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Plant growth, biomass production and nutrient accumulation by slash/mulch agroforestry systems in tropical hillsides of Colombia

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Abstract

Planted fallow systems under 'slash and mulch' management were compared with natural fallow systems at two farms (BM1 and BM2) in the Colombian Andes. The BM1 site was relatively more fertile than the BM2 site. Planted fallow systems evaluated included *Calliandra calothyrsus CIAT 20400* (CAL), *Indigofera constricta* (IND) or *Tithonia diversifola* (TTH). During each pruning event slashed biomass was weighed, surface-applied to the soil on the same plot and sub-samples taken for chemical analyses. While *Indigofera* trees consistently showed significantly greater ($p < 0.05$) plant height and collar diameter than *Calliandra* trees at both study sites, only collar diameter in *Indigofera* was significantly affected at all sampling times by differences between BM1 and BM2. After 27 months, TTH presented the greatest cumulative dry weight biomass (37 t ha^{-1}) and nutrient accumulation in biomass (417.5 kg N ha^{-1}, 85.3 kg P ha^{-1}, 928 kg K ha^{-1}, 299 kg Ca ha^{-1} and 127.6 kg Mg ha^{-1}) among planted fallow systems studied at BM1. Leaf biomass was significantly greater ($P < 0.05$) for CAL than IND irrespective of site. However, CAL and IND biomass from other plant parts studied and nutrient accumulation were generally similar at BM1 and BM2. At both sites, NAT consistently presented the lowest biomass production and nutrient accumulation among fallow systems. Planted fallows using *Calliandra* and *Indigofera* trees had the additional benefit of producing considerable quantities of firewood for household use.

Introduction

Traditional agricultural systems in tropical hillsides, based on shifting cultivation, involve slashing and burning of the native vegetation, followed by continuous cultivation and abandonment after few years because of low crop yields (Chinene and Dynoodt 1994). The observed decrease in crop yields has been primarily attributed to soil nutrient depletion. Soil nutrient depletion results from a negative nutrient budget, that is, when greater amounts of soil nutrients are removed from the system due to soil erosion, leaching and through crop off-take (i.e., nutrient mining), than returned to the soil in the form of crop residues and fertilizers (Sanchez 1995).

Leaving degraded soils "rest" or fallow during regeneration of the native vegetation is a traditional management practice throughout the tropics for restoration of soil fertility lost during cropping (Sanchez 1999). Traditional fallows often require long periods before adequate soil fertility regeneration is achieved. Increasing population pressure on limited agricultural land requires a reduction in length of fallows and one alternative to traditional fallows is to include shrub or tree species that replenish soil nutrient stocks faster than plants in the natural succession (Barrios et al. 1997).

Successful restoration of soil fertility normally requires a long fallow period for sufficient regeneration of the native vegetation so that tree species can es-

tablish (Young 1997). The capacity of trees to maintain or improve soils is shown by the high fertility status and closed nutrient cycling under natural forest and the restoration of fertility under forest fallow in shifting cultivation (Szott LT and Palm CA 1996). Agroforestry systems provide ways of simultaneously tackling soil constraints such as loss of soil organic matter, limited nutrient availability and water holding capacity (Sanchez 1995; Young 1997).

Agroforestry systems for soil fertility recovery usually involve planting of fast growing N-fixing trees or shrubs on degraded soils (Giller 2001). Soil fertility restoration involves nitrogen (N) inputs *via* biological N fixation and improved nutrient recycling (Barrios et al. 1997) as well as nutrient uptake by trees from below the rooting depth of crops (Young 1997). The quantity, quality, timing and mode of application of organic materials in different fallow systems would strongly influence decomposition processes and their contribution to soil organic matter (SOM) pools and nutrient availability (Palm 1995).

Multiple agroforestry systems have been identified in the tropics (Young 1997). Slash and mulch agroforestry systems include alley cropping systems where pruned biomass from tree rows is applied in the alleys between the rows before planting (Kang et al. 1981). Biomass transfer systems where harvested plant biomass (i.e., live fences) is transported to another farm location as a source of nutrients for crops are also included in this category (Jama et al. 2000). Fallow enrichment of traditional slash/mulch systems of 'frijol tapado' in Costa Rica have also shown the importance of the inclusion of trees as a source of biomass and nutrients during soil fertility recovery (Kettler 1997).

The slash/mulch system described in this study has the spatial design features of an agroforestry planted fallow system but involves pruning where resulting biomass is applied to the same fallow plot. Our objective was to determine whether planted fallow systems under slash and mulch management would perform better than the predominant practice of natural fallow, which allows regeneration of secondary vegetation. In this study we evaluated: a) the growth parameters of two planted fallow species prior to slash and mulch management, and b) the aboveground biomass production and nutrient accumulation in biomass of three planted fallow systems under 'slash and mulch' management compared with the natural fallow system

Materials and Methods

Site description

The study was conducted at two farms in Pescador, located in the Andean hillsides of the Cauca Department, southwestern Colombia (2°48' N, 76°33' W) at about 1500 m above sea level. They represented two typical small farms, on a common soil type, just prior to traditional fallow management following cassava cultivation at the end of the cropping cycle. The area has a historic mean temperature of 19.3 °C and a mean annual rainfall of 1900 mm (bimodal). However, during the experimental time the mean temperature and annual rainfall were 20.2 °C and 2300 mm, respectively.

