping seasons were 161–272% or 61–103% higher when compared with continuous maize without or with N fertilizer, respectively. Long-term postfallow effects on maize yield were linearly related to the amount of recycled fallow N yield. Thus, choice of fallow species to mix should be primarily driven by a better risk management strategy and an increased basket of multiple products and services.

Subsistence farming in sub-Saharan Africa is characterized by low per capita food production. According to the World Bank (1996), the per capita food production in sub-Saharan Africa declined by 1.0% annually between 1980 and 1993. Declining soil fertility and increasing nutrient depletion due to continuous cultivation without the use of external inputs is a major biophysical cause of low food production (Sanchez et al., 1997). Long duration natural weed fallows that traditionally were used to restore soil fertility are no longer feasible because of declining farm sizes due to the population increase and resulting competing land demand (Nye and Greenland, 1960). Results from West Africa have shown that short duration, natural unmanaged fallows (3–6 yr) normally do not restore soil fertility to that achieved under long duration fallows (Aweto et al., 1992). In western Kenya, due to extremely high population densities and declining farm sizes, farmers have replaced long duration fallows with short duration native weed fallows that last for only 1–3 seasons on a small portion of their cropping land (Swinkels et al., 1997). Nutrient budgets of smallholder farms show net annual depletion of N, P, and K as a result of long-term cropping with little or no addition of external inputs (Shepherd et al., 1996). The majority of farmers lack cash to buy fertilizer, especially after government removal of subsidies through structural readjustment programs. Maize is the main staple food and seasonal maize yields rarely exceed 1 Mg ha^{-1} in the two seasons per year (Shepherd and Soule, 1998) that is hardly enough to feed an average family of seven members per household.

Legumes can play an important role in supplying N for cereals in tropical farming systems where there is little use of fertilizer (Giller, 2001; Giller et al., 1994; Peoples et al., 1995). In Africa, deliberate planting of fast-growing trees, shrubs, and herbaceous legume species (referred to as improved fallow) has become a central agroforestry technology for soil fertility improvement (Buresh and Tian, 1997). This farming technology was rapidly taken up and tested by smallholder farmers (1–5 ha) in western Kenya (Niang et al., 2002) and eastern Zambia (Kwesiga and Coe, 1994), although recent studies indicate that true 'adoption' is restricted (Kiptot et al., 2007). Fallow trees improve soil fertility through biological dinitrogen fixation (Gathumbi et al., 2002a), through deep N capture from the subsoil (Gathumbi et al., 2003; Hartemink et al., 1996), and by roots providing a safety-net to reduce N losses through leaching (Rowe et al., 1999).

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Published in Agron. J. 101:1352–1362 (2009)
Published online 26 Aug. 2009
doi:10.2134/agronj2008.0208x

Abbreviations: ADF, acid detergent fiber; LR, long rainy season; SR, short rainy season.

Large yield responses by the subsequent crop have been reported after 9 to 18 mo of improved monoculture-species fallows with substantial residual benefits for the following crops (Jama et al., 1998; Kwesiga and Coe, 1994) for at least two cropping seasons (Rao et al., 2002). The residual maize yield benefit after the fallow is greatly influenced by fallow duration (Kwesiga et al., 1999; Mafongoya and Dzowela, 1999), fallow species (Drechsel et al., 1996), and soil type (Phiri et al., 1999b). Ayanaba et al. (1976) reported that after the fallow and during the cropping period, the proportional decline in labile soil N was greater than the decline in total soil N, indicating that the capacity of soil to supply N declines even more rapidly than the soil N reserve. Sesbania, a fast growing, N_2–fixing tree has been reported to increase crop yield, soil organic N, soil N mineralization, and the amount of N in the light fraction of soil organic matter (Barrios et al., 1997). However, sesbania litter decomposes rapidly, as it is rich in N with little lignin and polyphenols (Mafongoya et al., 1997). Therefore, it is unlikely to contribute to long-term enhancement of soil organic matter and the rapidly released N is prone to leaching due to poor synchrony with crop N demand.

Barrios et al. (1997) reported differences in *Leucaena leucocephala* [(Lam.) de Wit], calliandra, *Flemingia macrophylla* [(Willd.) Merr], *Gliricidia sepium* (Jacq), *Senna siamea* (Lam.), and sesbania effects on soil organic matter (SOM), soil mineral N, and N mineralization, suggesting the importance of litter quality in influencing soil fertility. Kwesiga et al. (1999) and Mafongoya and Dzowela (1999) also observed that different monoculture-species fallows led to different maize yield benefits after the fallow and different residual effects after the first maize crop, indicating that they contribute differently to soil fertility. Differences in yield responses to monoculture-species fallows may be associated with differences in fallow biomass recycled back into the soil and/or differences in litter quality and hence nutrient release patterns. Therefore, mixing of species of different residue quality in the fallow may led to differences in litter decomposition and nutrient release, and hence to a better synchronized N release with crop N demand as well as increased SOM, and hence long-term effects. Cadisch et al. (2000) and Gathumbi et al. (2002b) reported the beneficial effects of mixed fallows in terms of nutrient sourcing from different soil depths and complementarity in aboveground resource utilization that leads to increased biomass productivity. Apart from soil fertility improvement aspects, mixed fallows can benefit farmers through provision of multiple products and reduce risk of fallow establishment (Cadisch et al., 2000; Gathumbi et al., 2002b). Mixed species also have the potential of reducing or increasing pests and diseases associated with monoculture species (Sileshi et al., 2000) and controlling striga (*Striga* spp.) seed population in the soil and striga emergence (Gacheru et al., 1999)

Whereas Cadisch et al. (2000) and Gathumbi et al. (2002b) strongly recommended the utilization of mixed species in terms of aboveground and belowground resource utilization by the fallows, there is little information on the benefit of mixed species on subsequent crops in the short and long term. Therefore, there is a need to investigate if and how mixed species increase the beneficial effects of fallows on subsequent crops. We hypothesized that mixed-species fallows have the potential to provide greater residual long-term benefits to the postfallow crops because they produce (i) larger amounts of biomass, hence return larger amounts of nutrients to the soil, leading to greater nutrient availability to the subsequent crop, as well as improved soil organic matter content; and (ii) have a more diverse residue quality that affects short and long-term N dynamics. With respect to residue quality, it is hypothesized that mixing of high quality residues (e.g., from Sesbania) that decompose fast, with low quality residues that decompose slowly, improves synchrony of nutrient release with crop N demand as well as improving longer-term N supply. Mixing high quality fallow residues with polyphenol-rich legume material (e.g., from calliandra) may also result in the formation of complexes with proteins and carbohydrates that are resistant to microbial degradation (Handayanto et al., 1994, 1997) and hence increase soil organic matter and long-term benefits of such systems (Cadisch and Giller, 2000).

