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Planted tree fallows for improving land productivity in the humid tropics of Peru

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Abstract

The increased population pressure in the Peruvian Amazon has reduced the fallow periods from 10–15 to 3–5 years in recent years, leading to rapid soil degradation, low crop yields and greater deforestation. Short-duration planted tree fallows have been considered as a solution to overcome the problems of the traditional land use system and increase crop production and income. An experiment was conducted at Yurimaguas evaluating planted tree fallows of inga (*Inga edulis*) and colubrina (*Colubrina glandulosa*), with and without centrosema (*Centrosema macrocarpum*) cover, compared with the traditional bush fallow and herbaceous centrosema cover crop in terms of weed suppression, their ability to increase subsequent crop production and overall economic benefits. The fallow vegetation was cleared and burnt after 3 years of growth for cropping. Maize, cowpea, and rice were grown in the three subsequent seasons. The planted trees grew faster and accumulated more biomass than those in natural fallow. Centrosema as a pure cover crop as well as an understorey between trees effectively suppressed weeds. The tree fallows with or without centrosema did not increase crop yields compared with natural fallow and resulted in significantly lower yields in the third post-fallow season. Only pure centrosema significantly increased maize yields in the first season after its harvest compared with natural fallow. Utilizing very conservative price and production parameters for the improved fallow systems, the inga and inga + centrosema systems had the highest net present values (NPV) of USD 509 and 392 ha^{-1}, respectively. However, natural fallow had the highest benefit/cost ratio of 1.5, due to its lower costs relative to the more intensive fallow systems. All other fallows had lower benefit/cost ratios. Using the sensitivity analysis of NPV and returns to labor under more optimistic conditions in a graduated manner, the NPV for the two systems with colubrina (poles) increased to USD 1421 and 1782, with higher labor returns. Planted fallows with economically valuable trees such as inga and colubrina have the potential to raise farmers' income and alleviate degradation of natural resources in the humid tropics of Peru, but they require more extensive testing under a range of biophysical and socio-economic conditions.

Keywords: Amazon; Centrosema; Colubrina; Leguminous cover crop; Inga

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1. Introduction

Large-scale human migration from the Andean and Coastal regions to the Amazon has been causing extensive deforestation due to increased shifting agriculture and wood extraction. In 1972, the forest zone of Peru had 70 million ha of primary forest, of which 10 million ha were already deforested by the mid-nineties (INEI, 1997). In 1940, the total population was 702,311 and by 1993 it rose to 2,263,944. Since then the population has been increasing at a rate of 3.6% per annum (INEI, 1997).

The primary factors attracting people to the Amazon region have been infrastructure development, abundant land, job opportunities, and until recently, coca (*Erythroxylum coca*) production. Farmers arriving into the Amazon are extremely poor with few capital resources to invest in farming.

In the early 1990s, the Peruvian government substantially reduced its support for the agricultural sector. Prices of the principal semi-subsistence crops (maize, rice, cassava, beans, cowpea and plantains) are low but farmers generally incur high expenses for marketing the farm products due to poor infrastructure to reach the main highways. A recent land entitling program has increased the number of farmers with formal title from 5 to 45% (Labarta, 1998).

Soils inherently have low fertility and high levels of acidity and aluminum content are limiting crop growth. Most nutrients are contained in the above ground fallow biomass. Use of capital inputs such as fertilizers, pesticides and amendments is extremely limited. The dominant production practice is slash and burn agriculture. Land is typically cultivated for 1.5–2 years before being fallowed. Median farm size is 30 ha divided for five principal uses as follows: 31% under primary forest, 30% under forest fallows, 25% under pasture, 10% under annual crops, and 4% under perennials (Labarta, 1998). Rural population density is estimated at 7 persons per km^2. Capital and labor resources are the most limiting factors of production relative to plentiful land.