Soils in the region are derived from volcanic-ash deposition and are classified as Oxic Dystropepts in the USDA classification with predominant medium to fine textures, high fragility, low cohesion, and shallow humic layers. Soil bulk density is close to 0.8 $Mg.m^{-3}$. Soils in the top 20 cm are moderately acid ($pH_{H20} = 5.1$), rich in soil organic matter ($C > 52$ g kg^{-1}), low in base saturation (57%) and effective CEC (6.0 cmol kg^{-1}), and also low P availability (Bray-II $P = < 10.8$ mg kg^{-1}).

Experimental design and management

The study started in November 1997 and the fallow phase concluded in February 2000 after 27 months. Planted fallow system experiments were set up at two farm locations on hillsides of the Cauca Department, on degraded soils previously cultivated with cassava for three years, corresponding to the typical end of cropping cycle when soils are left to natural fallow. The BM1 experiment was established at San Isidro Farm in Pescador as a random complete block (RCB) design with four fallow system treatments and three field replications. Planted fallow system treatments included two tree legumes, *Calliandra calothyrsus* Meissn.–CIAT 20400 (CAL) and *Indigofera constricta* Rydb. (IND) and one shrub *Tithonia diversifolia* (Hems.) Gray (TTH) from the Asteraceae family, compared to a natural fallow system (NAT). Experiment BM2 was established at the Benizio Velazco Farm also in Pescador. It was also established as a RCB design but due to limited space it consisted of three fallow system treatments with three field replications. Treatments included IND, CAL and NAT with same plot size and management as in BM1.

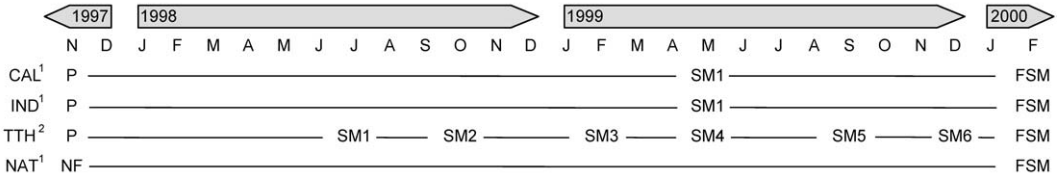

Figure 1. Experimental management schedule in experimental sites at San Isidro farm (BM1) and Benizio Velazco farm (BM2) in Pescador, Cauca – Colombia. P = Planting, NF = Natural Fallow, SM = Slash and Mulch, FSM = Final Slash and Mulch, [1]= Treatments in BM1 and BM2, [2]= Treatment only in BM1

Plant species used in planted fallow systems were selected on the basis of their adaptation to the hillside environment, ability to withstand periodical pruning and the contrasting chemical composition of their tissues. Plot size was 18 m by 9 m and each plot was delimited with a plastic sheet down to 50 cm soil depth in order to minimize root exploration outside to the treatment plots. Plants of *Indigofera* and *Calliandra* were established at 1.5 m × 1.5 m (4,444 plants ha^{-1}) following a triangular planting arrangement. Plants of *Tithonia* were established at 0.5 m × 0.5 m (40,000 plants ha^{-1}) also following a triangular planting arrangement. No fertilization was used in planted fallows except a single 50 g initial application of chicken manure (2.9% N, 1.4% P, 1.8% K) per planting hole in IND and CAL. TTH, a naturalized plant, did not receive fertilizer application because of its vigorous growth in unfertilized soils of the region.

Glasshouse grown *Calliandra* and *Indigofera* plants were inoculated with *Rhizobium* strains CIAT 5071 and CIAT 4910, respectively, and a common *Acaulospora longula* mycorrhizal strain and kept in plastic bags for two months before transplanting to the field. Similarly, *Tithonia* cuttings were initially rooted in plastic bags for two months before transplanting to the field but received no inoculation.

All planted fallow systems were weeded during the first 2 months to facilitate rapid establishment; thereafter, no additional weeding took place. The natural regeneration fallow system treatment, NAT, received no management at all and served as control since this is the common practice by local farmers once their soils have become 'tired' and unproductive. Preliminary experiments and local practices guided the pruning regimes of 'slash and mulch' planted fallow systems. In CAL and IND plants were pruned to 1.5 m height at 18 months after planting in the field and weighed biomass was laid down on the soil surface. In TTH plants were pruned to 20 cm for a total of six times, starting eight months after planting and weighed biomass laid on the soil surface. Pruning intensity of *Tithonia* was guided by farmers concern that this plant may become too competitive if allowed to produce seeds. In the case of *Calliandra* and *Indigofera* the strategy was to reduce the impact of pruning on stem diameter increase and thus value as firewood at the end of the fallow phase.