The specific objectives thus were (i) to determine the effect of mixed-species fallows on aboveground biomass and fallow N accumulation as compared with monoculture-species fallows and natural fallow; (ii) to study the effect of fallow species mixtures on maize yields compared with monoculture-species stands, continuous maize and natural weed fallows and N fertilizer; and (iii) to determine whether there is a relationship between maize yield and biomass amount and/or litter quality.

MATERIALS AND METHODS

Site Description

A field experiment was conducted on farmers' fields at two sites in the Highlands of western Kenya. Owano farm was located at 0°06′ N, 34°34′ E at an altitude of 1420 m, and Dindi farm was located at 0°06′ N, 34°34′ E at an altitude of 1330 m. The sites are about 20 km apart having a typical subsistence-level, mixed crop-livestock farming system (Shepherd et al., 1996). The plots had been continuously cultivated for many years with maize, with occasional natural fallowing to restore soil fertility. Both sites have a mean annual rainfall of 1800 mm that is bimodally distributed over two cropping seasons. The growing season during the long rainy season (LR) is from March to July and short rainy season (SR) from September to December. During the experimental period, rainfall gauges were installed at the experimental sites.

Soils at both sites are considered highly weathered and generally low in fertility. At Owano farm the soil is classified as very fine, isohyperthermic kandiudalfic Eutrudox (Ferralsol) with the following properties at the 0- to 15-cm depth: pH (1:2.5 soil/water suspension) of 5.6, 1.6% organic carbon, 0.14% N, 1.6 mg kg^{-1} bicarbonate-ethylenediaminetetraacetic acid extractable P, KCl extractable Ca and Mg of 2.9 and 1.0 $cmol_c$ kg^{-1} respectively, 33% clay and 51% sand and a slope of 2%. Soil control structures (trenches) were installed between plots down the slope. The soil at Dindi farm is a very fine kaolinitic, isohyperthermic kandiudalfic Eutrudox with a pH of 5.8, 1.8 mg kg^{-1} bicarbonate-ethylenediaminetetraacetic acid extractable P, 1.4% organic carbon, 0.13% N, KCl extractable Ca and Mg of 5.4 and 1.6 $cmol_c$ kg^{-1} respectively, 54% clay and 25% sand. The soils on both farms were well-drained to >200 cm depth.

Experimental Design

The experiments on both farms were established during the LR in May 1998. The experimental design at both farms was a randomized complete block design (RCBD) with 12 treatments replicated four times. Blocking was based on cropping history, P levels in the soil characteristics, slope and uniformity in the previous cover maize crop. Monoculture and mixed species improved fallow–maize crop rotations and their respective controls were set up as follows: (i) sesbania (Ss) (seed fromYala, Kenya) alone; (ii) pigeonpea (Cc) (ICP13211 from ICRISAT, Hyderabad, India) alone; (iii) crotalaria (Cg) (Marrano, Madagascar) alone; (iv) siratro (Ma) (accession GB12102 from ILRI, Addis Ababa, Ethiopia) alone; (v) calliandra (Cal) (Kakamega, Kenya) alone (biomass transfer); (vi) sesbania mixed with crotalaria; (vii) sesbania mixed with siratro; (viii) sesbania mixed with pigeonpea; (ix) sesbania mixed with calliandra (biomass transfer); (x) continuous maize cropping; (xi) continuous maize cropping + 100 kg ha^{-1} N fertilizer; and (xii) natural weed fallow. The individual experimental plot size was 8.25 m by 6 m. The seed sources and the provenances are given by Gathumbi et al. (2002b). Calliandra is a slower-growing species and therefore usually not suitable for short duration fallows but was included (as biomass transfer option) because its pruning material is rich in reactive polyphenols and hence allowed to test the scope of manipulating N supply dynamics. Calliandra pruning material was obtained from an existing hedgerow intercropping in a nearby farm (biomass transfer) and was applied at a rate equivalent to sesbania fresh weight on half of the sesbania fallow plot. Calliandra and N fertilizer treatments were applied after fallow harvest at the end of LR1999.

Maize and Fallow Establishment

During mid-March 1998, all plots were planted with maize crop at a rate of three maize seeds (hybrid 513) per hole with a spacing of 75 cm by 25 cm. Before maize planting, triple superphosphate and muriate of potash fertilizers were broadcast in all plots at a rate of 100 kg P and 100 kg K ha^{-1}. Fallows were established into the growing maize crop. One month after maize planting just after the second weeding, tree seeds were direct seeded within the maize row at the same spacing of 75 cm by 75 cm (17,777 trees per ha^{-1}). Mixed species were planted as a 50/50 substitutional design by alternating plant species rows. During the intercropping phase, the legumes grew slowly and offered little competition to the companion maize crop. After maize harvest, the legumes were allowed to fully establish and to grow through the SR of 1998 and the LR of 1999 (total fallow duration of 17 mo).

The maize treatment plot was continuously cropped with maize (at 75 cm × 25 cm spacing) throughout the fallow establishment phase, while the natural weed fallow plots were dominated with regrowth of native weeds throughout the entire fallow phase. At Owano farm, the predominant weed species were *Guizotia scabra* [(Vis.) Chiov.], goat weed [*Ageratum conyzoides (L.)*], lion's ear [*Leonotis nepetifolia* (L.) R.Br.], and love grass [*Eragrostis aspera* (Jacq.) Nees], while blackjack [*Bidens pilosa* (L.)], Florida pulsey [*Richardia scabra* (L.)], ragwort [*Senecio abyssinicus* (Sch. Bip.)], and natal grass [*Rhynchelytrum repens* (Willd.) CE Hubb.] were less dominant. At Dindi farm, couch grass [*Digitaria abyssinica* (Horchst ex A. Rich.)] was predominant while deccan herp [*Habiscus cannabinus* (L.)], blackjack, *Guizotia scabra* [(Vis.) Chiov.], lion's ear and wandering Jew [*Commelina benghalensis* (L.)] were less dominant.