In shifting agriculture, the cropping phase is usually characterized by a decline of crop yields due to soil nutrient depletion and increase of weed pressure, insect pests, and diseases over the years (Nicholaides et al., 1984; Trenbath, 1984). In many parts of the Peruvian Amazon, the increased pressure on land has resulted in the reduction of fallow periods from the traditional 10–15 to 3–5 years (Fujisaka et al., 1999). This reduction of the fallow period has led to increased degradation of the soil resource base, lower crop yields, and greater deforestation (Luna-Orea and Wagger, 1996). There is a need to find technologies that increase land use intensification to meet the needs of the growing population and reduce deforestation in the humid tropics. Previous studies in the region reported improved soil fertility and yields of annual crops subsequent to 2–3-year herbaceous cover crops of centrosema (*Centrosema macrocarpum*) or kudzu (*Pueraria phaseoloides*) (Szott et al., 1991). Planted tree fallows with appropriate species were considered to have greater potential than cover crops because of the combined benefits of improving soil fertility and crop yields, smothering weeds, and yielding economically valuable products during the fallow phase (Sanchez et al., 1985). Leguminous N_2-fixing trees may have a comparative advantage over herbaceous legumes, as they recycle nutrients from greater soil depths and produce larger quantities of biomass (Domergues, 1995). But no formal studies had been conducted to test the potential of tree fallows to meet the challenge of increasing food crop production and generating cash income.

Against the above background, the present study was conducted with the following objectives: (1) evaluate the effects of short-term tree fallows with and without a leguminous cover crop on replenishing soil fertility and reduction of weeds compared with natural fallows; (2) evaluate the effects of N_2-fixing and non N_2-fixing tree fallows on the productivity of subsequent crops; and (3) determine the economic returns from planted tree fallow–annual crop rotations compared with those from the traditional natural fallow–crop rotation.

2. Materials and methods

2.1. Treatments and crop management

The experiment was conducted on-farm at Yurimaguas (76°05′W, 5°45′S and 180 m above sea level) in the Peruvian Amazon basin. The area receives an annual rainfall of 2,200 mm, mostly during October–February and April–June periods. The soil is classified

Table 1
Initial soil physical and chemical properties of the experimental area[a]

Depth (cm)	Particle distribution ($g\ kg^{-1}$)			pH in water	Organic C ($g\ kg^{-1}$)	Total N ($g\ kg^{-1}$)	Available P ($mg\ l^{-1}$)	Acidity ($cmol_c\ l^{-1}$)	Ca ($cmol_c\ l^{-1}$)	Mg ($cmol_c\ l^{-1}$)	K ($cmol_c\ l^{-1}$)	ECEC ($cmol_c\ l^{-1}$)	Al saturation (%)
	Clay	Silt	Sand										
0–5	60	140	800	4.7	13.7	1.0	10.5	0.89	1.17	0.38	0.24	2.62	37
5–15	100	200	700	4.6	9.5	0.7	4.2	2.00	0.22	0.11	0.07	2.43	82
15–30	260	200	540	4.6	–	–	3.0	2.70	0.13	0.06	0.06	2.58	88

[a] Soil analyses methods followed for based on Hunter (1979).

in US Soil Taxonomy as fine loamy siliceous Isohyperthermic Typic Paludults (equivalent to Acrisol-Alisol groups—FAO Soil Map), acid infertile, low in organic C, N, P, Ca and Mg, but high in aluminum saturation (Table 1). The study was initiated in October 1994 when the farmer was about to abandon the field for natural fallow after cropping it for 1 year with rice (*Oryza sativa*) and cassava (*Manihot esculenta*) following slash and burn of an 8-year-old secondary forest. The study evaluated the following six fallow systems: (1) natural fallow; (2) planted fallow with inga (*Inga edulis*); (3) planted fallow with inga + centrosema (*Centrosema macrocarpum*), an herbaceous legume cover; (4) planted fallow with colubrina (*Colubrina glandulosa*); (5) planted fallow with colubrina + centrosema; and (6) pure centrosema fallow. The six fallow systems were replicated four times in a completely randomized block design in 15 m × 9 m plots. The plots were separated by paths (3–4 m wide) and blocks were separated by 6 m paths to minimize interaction between plots within and across blocks.