Whole plot measurement of biomass production during each pruning event by plant component was carried out and a composite sub-sample by each plant component taken for laboratory analyses before laying down the pruned biomass on the soil surface. All above ground biomass was harvested after 27 months with the conclusion of the fallow phase, weighed, sub sampled and laid on the soil surface. Firewood biomass (stems and large branches) was removed from the field and weighed, while leaving leaves, sexual structures (flowers&pods) and small branches on the soil surface. Whole plot measurements of biomass production in NAT was only conducted once at the end of the fallow period (27 months) when all existing natural re-growth vegetation was slashed and sub-samples for analysis taken prior to applying the biomass on the soil surface. The experimental management schedule can be visualized in Figure 1.

At 12 and 18 months plant height and collar diameter of all *Calliandra* and *Indigofera* trees were recorded as measures of plant growth potential. Height was measured from the base of the plant to the last branch developed. Collar diameter was measured by taking the stem circumference at the base of each plant and converting it to diameter. Another measure was carried out at the end of the fallow period (27 months) just before trees were cut at the base and laid on the soil surface. Re-growth potential was estimated by subtracting the pruning height (1.5 m) at 18 months from the height at 27 months.

Chemical analysis of plant materials

Sub-samples of each plant material evaluated were analyzed for total amounts of carbon (C), nitrogen (N), phosphorus (P), potassium (K), calcium (Ca) and magnesium (Mg). All plant material was ground and passed through a 1 mm mesh before analysis. C, N and P were determined colorimetrically with an autoanalyzer (Skalar Sun Plus, The Netherlands). Potassium, Ca and Mg were determined by wet digestion with nitric-perchloric acid followed by atomic absorption spectrometry (CIAT 1993).

Calculations and statistical analyses

Means of plant growth measurements were calculated for each treatment and sampling time, and reported with their standard errors. Nutrient accumulation (kg ha^{-1}), by different fallow system treatments during each slash and mulch event, was calculated by multiplying pruning dry weights by their nutrient contents. T-tests were conducted to compare soil parameters at BM1 and BM2, as well as plant growth parameters, biomass production and nutrient accumulation in *Calliandra* and *Indigofera* within and between BM1 and BM2. Analysis of variance, followed by a LSD test, was conducted to compare biomass production and nutrient content among treatments within each experiment. All statistical analyses were performed using SAS (SAS Institute 1989).

Results

Initial soil conditions

Experimental sites were of the same soil type and had similar recent cropping history (i.e., 3 yrs of cassava cultivation); however, they showed differences in certain soil parameters probably as a result of previous difference in soil management. Significant differences ($p < 0.001$) in soil parameters included lower pH and higher total P, Bray-II P and exchangeable Al at BM1 than soil at the BM2 experimental site (Table 1).

Growth of Calliandra and Indigofera trees

Tree growth parameters were significantly greater ($p < 0.001$) for *Indigofera* than *Calliandra* in both experiments (Table 2). After 12 months, plant height

Table 1. Initial soil conditions in experimental sites at San Isidro farm (BM1) and Benizio Velazco farm (BM2) in Pescador, Cauca – Colombia.

	pH	C tot	N (mg kg^{-1})		P (mg kg^{-1})		K	Ca	Mg	Al
	(H_2O)	(mg kg^{-1})	Total	Inorganic	Total	Bray-II	——— (cmol kg^{-1}) ———			
BM1	4.67 ± 0.06	52674 ± 3134	4240 ± 254	37.4 ± 2.0	653 ± 31	10.8 ± 0.9	0.4 ± 0.05	1.7 ± 0.14	0.65 ± 0.11	1.92 ± 0.17
BM2	5.28 ± 0.02	61741 ± 3840	4249 ± 211	33.6 ± 2.5	486 ± 17	1.6 ± 0.2	0.3 ± 0.02	1.8 ± 0.09	0.57 ± 0.04	0.50 ± 0.07
t-test	−9.729 ***	−1.804 ns	−0.025 ns	1.161 ns	4.798 ***	9.743 ***	1.738 ns	−0.529 ns	0.708 ns	7.808 ***

Values are means ± standard errors. A t-test was used for comparisons and the t value and significance level are reported. ns = non significant ($p > 0.05$), *$p < 0.05$, **$p < 0.01$ and ***$p < 0.001$.

Table 2. Growth of *Calliandra* and *Indigofera* trees in experimental sites at San Isidro farm (BM1) and Benizio Velazco farm (BM2) in Pescador, Cauca – Colombia.