The fallow plots were kept free of weeds before the tree canopy closure and thereafter the fallow provided enough shading to suppress weeds. To prevent roots growing into the neighboring plots, trenches of approximately 1 m depth and 0.5 m wide were dug around the fallow plots in January 1999. The trenches were left open for about 7 d to allow roots to die-back before they were back filled with soil. During the fallow growth, one litter trap was installed in each plot. The litter traps were made with a wire mesh (<1 mm in diameter) and a wooden frame and covered a surface area of 0.75 m × 0.75 m, an equivalent area covered by one tree. Each trap was supported on a stand at 30 cm above the soil surface. Litterfall was collected every 2 wk and dried at 40°C for 48 h. In the macroptilium plots, litterfall was collected from a 0.75 × 0.75 m quadrat on the ground. Litterfall was not collected from natural fallow plots due to the apparently low litter production and difficulty in collection.

Fallow Harvesting Procedures

At the fallow harvest in September 1999, trees were cut down at the ground level and separated into woody biomass (main stem and branches) and foliage (foliage, twigs and pods). Foliage was stripped by hand. The fresh weight of each plant component was determined and a subsample of each component was taken by spreading the harvested biomass on a polythene sheet and quartering. Subsamples were oven dried at 40°C for 72 h to a constant weight to determine dry matter. The dry weight from oven dried samples was used to determine the dry/fresh weight ratio that was used to back calculate dry biomass weight. The dried subsamples were ground to pass through 1.0 or 0.5-mm sieve using a micro-hammer mill and stored for subsequent analysis. The ground samples were subsequently analyzed for N, carbon, lignin, polyphenols, and protein binding capacity.

Maize Establishment after Fallow

After fallow harvesting in September 1999, fallow biomass (foliage) was incorporated immediately to about a 15-cm depth using a hand hoe in the tillage plot. Thereafter fertilizer, equivalent of 100 kg ha^{-1} P and K, was broadcast and incorporated into the 15-cm depth in each plot with a hand hoe to eliminate P and K deficiency. In the continuous cropping plot with N fertilizer, one third of the 100 kg ha^{-1} N ha as urea was broadcast at planting and two thirds applied after the second weeding as a top dressing in each cropping season. Hybrid maize 513 was then planted at 25 cm within row and 75 cm between rows. Three maize seeds were sown per hole and later thinned to one maize plant per hole (53,333 plants per ha^{-1}) and the crop was weeded twice per season at two and 4 wk after maize planting. After top dressing the continuous cropping plot, trichlorfon (Dipterex, dimethyl (2,2,2-trichloro-1-hydroxyethyl phosphonate) granules were applied in maize funnels to control maize stalk borer [*Buseola fusca* (Fuller)] in all plots.

Maize was harvested at physiological maturity from a harvest area of 4.5 by 7.25 m. Maize cob and stover fresh weight from the net plots was quantified in the field. A subsample was taken for dry weight determination. After sun drying, the maize cob

Table 1. Cumulative rainfall received in long rains (LR) and short rains (SR) growing seasons from Dindi and Owano experimental sites from 1999 to 2001. Long rains season: March to August, and short rains season: September to December.

Season	Rainfall amount	
	Dindi farm	Owano farm
	———mm———	
Fallow period (15 mo)	2499	2463
First postfallow maize crop (SR) 1999	679	963
Second postfallow maize crop (LR) 2000	572	783
Third postfallow maize crop (SR) 2000	657	657
Fourth postfallow maize crop (LR) 2001	764	922
Fifth postfallow maize crop (SR) 2001	775	890

was further separated into grain and core. Grain moisture was then determined with a moisture meter. Core and stover was subsequently oven dried at 70°C to a constant weight (usually 72 h) and exact moisture of the grain measured with a moisture meter again. Maize grain yield was determined at 15% moisture content. The samples were ground to pass through a 0.5-mm sieve and kept in plastic airtight bottles and stored in a cool dry place for subsequent nutrient N analysis. After maize harvest in each of the four seasons, all the stover and weeds were removed from all the plots to eliminate confounding effects on nutrient additions into the soil.

Total C and N contents of the fallow plant samples were determined by dry combustion using a Roboprep automatic C/N analyzer coupled to a Europa Scientific 20-20 stable isotope mass spectrometer (PDZ, Crewe, UK). The acid detergent fiber (ADF) and the acid detergent lignin were determined using an ANKOM$^{220/220}$ fiber analyzer (ANKOM Technology corporation, Fairport, New York) based on the procedure by Goering and van Soest (1970). Total extractable polyphenol content was determined using the Folin-Ciocalteu reagent (Anderson and Ingram, 1993) while the protein binding capacity procedure was adapted from Dawra et al. (1988). Total N in maize grain stover and cob cores was analyzed by a modified Kjeldahl digestion (Anderson and Ingram, 1993).

Statistical Analysis

Foliage biomass, residue quality parameters, maize yield (grain, stover), and grain/stover nutrients were tested for normality using ANOVA with untransformed data, thereafter the residuals were examined (Lane et al., 1987). If the residuals were not normally distributed and showed a variance that increased with the mean, a logarithmic transformation of data was used and then analyzed by GENSTAT version 5. Analysis of variance was used to test significance of differences between means, and regression analysis was used to determine the relationships between different variables such as litter quality parameters and maize grain yield. The standard errors of the differences of means are presented for treatment comparison. Mention of statistical significance refers to $P < 0.05$ unless otherwise stated. Interactions in mixed-species fallows were assessed by comparing yields of maize after mixed-species fallows with the average yield of maize after each of the two monoculture-species fallows of the components in the mixture, that is,

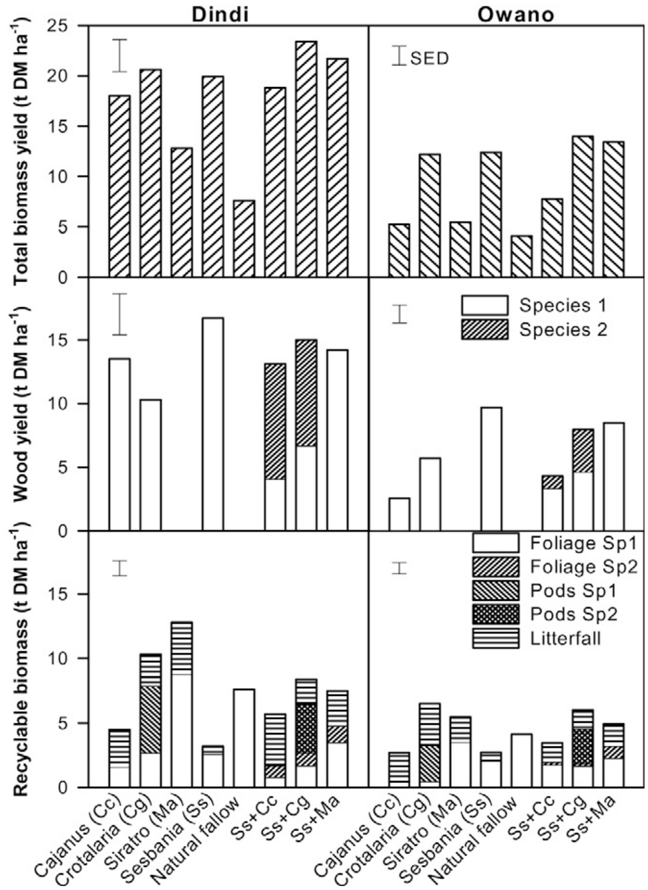

Fig. 1. Total, wood, and recyclable (foliage + pods + litter) aboveground DM yields (t ha^{-1}) of pure and mixed (species 1 + 2) legume fallows and natural weed fallow at Owano and Dindi farm in western Kenya. Vertical bars are standard error of mean difference (SED).