Inga is a fast growing N_2-fixing leguminous tree, which produces valuable firewood and fruits. It was planted at 1.5 m × 1.5 m spacing using 3-month-old nursery-grown seedlings. Colubrina is a non-leguminous fast growing tree of the buckthorn family (Rhamnaceae) that produces valuable poles; it was planted using 4-month-old seedlings at 3 m × 3 m. Centrosema is a leguminous N_2-fixing herbaceous cover crop that withstands shade and is used as forage. It was directly sown at 0.5 m × 0.5 m with three seeds per hole. Any gaps in the tree stands were filled in within 2 weeks. The trees in the planted fallows were weeded two times in the first 6 months at the base over a 0.5 m diameter area. The pure centrosema and natural fallow systems were not weeded. No fertilizer was applied to trees in the fallow systems. The natural vegetation that grew in the paths surrounding the plots was periodically mowed using a mechanical mower.

The fallow phase lasted for 3 years, until October 1997, when trees and other species in the different systems were harvested. Economically valuable products such as poles and firewood (wood >2.5 cm diameter) were removed from the plots and the rest of the biomass (leaves, litter and wood <2.5 cm diameter) was burnt in situ after 2 weeks, allowing the material to dry. Ash and the unburned biomass were incorporated into the soil in the course of land preparation. The fallow phase was followed by a cropping phase with three successive annual crops: maize (cv. Marginal 28), cowpea (*Vigna unguiculata*, cv. Yurimaguas Vita 7), and rice (cv. Cica). Maize was cropped from November 1997 to March 1998 using a spacing of 0.8 m × 0.25 m. Cowpea was grown from May to July 1998 with 0.5 m × 0.25 m spacing. Rice was grown from November 1998 to March 1999 with 0.5 m × 0.15 m spacing. Except for hand weeding two times and localized control of ants (*Atta* spp.) using either 3% fenil or methyl parathion, no other inputs were given to the crops.

2.2. Data collection and analyses

Tree growth in terms of height and diameter at breast height (dbh) was measured annually on 21 inga trees and 15 colubrina trees per plot. In the natural fallow, a 9 m × 3 m transect was marked per plot, the species composition within this area was noted and the growth of all the trees measured annually. Herbaceous vegetation in the plots (hereafter referred to as weeds) and its biomass in different treatments was determined at the beginning of the study and at 12, 24, and 36 months after establishing the fallows by sampling three quadrates of 1.0 m^2 each per plot. Centrosema biomass and litter of trees and/or centrosema were determined at harvest of tree fallows from three randomly selected 1.0 m^2 quadrates per plot. Biomass of poles and firewood was measured on a sample of five trees per plot. Weights of twig wood (<2.5 cm diameter) and foliage of trees were also determined on the same five trees in each plot. Wood was cut into small pieces before drying in an oven. Dry weights of these different components were determined by drying 1–1.5 kg of material in an oven at 70 °C for constant weight. To measure ash following burning of the biomass in different fallow systems, four metallic plates of 0.5 m × 0.5 m were randomly located per each plot under biomass. The ash collected in the plates was weighed and based on the average of four samples total ash per hectare in each plot was estimated. Concentration of nutrients in the fallow biomass and ash was determined following the methods described by Hunter (1979). Nutrients were extracted using 100% H_2SO_4 and 30% H_2O_2. Calcium, Mg, and K were determined with an atomic absorption spectrophotometer, N by micro-Kjeldahl, and P by the modified Olsen method.

Nitrogen leaching under different fallows was measured by installing two suction cup lysimeters per plot at 0.5 and 1.0 m soil depths and the leachate collected through a suction pump at 1-week intervals during the rainy season and at 2-week intervals during the post-rainy season. The leachate was analyzed for inorganic N ($NO_3 + NH_4$) concentration. The total quantity of inorganic N that moved beyond 0.5 m and 1.0 m depths was estimated as per the following steps: (1) determination of the volumetric soil water content available to lysimeter tension (volumetric water content at saturation minus the volumetric water content at wilting point); (2) determination of the volume of soil layer equivalent in thickness to the length of the porous cup (5.8 cm) over one hectare; (3) determination of the volume of water in this soil volume, which is the volume of soil (from step 2) times the volumetric soil water content (from step 1); and (4) determination of the kg N sampled per hectare by multiplying the volume of soil water (l ha^{-1}) with concentration of mineral N in soil water (mg l^{-1}).