	Time	Height (cm)			Collar diameter (cm)		
	(months)	CAL	IND	CAL vs IND (t-test)	CAL	IND	CAL vs IND (t-test)
BM1	12	236 ± 12	380 ± 6	− 10.846 ***	3.71 ± 0.2	5.71 ± 0.1	− 7.534 ***
	18	357 ± 10	491 ± 7	− 10.803 ***	4.85 ± 0.2	7.25 ± 0.2	− 7.439 ***
	27				6.73 ± 0.4	8.45 ± 0.3	− 3.368 ***
	RP[&]	136 ± 8	169 ± 7	− 3.263 ***			
BM2	12	246 ± 7	308 ± 10	− 5.145***	3.47 ± 0.1	3.87 ± 0.2	− 1.868 ns
	18	378 ± 6	475 ± 9	− 9.425 ***	5.19 ± 0.2	6.23 ± 0.2	− 3.779 ***
	27				5.64 ± 0.2	7.25 ± 0.2	− 5.051 ***
	RP[&]	122 ± 6	160 ± 6	− 4.331 ***			
BM1 vs BM2 (t-test)	12	− 0.711ns	6.206 ***		0.951ns	8.129 ***	
	18	− 1.852ns	1.359 ns		− 1.206ns	3.206 ***	
	27				2.275 *	3.309 ***	
	RP[&]	1.384ns	1.043 ns				

Values are means ± standard errors. [&]RP = Regrowth Potential. A t-test was used for comparisons among planted fallow system treatments (CAL and IND) and experimental sites (BM1 and BM2) during evaluation times. The t values and significance levels are reported. ns = non significant ($p > 0.05$), *$p < 0.05$, **$p < 0.01$ and ***$p < 0.001$.

was 61% and collar diameter 54% greater for *Indigofera* than *Calliandra* at BM1, while at BM2, plant height was 25% and collar diameter 12% greater for *Indigofera* than *Calliandra*. After 18 months these trends were maintained at BM1 and BM2. Regrowth potential after pruning was about 25% greater for *Indigofera* compared to *Calliandra* for both sites. In general, plant height was less affected by site differences than collar diameter as measures of plant responses to site differences. Nevertheless, *Indigofera* showed significantly greater ($p < 0.01$) height (12 months) and collar diameter at BM1 than BM2, while significant differences ($p < 0.05$) in *Calliandra* were only found in collar diameter at the end of the fallow period.

Biomass production

After the first 18 months, significant differences ($p < 0.001$) in dry weight biomass production among planted fallow systems at BM1 were only found for leaves and sexual structures after the first 18 months (Table 3). CAL produced 155% and TTH produced 114% more leaf biomass than IND. On the other hand, TTH produced about 54% and 132% more stem biomass than IND and CAL respectively. A similar trend was observed in BM2 showing significant differences at $p < 0.01$. This was the case for leaves with CAL showing 193% more biomass production than IND, while stem biomass values were remarkably similar for CAL and IND. Sexual structures biomass production was minimal in all treatments except TTH.

In the 18-27 months period, significant differences ($p < 0.05$) at BM1 in dry weight biomass production were found for all plant tissues except weeds. CAL produced 51% and 154% more leaf biomass than TTH and IND respectively. Conversely, TTH produced about 85% more stem biomass than IND or CAL. Firewood biomass production was highest in IND that corresponded to values 43% more than CAL and 185% more than TTH. At BM2, significant differences ($p < 0.05$) were only found for leaf biomass with CAL producing 217% more than IND. Conversely, no significant differences were found in other plant parts or weed biomass. Leaf biomass was the only measure that showed consistently and significantly greater ($p < 0.002$) values for CAL compared to IND at both BM1 and BM2 despite sampling date (data not shown).

Nutrient accumulation in plant tissues

Significant differences ($p < 0.05$) in N accumulation were found in sexual structures biomass at 18 months and in sexual structures, firewood and weed biomass from 18-27 months (Table 3). Nitrogen accumulation by sexual structures in CAL and IND represented as

Table 3. Dry weight (DW) biomass production and nutrient accumulation by planted fallows after 18 and 27 months in experimental sites at San Isidro farm (BM1) and Benizio Velazco farm (BM2) in Pescador, Cauca – Colombia.