$$\mathrm{ABMF} = \mathrm{YAMF} - \frac{\mathrm{YAS1} + \mathrm{YAS2}}{2}$$

where ABMF is added befefit mixed fallow, YAMF is yield after mixed fallow, and YAS is yield after species.

RESULTS

Rainfall Distribution during Fallow and Cropping Phases

During the fallow period and the five maize growing seasons, annual rainfall was 1656, 2022, 1366, and 1789 mm for Dindi, and 2035, 2058, 1375, and 2054 mm for Owano over 4 yr from 1998 to 2001 compared with 1721 mm for long-term average. The seasonal mean total rainfall during the LR2000 and SR1999 cropping season in both Dindi and Owano are shown in Table 1. On site rainfall did not significantly differ from rainfall recorded at the automated meteorological weather station at Ochinga for Owano farm and Nyabeda for Dindi farm.

Fallow Biomass Yield

At Dindi farm, total aboveground biomass yield varied from 12.8 to 20.5 Mg DM ha^{-1} for the monoculture-species fallow treatment as compared with 19.0 to 23.3 Mg DM ha^{-1} for mixed species fallows (Fig. 1). Pure crotalaria fallow produced the highest biomass, but was not significantly different from

Table 2. Chemical composition of residues from improved fallows species incorporated into soil after fallow harvest in western Kenya (average of Dindi and Owano farms).†

Treatment	Species	Parts	N	C	TEP	ADF	ADL	PBC	C/N ratio	Lignin/N ratio	TEP/N ratio	(TEP + ADL) /N ratio
			%					μg BSA mg^{-1} plant				
Pigeonpea (Cc)	pigeonpea	foliage	3.5	46	3.8	38	13	50	13	6.1	1.1	7.2
		litterfall	2.3	45	5.0	49	21	nd‡	20	13.3	2.2	15.5
Calliandra (Cal)	calliandra	foliage	3.2	46	13.1	26	10	218	15	3.2	4.1	7.2
Crotalaria (Cg)	crotalaria	foliage	3.6	42	1.9	27	5	18	12	1.3	0.5	1.9
		litterfall	1.8	40	1.4	37	14	nd	22	7.6	0.8	8.4
		pods	2.4	42	0.9	35	6	nd	18	2.5	0.4	2.9
Siratro (Ma)	siratro	foliage	2.8	43	1.7	41	10	24	16	3.7	0.6	4.3
		leaves	3.3	43	2.8	35	9	nd	13	2.7	0.8	3.6
		vines	2.8	42	1.5	44	11	nd	15	4.1	0.5	4.6
		litterfall	2.0	35	0.6	24	7	nd	17	3.5	0.3	3.8
Sesbania (Ss)	sesbania	foliage	3.6	45	3.1	25	9	50	12	2.6	0.9	3.4
		litterfall	2.1	43	1.6	41	16	nd	21	7.4	0.8	8.2
Ss + Cc	sesbania	foliage	3.6	45	2.6	28	9	50	12	2.5	0.7	3.2
	pigeonpea	foliage	3.6	47	4.3	36	19	32	13	5.3	1.2	6.5
	Ss + Cc mix	litterfall	2.2	44	3.3	45	25	nd	20	11.2	1.5	12.7
Ss + Cg	sesbania	foliage	3.8	44	3.3	24	10	50	12	2.7	0.9	3.5
	crotalaria	foliage	3.5	42	1.7	26	6	18	12	1.6	0.5	2.1
	crotalaria	pods	2.5	43	1.5	38	13	nd	17	5.2	0.6	5.8
	Ss + Cg mix	litterfall	2.1	41	1.3	38	13	nd	20	6.1	0.6	6.7
Ss + Ma	sesbania	foliage	3.5	44	2.3	26	11	50	12	3.1	0.6	3.7
	siratro	foliage	3.1	43	1.5	42	12	24	14	3.8	0.5	4.2
	Ss + Ma mix	litterfall	2.1	39	1.5	41	15	nd	18	7.3	0.7	8.0
Natural fallow		foliage§	1.6	39	1.2	42	8	nd	25	5.2	0.7	5.9

† ADF = acid detergent fiber; ADL = acid detergent lignin; BSA = bovine serum albumin; PBC = protein binding capacity; TEP = total extractable polyphenols.

‡ nd = not determined.

§ Litterfall not determined.

sesbania and pigeonpea. There were no significant differences between mixed and monoculture-species fallows except when compared with siratro that had the lowest improved fallow yield. Natural weed fallow produced significantly lower total biomass than both mixed and monoculture-species legume fallow treatments. Generally, total biomass yield at Owano farm was lower compared with Dindi farm. Crotalaria (12.2 Mg DM ha^{-1}) was again among the highest monoculture species biomass producers together with sesbania. Pigeonpea, siratro, and natural weed fallows produced significantly less total biomass yield compared with crotalaria and sesbania. Mixed species fallows at Owano produced between 7.8 and 14 Mg DM ha^{-1}, but these yields were not significantly different from average monoculture-species fallow treatments apart from the sesbania-siratro combination that produced higher yield in mixture than the average of their monoculture species yields at both sites. At both sites, species mixtures produced similar amounts of wood compared with the average of single species fallows apart from the sesbania + siratro mixture in which sesbania largely compensated for the lack of wood production in siratro.

At both sites, total aboveground recycled biomass (foliage, litterfall and pods) was highest for crotalaria and siratro and lowest for pigeonpea and sesbania monoculture-species fallows (Fig. 1). Furthermore, in mixed fallows, at both farms, the combinations of sesbania + crotalaria and sesbania + siratro produced the highest recyclable biomass. At Dindi, the sesbania + pigeonpea mixture produced significantly more recyclable biomass compared with their monoculture-species stands, while at Owano farm there were no significant differences between pure and mixed stands.