Soil samples were taken for nutrient analysis from different layers (depths of 0–5, 5–15, 15–30, 30–50 and 50–100 cm) in each plot three times in the course of the experiment: (1) following plot layout before the start of the study; (2) at fallow harvest; and (3) after burning of fallow biomass. Soil physical properties such as bulk density, cumulative infiltration and mechanical resistance in the 0–50 cm depth were measured at five locations within each plot. Bulk density was determined on 76 mm high by 76 mm diameter undisturbed soil cores (Uhland, 1950). Cone index (CI), defined as the force required to push a penetrometer through an increment of soil divided by the projected cross sectional area of the penetrometer tip, was measured using a ring cone penetrometer, Soil test model CN-970 (Alegre et al., 1986). Cumulative infiltration was measured in each of the plots by driving a 110-mm, open-ended steel cylinder into the soil to a depth of 150 mm, following the procedure outlined by Van Es et al. (1988). Four layers of cheesecloth were placed over the soil surface enclosed by the cylinder. Instantaneous water ponding on the undisturbed soil surface was established by adding the equivalent of a 76 mm-high column of water. Water intake was measured at 5-s time intervals after the onset of ponding until 20 s had elapsed and at 10-s intervals thereafter until 120 s had elapsed.

Crop yields were estimated by harvesting three sub-samples (two 2 m long rows per sub-sample) from each plot, spread over the plot. Results of crop yields, soil analyses, and weed observations were subjected to the analyses of variance (ANOVA) and treatment means separated using the least significant difference (LSD) test at 5% probability. Financial analysis of the six systems was conducted. The analysis is financial (and not economics) because market processes are utilized (and not the social prices needed for economic analysis) and the perspective taken is that of the returns to a farm family and not the returns to the economy as a whole (Gittinger, 1982). Inputs such as hand labor for different field operations, tree seedlings, seeds of centrosema and annual crops, insecticides, tools, and bags used for handling the produce in each treatment plot were recorded during the experimental period (Table 2). Prices were actual farm-gate levels in local markets in April 1999. Net returns were calculated plot-wise by subtracting the costs from the gross returns each year to determine the evolution of returns over the experimental period. The returns were discounted at 20% to determine the net present value (NPV). The benefit/cost ratio and returns

Table 2
Inputs, outputs, and their costs by treatment

Inputs and outputs	Quantity of inputs and outputs					
	Natural fallow	Inga	Inga + centrosema	Colubrina	Colubrina + Centrosema	Centrosema
Year 1994						
Labor (workdays ha^{-1})	–	42	49	40	46	37
Machetes (no.)	–	3	3	3	3	3
Tree seedlings (no. ha^{-1})	–	4444	4444	1111	1111	–
Centrosema seed (kg ha^{-1})	–	–	6	–	6	6
Year 1995						
Labor (workdays ha^{-1})	–	55	55	55	55	55
Machetes (no. ha^{-1}	–	3	3	3	3	3
Insecticide (kg ha^{-1})	–	20	20	20	20	20
Year 1996						
Labor (workdays ha^{-1})	–	48	78	20	53	33
Machetes (no. ha^{-1})	–	3	3	3	3	3
Bags (no. ha^{-1})	–		2		2	2
Insecticide (kg ha^{-1})	–	20	20	20	20	20
Inga pods (no. ha^{-1})[a]	–	8321	7634	–	–	–
Centrosema seed (kg ha^{-1})[a]	–	–	40		40	40
Year 1997						
Labor (workdays ha^{-1})	86	159	149	83	85	78
Insecticide (kg ha^{-1}	20	20	20	20	20	20
Maize seed (kg ha^{-1})	80	80	80	80	80	80
Bags (no. ha^{-1})	10	12	10	10	18	19
Firewood (t ha^{-1})[a]	7.8	31.3	38.1	–	–	–
Inga pods (no. ha^{-1}) [a]		22770	19171	–	–	–
Poles (no. ha^{-1})[a]	220	–	–	910	950	–
Year 1998						
Labor (workdays ha^{-1})	143	143	143	143	143	143
Insecticide (kg ha^{-1})	6	6	6	6	6	6
Machetes (no. ha^{-1})	3	3	3	3	3	3
Cowpea seed (kg ha^{-1})	50	50	50	50	50	50
Rice seed (kg ha^{-1})	60	60	60	60	60	60
Bags (no. ha^{-1})	14	14	10	13	8	16
Year 1999						
Labor (workdays ha^{-1})	30	30	30	30	30	30
Bags (no. ha^{-1}	22	14	16	10	12	20