			BM1						BM2					
Harvest	Plant		DW	N	P	K	Ca	Mg	DW	N	P	K	Ca	Mg
Date	part	Treat	(t ha^{-1})	(Kg ha^{-1})					(t ha^{-1})	(Kg ha^{-1})				
0-18 months	Leaves	CAL	5.44	114.40	6.60	34.21	36.94	12.60	4.84	116.70	5.06	30.81	37.90	10.54
		IND	2.13	101.00	5.61	27.55	41.80	10.64	1.65	79.90	4.60	25.25	38.10	9.25
		TTH	4.56	140.10	21.07	146.50	104.26	28.90						
		LSD	*1.40* ***	*48.33* *ns*	*11.33* *	*47.51* ***	*22.51* ***	*8.54* ***	*0.89* ***	*31.54* *	*1.44* *ns*	*10.08 ns*	*12.45 ns*	*2.66 ns*
	Stems	CAL	8.08	60.59	7.21	49.00	23.01	11.00	7.69	79.29	6.10	57.83	29.66	12.71
		IND	12.20	95.51	11.47	65.00	34.14	19.37	7.22	113.96	8.80	72.84	63.38	24.46
		TTH	18.78	102.11	30.07	413.40	57.64	40.61						
		LSD	*8.69 ns*	*63.15* *ns*	*17.54* *	*235.94* **	*32.44* *ns*	*21.30* *	*1.86* *ns*	*44.00* *ns*	*3.97* *ns*	*34.21 ns*	*20.63* **	*7.51* **
	Sexual	CAL	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Structures	IND	0.07	2.06	0.21	0.89	0.89	0.31	0.05	1.38	0.12	0.77	0.62	0.20
		TTH	1.51	32.90	5.84	37.41	12.41	5.90						
		LSD	*0.66* ***	*17.08* **	*2.96* ***	*16.24* ***	*5.64* ***	*2.64* ***	*0.03* **	*0.86* **	*0.08* **	*0.49* **	*0.39* **	*0.12* **
18-27 months	Leaves	CAL	3.58	82.85	4.24	33.70	21.86	8.47	3.45	74.76	3.48	27.03	23.45	7.84
		IND	1.41	53.92	3.54	24.41	22.65	7.89	1.09	42.27	2.59	20.08	23.49	6.72
		TTH	2.37	79.21	11.19	105.89	77.03	23.32						
		LSD	*0.74* ***	*26.93* *ns*	*4.01* **	*39.56* **	*22.87* ***	*6.58* ***	*0.74* ***	*19.59* **	*0.86* *	*7.42 ns*	*6.08 ns*	*1.96 ns*
	Stems	CAL	3.93	27.65	2.52	34.89	7.64	5.64	3.38	24.09	1.83	26.71	8.16	4.88
		IND	3.98	29.42	3.02	31.88	10.10	5.65	3.69	29.64	2.45	37.02	14.9	7.85
		TTH	7.28	38.88	11.33	179.58	33.30	20.99						
		LSD	*2.43* *	*15.22* *ns*	*5.55* **	*70.68* ***	*12.08* ***	*8.21* **	*1.31* *ns*	*10.13* *ns*	*1.11* *ns*	*16.11 ns*	*5.33* *	*3.21 ns*
	Sexual	CAL	0.01	0.23	0.02	0.14	0.04	0.03	0.01	0.08	0.01	0.07	0.01	0.01
	Structures	IND	0.01	0.50	0.05	0.26	0.21	0.09	0.01	0.29	0.02	0.17	0.17	0.06
		TTH	0.24	4.51	0.98	6.77	2.72	1.18						
		LSD	*0.16* *	*2.62* **	*0.57* **	*4.29* **	*1.57* **	*0.79* *	*0.01* *ns*	*0.25* *ns*	*0.02* *ns*	*0.18 ns*	*0.12* *	*0.04* *
	Firewood	CAL	7.82	29.30	0.96	28.20	10.85	3.30	7.36	32.50	1.57	24.30	12.31	3.07
		IND	11.16	37.50	2.60	30.90	16.14	6.91	6.69	21.20	1.53	21.40	11.86	3.00
		TTH	3.92	7.60	2.99	41.80	7.25	6.48						
		LSD	*2.65* ***	*8.70* ***	*1.65* *	*21.96* *ns*	*5.01* **	*2.84* *	*1.62* *ns*	*10.87* *	*1.09* *ns*	*11.82 ns*	*8.10 ns*	*2.08 ns*
	Weeds	CAL	2.10	22.70	3.08	39.30	9.91	5.91	1.81	16.76	1.95	28.17	9.67	4.84
		IND	3.70	39.40	3.71	50.80	15.08	9.74	3.34	26.41	3.11	50.69	20.75	10.11
		TTH	2.26	19.80	4.77	38.80	11.64	6.68						
		LSD	*1.85 ns*	*11.63* **	*2.31 ns*	*20.22* *ns*	*7.21* *ns*	*3.59* ns	*1.66* *ns*	*11.15* *ns*	1.55 *ns*	*27.14 ns*	*10.15* *	*4.47* *

ns = non significant ($P > 0.05$), * $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$.

much as 6% of that in TTH during the study period. IND and CAL showed greater N accumulation in firewood biomass compared to as much as 5 times less in TTH. Greatest N accumulation in weed biomass occurred in IND that was about twice that in CAL or TTH. At BM2, CAL had significantly greater ($p < 0.05$) N accumulation than IND in leaf and sexual structures (0-18 months) and leaves and firewood biomass (18-27 months).