Litterfall made a substantial contribution to the recyclable biomass in all species, particularly in pigeonpea. For crotalaria, seedpods were a highly significant proportion of the recyclable biomass. Green leaf biomass for these two species contributed <50% of recyclable biomass while with sesbania and siratro it was >50%.

Plant Residue Characterization

There were no significant differences in the chemical properties of the foliage biomass of species between the two farms and therefore means are reported (Table 2). Foliage N concentration ranged from 2.8% for siratro to 3.8% for sesbania in the sesbania + crotalaria mixture. Residue C concentrations generally ranged from 40–47% except for siratro litterfall (34.5%), the latter indicative of some soil contamination. Variation in the C-to-N ratio between improved fallow species within the same plant parts was relatively small with fresh litterfall having the highest C-to-N ratios of 17–22. Foliage of natural fallow had the highest C-to-N ratio (24.5%). Lignin concentration was substantially higher in litter materials (14–25%) except for siratro litter (7%) that consisted mainly of leaf fall. The total extractable polyphenol and protein binding capacity were mostly relatively low (<5%) except for calliandra foliage that

Table 3. Recycled biomass (foliage, pods and litterfall) N yield of monoculture and mixed-species fallows at Dindi and Owano farm in western Kenya.

Treatment	Dindi farm					Owano farm				
	Foliage Species 1	Foliage Species 2	Pods	Litterfall	Total	Foliage Species 1	Foliage Species 2	Pods	Litterfall	Total
	kg ha^{-1}									
Pigeonpea	54	–	–	66	120	15	–	–	54	70
Pigeonpea + sesbania	34	30	–	83	144	7	66	–	34	107
SED†	6.3*			18.7 ns‡	10.8 ns	4.4 ns			12.9 ns	2.8**
Calliandra	78	–	–	–	80	68			–	68
Calliandra + sesbania	78	91	–	11	185	68	76		19	165
SED	na§				8**	na				4.4***
Crotalaria	102	–	125	41	267	17	–	67	65	149
Crotalaria + sesbania	40	67	102	38	246	6	64	73	32	175
SED	8.2**		16.9 ns	4.6 ns	21 ns	5.7 ns		9.5 ns	14.7 ns	10.7 ns
Siratro	230	–	–	83	313	102	–	–	39	141
Siratro + sesbania	45	104	–	60	209	29	80	–	35	143
SED	29.7**			5.9 ns	49.3 ns	15.0*			6.2 ns	21 ns
Sesbania	91	–	–	11	103	78	–	–	19	97
Sesbania + pigeonpea	30	34	–	83	144	66	7	–	34	107
Sesbania + calliandra	91	78	–	11	181	78	68	–	8	165
Sesbania + crotalaria	67	40	102	38	246	64	6	73	32	175
Sesbania + seratro	104	45	–	60	209	80	29	–	35	143
SED	15.5**	6.7***	–	12.2***	33.5**	16.3 ns	4.1***		9.4 ns	18.4**
Natural weed fallow	151	–	–	–	151	49	–	–	–	49
Overall SED					29.6***					17.8***

* $P \leq 0.05$.

** $P \leq 0.01$.

*** $P \leq 0.001$.

† SED, Standard error of differences between treatment means.

‡ ns, not significant at $P \leq 0.05$.

§ Na, not available.

had 13% polyphenols and 218 μg bovine serum albumin mg^{-1} sample protein binding capacity.

Amount of Potentially Recycled Nitrogen

Amount of N recycled through foliage, pods, and litterfall was higher at Dindi than at Owano farm (Table 3). At Dindi farm, the monoculture-species fallows yielded up to 313 recyclable N kg ha^{-1} (siratro) as compared with maximum of 246 N kg^{-1} ha for the sesbania + crotalaria mixture, respectively. At Owano farm, the highest recyclable N yield was obtained in the sesbania + crotalaria mixture (175 N kg ha^{-1}). At both farms, crotalaria pods in the pure and mixed treatment accounted most for the high N yields in the respectively recycled biomass. Among the monoculture-species fallows, sesbania recycled the lowest amount of N in litterfall (11–19 kg N ha^{-1}) at both sites, while siratro showed a litterfall of up to 83 kg N ha^{-1} at Dindi farm. Natural weed fallows produced a higher foliage N yield at Dindi (151 kg N ha^{-1}) compared with only 49 kg N ha^{-1} at Owano. A significant interaction occurred in the mixture in that the recycled N yield of the mixed fallow was greater than the average yield of the monoculture-species fallows (Table 3). This yield advantage reached 60 kg N ha^{-1} in the sesbania + pigeonpea mixture and about 22–32 kg N ha^{-1} in the sesbania + crotalaria mixture. For the less productive pigeonpea and sesbania, this led also to an absolute higher recycled N yield of the mixture than any of the monoculture-species fallows but for the highest yielding monoculture species, crotalaria and macroptilium, the mixture did not yield more than the best monoculture-species fallow.

Maize Grain Yields over Five Successive Seasons after the Fallow

There was a significant treatment × farm interaction for maize grain yield, and therefore the maize yield data was interpreted separately for the two sites (Table 4). At Dindi farm, the maize grain yields after monoculture and mixed-species fallows ranged from 2.7 to 6.7 Mg ha^{-1} in the first and second postfallow seasons (SR1999 + LR2000) then declined to 1.0 to 1.8 Mg ha^{-1} in SR2001. At Dindi, during the first season (SR1999), crotalaria and seratro based fallows resulted in highest maize yields that were significantly greater than maize yield after pigeonpea and calliandra. Similarly, in the second and fourth postfallow seasons (LR2000 + 2001), maize grain yields after crotalaria and seratro based fallows were higher compared with pigeonpea and calliandra on their own. After the fourth season of maize (LR2001), differences between improved fallow treatments became small and insignificant apart from the consistently poor performance of the maize after the calliandra-alone treatment. Maize grain yields after improved fallows were significantly higher than either continuous maize or natural fallow treatments, although after the third postfallow season (SR2000) differences were no longer significant in all cases. Improved fallow treatments produced maize grain yields similar or greater compared with the N fertilizer treatment

Table 4. Maize grain yield of four cropping seasons SR = short rains, LR = long rains) after monoculture and mixed-species legume as compared with continuous cropping, N fertilizer (100 kg N ha^{-1}) and natural weed fallow.