Financial input and output: hand labor = USD 3.03 per $workday^{-1}$, machete = USD 2.5 per one, insecticide = USD 4.0 kg^{-1}, tree seedlings = USD 12 per 100, Centrosema seed = USD 15 kg^{-1}, bags USD 17 per 100, firewood = USD 5.1 m^{-3}, maize seed and grain = USD 0.39 kg^{-1}, cowpea seed and grain = USD 0.90 kg^{-1}, rice seed and grain = USD 0.60 kg^{-1}, Inga pods = USD 6 per 100, poles = USD 1.06 each.

[a] These are outputs from trees and Centrosema. Crop yields subsequent to different fallow systems are given in Table 9.

to labor of the different systems were also determined. Sensitivity analysis was conducted as three critical variables (Gittinger, 1982): poles from production of colubrina and natural fallow at the higher price of USD 4.5 each, centrosema seed yield of 120 kg ha^{-1} with certainty each year, and inga fruit sales volume equal to total production.

3. Results and discussion

3.1. Growth and biomass production of tree fallows

Both inga and colubrina established and grew well following weeding two times in the first 6 months after transplanting. Although centrosema was competitive

Table 3
Height and diameter at breast height of trees in planted and natural fallows over a 3-year period at Yurimaguas, Peru

Treatment	Tree density (No. ha^{-1})	Year 1 (1995)		Year 2 (1996)		Year 3 (1997)	
		Height (m)	Diameter (cm)	Height (m)	Diameter (cm)	Height (m)	Diameter (cm)
Planted fallows							
Inga	4444	2.5	4.4	4.4	5.2	6.7	6.7
Inga+centrosema	4444	3.0	3.8	5.0	5.4	6.8	6.5
Colubrina	1111	2.8	3.6	6.1	6.4	9.3	9.5
Colubrina+centrosema	1111	2.2	2.6	5.9	6.3	9.0	9.3
SED	–	0.15	0.23	0.29	0.42	0.48	0.58
LSD (0.05)	–	0.34	0.52	0.65	–	1.08	1.31
Natural fallow							
Ocuera[a]	14815	3.2	1.9	4.1	2.6	5.9	3.6
Yanavara[b]	2222	2.7	2.0	4.4	3.2	5.9	3.8
Chicle caspi[c]	370	1.9	<1	2.7	1.4	3.7	2.1
Cetíco[d]	740	1.3	<1	1.9	1.4	3.6	1.9
Ocuera blanca[e]	370	2.2	<1	2.2	1.4	–	–
Ojo de gato[f]	370	1.5	1.7	2.3	2.3	3.1	2.5
Huamansamana[g]	740	1.0	<1	1.4	1.2	2.1	1.6

SED, standard error of difference of treatment means.
[a] *Vernonia baccharoides* (Asteraceae).
[b] *Pollalestra discolor* (Asteraceae).
[c] *Brosimum utile* (Moraceae).
[d] *Cecropia* spp. (Cecropiaceae).
[e] *Vernonia* sp. (Asteraceae).
[f] *Aspidospermua macrocarpum* (Apocynaceae).
[g] *Jacaranda copaia* (Bignoniaceae).

with trees in the first year, it did not affect them later and final growth of trees in pure tree and tree + centrosema fallows was similar (Table 3). In the first year, colubrina was shorter and thinner, but its growth in the subsequent 2 years was significantly better than that of inga. By the end of 3 years, inga trees attained a height of 6.7 m with a dbh of 6.6 cm and colubrina trees reached a height of 9.2 m with 9.4 cm dbh (Table 3).