Differences in P accumulation at BM1 were significant ($p < 0.05$) in all plant tissues and sampling times except that in weed biomass (Table 3). The greatest P accumulation consistently occurred in stem biomass (0-18 months), did not differ between leaves and stems (18-27 months) and generally followed the order TTH > IND = CAL. At BM2, significant differences ($p < 0.05$) were only present in sexual structures biomass (0-18 months) with minimal P accumulation, and leaf biomass (18-27 months) where P accumulation in CAL was 34% greater than in IND

Differences in K accumulation at BM1 were significant ($p < 0.01$) in all plant tissues and sampling times except firewood and weed biomass (Table 3). The greatest K accumulation generally occurred in stem biomass at both sampling times with the following order TTH > IND = CAL, while for leaf biomass the order was TTH > CAL = IND. At BM2, significant differences ($p < 0.05$) were only present in sexual structures biomass.

Differences in Ca accumulation at BM1 were significant ($p < 0.01$) in all plant tissues and sampling times except in stems (0-18 months) and weed biomass (Table 3). The greatest Ca accumulation consistently occurred in leaf biomass at both sampling times with the following order TTH > IND = CAL, while for stem biomass the order was the same. Calcium accumulation in firewood biomass showed the following order IND = CAL > TTH. At BM2, significant differences ($p < 0.05$) in Ca accumulation were only present in stem and sexual structures biomass at both sampling dates and also in weed biomass. IND was consistently greater in stem biomass Ca accumulation than CAL. Weed biomass Ca accumulation after 27 months in IND was 115% greater than in CAL.

Differences in Mg accumulation at BM1 were significant ($p < 0.05$) in all plant tissues and both sampling times except in weed biomass (Table 3). After 18-27 months, the greatest Mg accumulation in leaf and stem biomass occurred in TTH. Magnesium accumulation in firewood biomass had the following order IND = TTH > CAL. At BM2, significant differences ($p < 0.05$) in Mg accumulation were only present in stem and sexual structures biomass after 18 months, and sexual structures and weed biomass (18-27 months). IND presented more than twice the stem biomass Mg accumulation found in CAL. Weed biomass Mg accumulation after 27 months was about 110% greater in IND compared with CAL.

Total biomass and nutrient accumulation

Total biomass contributions of the planted fallow systems evaluated were significantly different ($p < 0.01$) at BM1 and indicated greatest values for TTH, followed by IND and CAL, and the lowest value from NAT (Table 4). Total biomass contributions of fallow systems evaluated at BM2 were also significantly different ($p < 0.001$) and indicated greatest values from CAL, followed by IND, and the lowest value from NAT.

Total nutrient accumulation in planted fallow systems studied can be considered as an indication of their nutrient recycling potential (Table 4). TTH clearly accumulated significantly greater ($p < 0.01$) amounts of nutrients in their biomass than other fallow systems studied at BM1 for all nutrients. The N accumulation in biomass by TTH was 35-30% greater than CAL and IND, respectively, and close to 190% greater than NAT. Phosphorus accumulation in biomass by TTH was more than 200% greater, while K accumulation was more than 250% greater than CAL, IND and NAT. Calcium accumulation in biomass by TTH was 200%, 140% and 296% greater than CAL, IND and NAT, respectively. Magnesium accumulation in biomass by TTH was 193%, 138% and 221% greater than CAL, IND and NAT, respectively. At BM2, significant differences ($p < 0.001$) were found among planted fallow treatments for all nutrients. Differences between CAL and IND were relatively small compared to their differences with NAT. The N accumulation in biomass for CAL and IND was about 450% greater than NAT; while for P accumulation in biomass it was about double that of NAT. Potassium accumulation in biomass for CAL and IND were respectively 96% and 138% greater than NAT. Calcium accumulation in biomass for IND was 48% greater than CAL and about 300% greater than NAT. Magnesium accumulation in biomass for IND was 43% greater than CAL and about 370% greater than NAT.

Table 4. Cumulative total dry weight biomass (DW) and nutrient accumulation after 27 months, by planted fallow and natural fallow systems in experimental sites at San Isidro farm (BM1) and Benizio Velazco farm (BM2) in Pescador, Cauca – Colombia.

	BM1							BM2						
	DW	N	P	K	Ca	Mg		DW	N	P	K	Ca	Mg	
Treat	(t ha^{-1})	(Kg ha^{-1})						(t ha^{-1})	(Kg ha^{-1})					
CAL	23.1	308.4	23.7	191.2	99.4	43.6		21.2	311.7	18.4	170.6	108.9	40.8	
IND	23.5	321.8	27.6	200.8	124.9	53.7		17.1	293.8	21.7	206.8	161.4	58.6	
TTH	37.0	417.5	85.3	928.4	299.0	127.6								
NAT	17.8	145.8	25.9	257.6	75.5	39.7		6.7	52.6	9.9	87.0	39.4	12.5	
LSD	*9.2*	*126.6*	*29.4*	*310.3*	*69.7*	*32.5*		*3.0*	*59.0*	*4.8*	*50.6*	*30.2*	*9.1*	
	**	**	***	***	***	***		***	***	***	***	***	***	

Firewood was not included in the calculations because it was removed from the field. ns = non significant at $p < 0.05$; *$p < 0.05$, **$p < 0.01$ and ***$p < 0.001$.