Site	Treatment	SR1999	LR2000	SR2000	LR2001	SR2001	Total
		Mg ha^{-1}					
Dindi	Pigeonpea (Cc)	4.7	4.1	3.4	2.9	1.4	16.4
	Calliandra calothyrsus (Cal)	2.7	2.6	2.3	2.0	1.0	10.5
	Crotalaria grahamania (Cg)	5.9	6.3	4.0	3.6	1.6	21.4
	Siratro (Ma)	5.7	6.5	4.0	3.6	1.7	21.5
	Sesbania sesban (Ss)	5.4	5.5	4.0	2.3	1.6	18.7
	Ss + Cc	5.2	5.5	3.2	2.7	1.2	17.9
	Ss + Cal†	5.1	5.8	3.2	3.2	1.6	18.7
	Ss + Cg	6.2	6.0	4.3	3.2	1.5	21.1
	Ss + Ma	6.7	5.6	4.1	3.3	1.8	21.4
	Natural fallow	1.3	2.2	2.1	2.8	1.4	9.7
	Maize + N	4.9	6.5	5.7	6.5	3.2	26.7
	Maize– N	1.7	2.7	2.0	2.2	1.3	9.8
	SED‡	0.32***	0.42***	0.31***	0.38***	0.24***	0.90***
Owano	Pigeonpea (Cc)	4.7	3.1	1.7	1.1	0.7	11.4
	Calliandra calothyrsus (Cal)	1.8	1.3	1.1	1.2	0.5	5.8
	Crotalaria grahamania (Cg)	5.5	5.0	2.0	1.7	1.1	15.2
	Siratro (Ma)	6.3	4.9	2.0	2.1	0.8	16.0
	Sesbania sesban (Ss)	6.0	4.3	4.4	3.7	0.9	19.3
	Ss + Cc	5.8	4.0	1.5	1.5	0.5	13.4
	Ss + Cal†	5.9	3.6	2.4	3.3	1.4	16.4
	Ss + Cg	6.7	5.6	1.8	2.2	0.6	16.8
	Ss + Ma	6.3	4.0	1.3	1.6	0.6	13.8
	Natural fallow	3.0	4.0	1.5	1.9	0.9	11.3
	Maize + N	4.4	3.9	3.2	3.7	3.5	18.7
	Maize – N	2.0	1.8	1.4	1.3	0.6	7.1
	SED	0.25***	0.32***	0.26***	0.33***	0.19***	0.64***

*** $P \leq 0.001$.

† Biomass transfer (e.g., added design).

‡ SED = standard error of the differences of between means.

in the first two postfallow seasons, but thereafter N fertilizer treatments greatly exceeded maize yields of fallows (Table 4).

At Owano farm, maize grain yield ranged from 1.8 to 6.7 Mg ha^{-1} in the first postfallow season (SR1999) but started to decline already the following cropping season to 1.3 to 5.6 Mg ha^{-1} and subsequently to only 0.5 to 1.4 Mg ha^{-1} in the fifth season of maize (SR2001). During the first postfallow season (SR1999), monoculture-species fallows of seratro, sesbania, and crotalaria led to significantly higher maize yield compared with pigeonpea fallow and even the N fertilizer treatments, and the effect persisted into LR2000 for crotalaria and seratro monoculture-species fallows. At Owano farm, sesbania fallow yielded significantly more maize compared with other monoculture-species fallows in the third and fourth seasons (SR2000 + LR2001), and in SR2000 even more than the N fertilizer treatment. In the fifth postfallow season (SR2001), maize yields from N fertilized treatment were significantly higher compared with other fallow treatments, that were at that time similar to continuous cropping without fertilizer inputs. In all years, continuous cropping and the calliandra biomass transfer plot resulted in the lowest maize yields, even lower than maize after the natural weed fallow. In the first postfallow season (SR1999), all mixed-species fallows led to high maize yields but comparable to seratro, crotalaria and sesbania pure stands. In the second season (LR2000), maize yield was significantly highest in the sesbania + crotalaria mixture compared with other mixtures. However, after the second season (LR2000) the sesbania + calliandra mixture yielded significantly higher maize yields compared with other mixed-species fallows. Nitrogen fertilizer and sesbania gave highest cumulative maize yields over five successive seasons. Continuously cropped maize plots without N inputs and natural weed fallow plots yielded least maize over the whole experimental period. Total maize yield in the five cropping seasons after the legume fallow were significantly higher than seven cropping seasons of continuous cropping except for pigeonpea and calliandra plots.

Benefits of Mixed Fallow Species on Maize Yield

At Dindi farm the first postfallow crop after the sesbania + seratro mixture yielded significantly more maize than the average of the two respective monoculture-species treatments (Table 4) or indeed any of the monoculture-species fallow derived yields. In the following cropping seasons these interactions were not any more significant. The cumulative maize yield advantage of mixed fallows over five cropping seasons compared with the average yield of its monoculture-species treatments was highest in the sesbania + seratro treatment at Dindi, with 1.3 Mg ha^{-1}. In the sesbania and biomass transfer calliandra combination, sesbania alone and the mixture gave significantly higher maize yield than calliandra in the first and second postfallow crops (SR1999 and LR2000), but sesbania alone and sesbania + calliandra were not significantly different from each other. Since calliandra material was added as a biomass transfer treatment, interactions have to be calculated by comparing the sum of the two individual species results rather

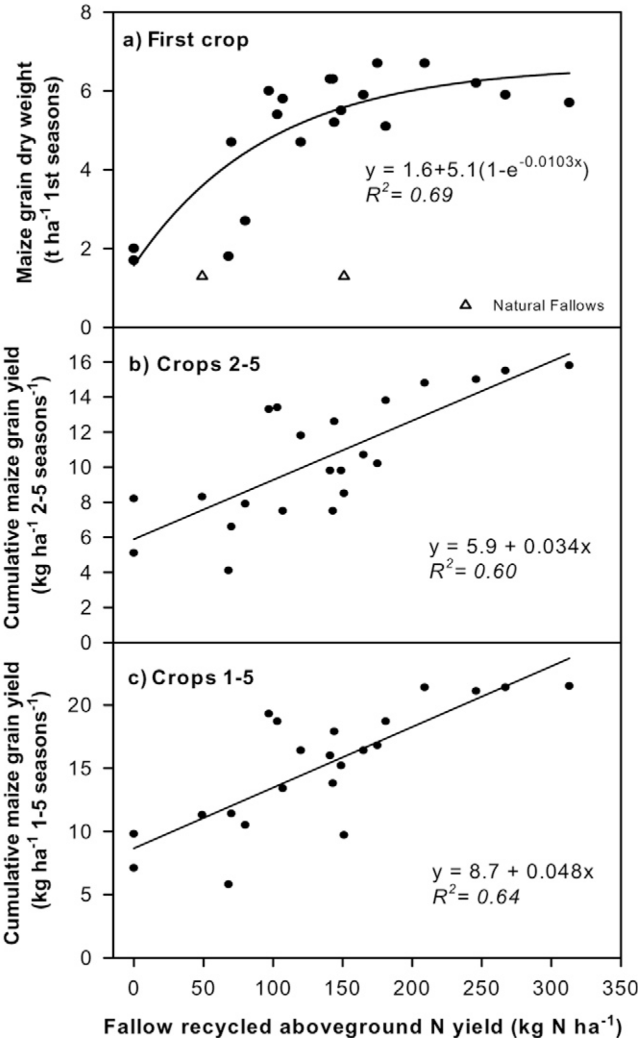

Fig. 2. Relationship between recycled fallow aboveground N yield on maize economic (grain) yield: (a) first postfallow maize crop (natural fallow data excluded from regression), (b) residual long-term effect (postfallow Crops 2–5) and (c) cumulative over all five seasons.