Discussion

Growth of Calliandra and Indigofera trees

Initial selection of *Calliandra* and *Indigofera* was based on being local germplasm options adapted to soils and climate predominant in the study area and also their capability to withstand pruning. In a recent study, McDonald et al. (2000) compared growth parameters for eight accessions of *C. calothyrsus* after 12 months of growth in Jamaica finding a range of collar diameters (1.0-3.5 cm) that compares well with our results after a year. Their range of values for plant height (80-170 cm) were lower than those found in this study (236-246 cm). Other studies, however, indicate that *C. calothyrsus* can reach up to 452 cm in the same growth period (Duguma and Mollet 1998). While specific reports for *Indigofera constricta* were not found in the literature, Kanmenge et al. (2000) reported that a close relative *Indigofera zollingeriana* grew up to 365 cm after 12 months that is within the range found for *I. constricta* in BM1 and BM2.

Plant height and collar diameter were consistently greater in *Indigofera* compared to *Calliandra*. While plant height was minimally influenced by site differences between BM1 and BM2, collar diameter clearly showed greater response by *Indigofera* to such differences. Because all plant management aspects were identical at both sites, these results would indicate that while *Indigofera* grew faster than *Calliandra* and was affected by site differences, plant height and collar diameter in *Calliandra* were not affected by site differences. It is possible that significant differences between BM1 and BM2 found in certain soil parameters (Table 1) may have been partly reflected in tree growth parameters. This would be consistent with results by Palmer et al. (1994) indicating than *C. calothyrsus* is usually less responsive to increased soil nutrient availability than other legumes.

Biomass production and nutrient accumulation in plant tissues

Nutrient accumulation and nutrient recycling potential, among plant parts studied, were highest in leaves and stems for all planted fallow system treatments (Table 3). Despite their relatively high nutrient concentrations, sexual structures represented a small proportion of the total nutrients because of their low relative weight. Firewood was also an important component at the end of the fallow phase because

considerable biomass and nutrients, especially K, are exported from the system. Firewood production in planted fallow systems is an added bonus because in natural fallow systems tree development is very slow and unable to cope with local firewood demand. Differences found in weed nutrient accumulation are likely a result of higher weed biomass production resulting from less shading in IND due to canopy structure.

Results on biomass production and nutrient accumulation in plant tissues from the literature are within comparable ranges to those found in this study. Balasubramanian and Sekayange (1991) reported for a 5 year study of *Calliandra* mean annual values of leaf biomass additions of 3.4 t DM ha^{-1} yr^{-1} and wood biomass export of 2.7 t DM ha^{-1} yr^{-1}. On the other hand, Duguma et al. (1994) reported for a 3 year experiment mean annual leaf biomass additions of 3.8 t DM ha^{-1} yr^{-1} and 11.5 t DM ha^{-1} yr^{-1} for wood biomass. These leaf biomass values were close to ranges in our studies while our values for wood biomass corresponded to intermediate values to those reported in the previous two examples (Table 3). In addition, Balasubramanian and Sekayange (1991) show mean annual nutrient additions to the soil through leaf biomass of 73.8 kg N ha^{-1}, 2.6 kg P ha^{-1}, 29.2 kg K ha^{-1}, 46.7 kg Ca ha^{-1} and 10.3 kg Mg ha^{-1}, which compared to our results were lower for N, P and K, higher for Ca and similar values for Mg. Mean annual nutrient additions to soil through leaf biomass reported by Duguma et al. (1994) of 110 kg N ha^{-1}, 5 kg P ha^{-1}, 15 kg K ha^{-1} and 45 kg Ca ha^{-1}; on the other hand, were higher than ours for N and Ca, similar for P and lower for K.

While no published reports were found on *I. constricta*, the study by van Man et al. (1995) for another close relative *Indigofera teysamii* grown in sandy acid soils reported values of leaf + stem biomass (6.3 t DM $ha^{-1}yr^{-1}$) and N accumulation (187 kg N $ha^{-1}yr^{-1}$). These plants received 5 t ha^{-1} of goat manure and crop residues in soil pits before planting and thereafter were fertilized with 60 kg ha^{-1} P_2O_5 and 40 kg ha^{-1} K_2O each year. While biomass values lie within the range found for *I. constricta* leaf+stem biomass our N accumulation values were lower. In another study, Kanmegne et al. (2000) found annual productions of 0.9 and 20.1 t DM ha^{-1} for leaf and wood biomass respectively for *Indigofera zollingeriana* grown in highly acid soils ($pH \leq 4$). These results are also comparable to our mean annual leaf biomass production but considerably higher than our wood biomass results.

Results for *Tithonia* by King'ara (1998), cited by Jama et al. (2000), show a cumulative stem and leaf biomass production (3 cuttings during 18 months) ranging between 8-13 t DM ha^{-1} which are lower than our stem and leaf biomass production during the same period (Table 3). Differences observed may be related to our inclusion of an additional pruning during 18 months and also by their selection of green tender stems and leaves while we included all stems and leaves produced. In another experiment, Jama et al. (2000) reported stem, litter and leaf biomass production by *Tithonia,* 8 months after establishment, ranging between 8.4-10.5 t DM ha^{-1}. They also reported on nutrient accumulation of 32-40 kg N ha^{-1}, 3.2-4.0 kg P ha^{-1} and 33-39 kg K ha^{-1} for leaf and litter tissues, and 55-70 kg N ha^{-1}, 4.6-6.7 kg P ha^{-1} and 80-112 kg K ha^{-1} for stems. Our *Tithonia* total biomass and nutrient accumulation results 8 months after establishment, when first pruning took place in TTH, were lower than those reported by Jama et al. (2000).

Total biomass and nutrient accumulation in biomass

Planted fallows usually include fast growing N-fixing legumes that can accumulate considerable quantities of N (Giller 2001). These plants, however, are often not able to supply other nutrients in sufficient amounts to crop demands (Palm 1995). Some non-legume species like *Tithonia,* on the other hand, can accumulate high quantities of N and other nutrients in their biomass (Cobo et al. 2002a) and this recognized ability is probably due to a better adaptation to site, a greater root volume and the mining of nutrients from the soil (Jama et al. 2000). Our results show that TTH, largely because of the high N-rich biomass produced, can potentially recycle 2.1 times more N than NAT, and 1.6 times more than CAL or IND. Furthermore, even though *Tithonia* cannot fix N, the content of N in their leaves was higher than *Calliandra*, a N-fixing species (data not shown) and this could be partly due to the increased capacity to explore a greater soil volume through its symbiosis with AM fungi (Phiri et al. 2003). Results of nutrient accumulation in biomass for other nutrients studied (P, K, Ca, Mg) show that TTH can generally accumulate 3-4 times greater amounts of these nutrients than other fallow system treatments.

The traditional natural fallow system (NAT) produced less biomass and accumulated fewer nutri-

ents than the planted fallows systems studied after 27 months. These results could be partly explained by the observation that degraded soils showing nutrient deficiencies and Al toxicity as a result of prior land use can also reduce the biomass and nutrient accumulation of native vegetation compared to planted fallow species used (Uhl et al. 1982). Plant species present in NAT as well as the ages of plant populations can also affect biomass and nutrient accumulation because each plant population affects the soil condition in a particular way (Ewel 1986). Herbaceous legume vegetation adapted to infertile soils, such as *Centrosema macrocarpum* Benth., can limit long term accumulation of biomass and nutrients as well as species diversity in fallows by excluding or delaying the invasion of trees and shrubs (Szott and Palm 1996). Abundance of *Mellinis minutiflora* Beauv., a naturalized tropical grass adapted to infertile soils, may be partly responsible for the low biomass and nutrients accumulated in NAT treatments at both BM1 and BM2 experiments. Grass fallows can also limit high nutrient accumulation because they are often shallow rooted (Chinene and Dynoodt 1994). Curiously, in many places the length of the fallow period is determined by the time it takes grasses to disappear (Ewel 1986).

Increasing the efficiency of nutrient recovery by crops, through better synchrony of nutrient release from organic materials and crop demand, is clearly an important aspect of improved fallow system management. It has been well established that the quality, quantity, timing and mode of application of organic materials would play important roles in better nutrient management strategies (Palm 1995; Cobo et al. 2002a). From the point of view of long-term nutrient use efficiency, a greater proportion of nutrients from CAL biomass applications to the soil are likely to benefit following crops because of their slower decomposition and nutrient release patterns that often synchronize better with crop demand than fast decomposing organic materials from IND and TTH (Cobo et al. 2002b). Nevertheless, while understanding of the practical ways by which organic resources can be managed for enhanced nutrient availability to the crop is important, enhancing short-term benefits are different from those that result in build-up of SOM reserves. Further studies should be directed towards identifying a suitable balance between short- and long-term benefits required for sustainable agriculture.

Conclusions

Planted fallow systems have the potential to generate rapid impacts on the soil condition because of their ability to produce greater biomass and accumulate more nutrients than natural fallows. TTH was a considerably superior fallow system than the other options studied in terms of biomass production and nutrient accumulation potential. The potential for planted fallow systems to produce quality firewood, like in CAL and IND, is an added benefit as it can reduce pressure on remaining natural forest patches where firewood is usually collected. Trade-offs between the short and long-term benefits of organic resource management should be taken into account for the long-term improvement of soil organic matter status required in sustainable agriculture.

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