than their average as with the substitutional design of the other treatments. Over five postfallow cropping seasons the mixture failed to out-yield the sesbania-alone treatment.

Similar to Dindi, positive interactions occurred between species when grown in mixtures for the first and second postfallow crops at Owano farm (SR1999 and LR2000). Maize after the sesbania + calliandra mixture had a yield advantage of nearly 2 Mg ha^{-1} over its average yields after monoculture-species fallows in first and second postfallow crops (SR1999 and LR2000). However, after the second postfallow crop (LR2000), only negative interactions in mixtures were observed due to the persistent high yields of the sesbania monoculture-species treatment during that time (Table 4). Thus, cumulative over five seasons none of the mixtures led to a positive interaction, and only the calliandra + sesbania mixture gave a positive interaction at Owano.

Relationship between Fallow Nitrogen and Maize Yield

Maize yield responded in a similar way to recycled fallow N biomass at both farms, thus their data were combined for investigations of fallow N–maize relationships. During the first postfallow crop, maize responded strongly to the first 100 kg fallow-N recycled but thereafter responded little to further increases in added fallow N (Fig. 2a). Similar relationships were observed with % N, standing biomass, total carbon, total ADF, and total lignin content (Table 5). In contrast the long-term residual effects during subsequent harvests were linearly related to aboveground fallow N recycled (Fig. 2b). As a result, over all five cropping seasons cumulative maize yield responded linearly to added fallow N (Fig. 2c). Natural fallow N yield was not a good predictor of maize benefit in the first crop. Also the tannin-rich calliandra biomass gave a poor relationship between amount of added biomass N and maize yield, strongly underperforming compared with other improved fallows.

Table 5. Percentage coefficient of determination (R^2) between maize yield and different biomass quality and quantity parameters.†

	First season‡	Seasons 1–5	Seasons 2–5
		R^2	
N, %	80.5	84.3	68.3
C, %	49.8	67.6	68.6
TEP, %	32.7	5.2	4.0
ADF, %	64.7	31.9	42.5
ADL, %	73.3	6.0	0.6
Standing biomass, kg ha^{-1}	80.8	71.1	48.7
Recycled biomass, kg ha^{-1}	41.3	59.1	69.3
Total N, kg ha^{-1}	84	65.2	42.7
Total carbon, kg ha^{-1}	74.8	60.7	38.5
Total TEP, kg ha^{-1}	46.3	20.0	9.9
Total ADF, kg ha^{-1}	70.6	58.7	39.9
Total lignin, kg ha^{-1}	67	13.0	2.7

† ADF = acid detergent fiber; ADL = acid detergent lignin; PBC = protein binding capacity; BSA = bovine serum albumin; TEP = total extractable polyphenols.

‡ Fitted with second order regression equation.

DISCUSSION

Is There Improved Biomass Production in Mixed-Species Fallows?

Soil fertility benefits of improved fallows to soil are accrued from recycled biomass (i.e., foliage, pods, and litter) rather than total biomass in tree-based fallows since woody parts are exported from the fields. In this study recycled biomass accounted for 17 to 50% of total biomass. Sesbania produced the largest amounts of wood and hence lowest amount of recycled biomass, consistent with previous observations (Gathumbi et al., 2002b). Thus, nonwoody species like siratro and natural weed fallow in our case, produced higher amounts of recyclable biomass. In longer-term fallows' litterfall (accounting for 17–76% of recycled biomass) become an important contributor to soil fertility and organic matter maintenance, particularly when trees shed most of their leaves during the pronounced dry season. Soil fertility improvements by legumes have mainly been associated with the quantity and quality of recycled biomass, that increases the amount of nutrients and soil organic matter in the soil (Barrios et al., 1996). Pure and mixed legume species can accumulate substantial amounts of recycled biomass, confirming similar observations by other authors (Gathumbi et al., 2002b; Kwesiga and Coe, 1994; Mafongoya and Dzowela, 1999) for similar environments in Africa. Large accumulation of biomass N is favored in these legume species due to their effective N_2–fixation ability (Gathumbi et al., 2002a) and deep soil nutrient uptake (Gathumbi et al., 2003). The higher biomass productivity at Dindi farm may partly be attributed to its higher clay content (54 vs. 33%) and the associated higher Ca and Mg contents.

While a substantial amount of literature exists on the performance of monoculture-species fallows there is little information about mixed-species fallows. In this experiment mixed-species fallows in general did not outperform monoculture-species fallows. However, positive interactions in some mixed-species fallows were observed sesbania + pigeonpea compared with the monoculture-species fallows. For the less-productive species like pigeonpea and sesbania, this led also to an absolute higher recycled N yield of the mixture than any of the monoculture-species fallows but for the highest-yielding monoculture species, crotalaria and siratro. The observed positive interactions can be attributed to complementarity in canopy structure for improved light interception (Gathumbi et al., 2002b) and perhaps complementarity in belowground resource use (Cadisch et al., 2000; Buresh et al., 2004). Sesbania and pigeonpea have relatively open canopies and mix well with the more dense lower-growing species such as crotalaria and siratro, and thus lead to complementary aboveground resource utilization (light). Gathumbi et al. (2002b) showed that spatial water use was significantly different between some of these species and that competition associated with root plasticity in mixed species led to more efficient exploitation of natural belowground resources.

Driving Factors of Effect of Fallows on Short and Long-Term Maize Response

The soil fertility benefit of fallows was reflected through increased maize yield harvested after the fallow rotation compared with continuous maize and natural fallow treatments. Under the non-PK-limiting conditions in this experiment monoculture-species fallows increased maize yield compared with continuous maize without N addition in SR1999. Such high yield increases are consistent with other results reported for the region (Niang et al., 2002). Their benefit was mainly restricted to maize increases in the first 2 to 3 postfallow seasons, and similar to results of Kwesiga and Coe (1994) who reported maize yields of 5.0 and 5.6 t ha^{-1} after fallows in 1990 and 1991 compared with 4.9 to 4.3 and 1.2 to 1.9 t ha^{-1} from continuously cropped maize with and without fertilizer, respectively. Low maize yields after natural fallow may be due to initial mineral N immobilization in the soil (residue % N = 1.6 and C/N ratio = 24.5) and the following increase in maize yield in the second postfallow crop (LR2000) may partly be attributed to remineralization of labile soil N pools.

In the first two postfallow seasons, improved fallows apparently contributed similar or more N than the N fertilizer treatment (100 kg N ha^{-1}). The fertilizer N response thus confirmed that the fallow effect was mainly a response to N, as expected since other potentially limiting nutrients (P, K) were supplied to each crop. The strong positive relationship between yield and recycled fallow N suggest that for the first crop most improved fallows supplied N in excess as there was little maize response above 100 kg ha^{-1} fallow N recycled. Indeed, 100 kg fallow N provided as good a response as 100 kg fertilizer N, suggesting that there had been added benefits such as improved soil structure and possibly weed suppression. Shorter-term fallows would thus be sufficient to obtain a good first season maize yield.

Fallow biomass productivity was also key for the long-term residual effect and appeared even more important than residue quality since inclusion of residue quality in the regression term did not significantly improve the prediction response. In fact, the hypothesis that recalcitrant residues, such as supplied by calliandra with high active polyphenol contents, would lead to substantially increased nutrient supply in the long-term was not proven. In contrast, a strongly negative interaction occurred at Owano. A similar effect had been observed by Cadisch et al. (1998) in pot trials.

Thus the amount of recycled biomass N remains the overriding factor for the long-term effect. There is ample scope to improve biomass N yields as this varies widely depending on species (Gathumbi et al., 2002b; Niang et al., 2002), fallow duration (Kwesiga and Coe, 1994; Mafongoya and Dzowela, 1999), environmental condition (Phiri et al., 1999a) and management practice (Ndufa et al., 1999). Although the continuous maize cropping treatment had maize during the fallow phase, cumulative maize yield for seven seasons in continuous cropping and five cropping seasons showed that there was no yield lost due to fallow except for pigeonpea and calliandra treatments. This clearly shows that fallows are more superior in providing long-term residual effects and save labor during fallow phase (Swinkels et al., 1997).

Effect of Mixed Fallows Residual Crop Response

Generally, during the first two postfallow seasons, positive interactions on maize yield occurred in mixtures at both farms. These could potentially be attributed to the observed increased fallow N yields in the mixtures. However, there was no direct relationship between the magnitude of the two interactions. Furthermore, cumulative interactions over five seasons remained positive only at Dindi. The reason for the latter is that sesbania at Owano showed a sustained residual effect lasting well into the fourth season. This resulted in the negative calculated interactions at Owano at later times. It is interesting to note that for both sites sesbania showed a proportionally stronger long-term effect compared with other improved fallows, e.g., the maize yield response per unit of recycled fallow N was greater. This may have been due to a large contribution of decomposing roots and N-rich nodules in sesbania. Thus, in the future, root contributions should be more explicitly taken into account, which could be facilitated by the development of stable isotope stem injection technologies suitable for shrubs and trees (Cadisch et al., 2002).

Overall, despite some positive interactions occurring in mixed-species fallow systems over five seasons, none of the mixtures had a higher yield than their best monoculture-species fallow treatment. However, mixed-species fallows improved soil fertility in all cases, at least to a similar extent as monoculture-species fallows. Thus, the use of mixed-species fallows may lead to short-term benefits and is likely to be more important in terms of risk evasion, in case one species partially fails (e.g., due to pests or environmental stress), rather than maximizing yields (Cadisch et al., 2004).

The hypothesis that mixing a high-quality fallow species with one of slow decomposition (high lignin, polyphenol content) would lead to a better long-term effect on economic maize yield was not supported. The variation in residue quality between species was perhaps too small to have a large impact on postfallow maize yield except for calliandra, that had a large amount of active polyphenols. Calliandra has been known to have a high proportion of condensed tannins with high protein binding capacities (Handayanto et al., 1995, 1997; Palm et al., 2001). However, release of complexed N was apparently too small to compensate in a reasonable timescale, confirming earlier observations in pot trials (Cadisch et al., 1998). Further investigations with isotopically-labeled materials are being performed to better understand these nutrients and soil organic matter dynamics. For example, Mutabaruka et al. (2007) showed that long-term addition of polyphenol-rich plant material led to the evolution of a more fungal-dominated microbial population better capable of breaking down such polyphenol-protein complexes.

Mixed-Species Fallows: Opportunities and Benefits

Mixed-species improved legume fallows have the potential to provide maize yields comparable or even above those obtained with 100 kg N ha^{-1} of mineral N fertilizer for a least two cropping season even though N fertilizer was applied in each of the monocrop maize growing seasons. While some mixed species fallow combinations provided additional yield benefits compared with monoculture-species fallows, it is difficult to predict this response because interactions and individual growth responses were strongly governed by environmental conditions (e.g., site/soil effects). Inclusion of recalcitrant fallow biomass (e.g., calliandra) had no positive effect on long-term maize yield. Even though some monoculture-species fallow performed as well as the mixed species fallow in terms of maize yield, mixed species are likely to be an interesting and attractive combination for the farmers due to risk evasion and farmers' preferences for multiple products with respect to food for human consumption from pigeonpea and forage from siratro in the fallow system. Diversification of species used in fallows can potentially alleviate the buildup of pests and diseases associated with monocultures; for example, monocultures of sesbania trees are a host to the root-knot nematode, *Meloidogyne javanica* (Desaeger and Rao, 2000). Mixing of species may thus provide an opportunity for spreading the risk of pest and diseases and environmental impacts and offer additional opportunities for increased exploration of aboveground and belowground nutrient resources.

ACKNOWLEDGMENTS

We thank Mr. James Dindi and Mrs. Mary Owano for provision of their farms for the experiments. We gratefully acknowledge the assistance of both the field staff at Dindi and Owano sites, and laboratory research teams at KEFRI/KARI/ICRAF Maseno Agroforestry Research Centre, KARI Muguga and at Imperial College, London. 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 Development (DFID) for the benefit of developing countries. The views expressed are not necessarily those of the funding agencies.

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