The natural fallow contained a high diversity of tree species, but ocuera (*Vernonia baccharoides*, family Astaraceae) and yanavara (*Pollalestra discolor*, family Asteraceae) were the most dominant species, constituting about 86 and 12% of total woody vegetation, respectively. These softwood trees grew to an average height of 5.9 m with a dbh of 3.7 cm by the end of 3 years (Table 3).

Table 4
Number of weed species and their total biomass in different fallow systems over a 3-year period at Yurimaguas, Perú

Fallow system	Initial		At 12 months		At 24 months[a]		At 36 months[a]
	Biomass (kg ha^{-1})	No. of species	Biomass (kg ha^{-1})	No. of species	Biomass (kg ha^{-1})	No. of species	Biomass (kg ha^{-1})
Natural fallow	581	12	107	12	390	5	1275
Inga	787	12	69	9	756	4	1287
Inga+centrosema	847	8	81	7	0	0	0
Colubrina	1097	8	79	8	473	7	1881
Colubrina+centrosema	585	10	64	8	0	0	0
Centrosema	537	11	55	9	0	0	0
SED	341	2	26	2	–	–	–
LSD (0.05)	716	–	55	–	–	–	–

SED, standard error of difference of treatment means.
[a] Data recorded at 24 and 36 months were not subjected to ANOVA as three out of six treatments had zero. values in all replications.

Weed infestation at the start of the trial was lower than in typical farmers' fields about to be abandoned for natural fallow, probably because the farmer managed the field well in the previous season. Planted fallows with any one or two species substantially smothered weeds in year 1 (Table 4). At the end of 2 years there was no weed growth under pure centrosema or its combinations with trees. In contrast, weeds persisted in natural and pure tree fallows throughout the fallow phase due to insufficient ground cover by the canopies of these systems. At the end of 3 years, there was 1.3–1.9 t ha^{-1} of weed biomass under natural and pure tree fallows. Weed growth was greater under pure colubrina than inga because of wider spacing and straight growth of colubrina with fewer branches compared with inga. The lowest groundcover under pure colubrina was reflected in the lowest amount of litter + foliage (tree + weeds) biomass of 6.7 t ha^{-1} produced by this system (Table 5). Even natural fallow with a biomass (tree foliage + weeds +litter) production of only 7.9 t ha^{-1} had poorer groundcover compared with pure centrosema or trees mixed with centrosema; pure inga had intermediate ground cover. Although inga suppressed the growth of centrosema in mixed system more than colubrina, it more than compensated through its greater litterfall. Shade is the major cause for efficient suppression of weeds under planted fallows, although several other mechanisms also play important roles (Gallagher et al., 1999; Rao et al., 1998). Herbaceous cover crops smother weeds in 9–12 months by rapidly covering the ground with a thick canopy. In contrast, trees and shrubs in natural and planted fallows take 3–4 years or longer, depending on their growth rates and canopy structure, to establish a canopy cover to suppress weeds (Rao et al., 1998). In a previous study conducted at Yurimaguas, inga, *Cajanus cajan*, and natural fallows required 3.5 years to achieve a level of weed control similar to that achieved by centrosema in 16 months (Szott, L., unpublished data). If trees are planted at wider spacing aiming for timber or other products, they may not achieve efficient weed suppression unless combined with herbaceous cover crops.

The total non-harvested biomass of leaf litter, foliage, and twig wood (i.e. biomass burnt) at the end of the fallow phase in pure colubrina and natural fallow was low at 9.5 and 10.0 t ha^{-1}, respectively (Table 5). The biomass burnt in pure centrosema fallow was 26 to 32% higher than in natural and colubrina fallows. However, the biomass burnt in inga fallows was two to four times higher than in other fallows because of higher amounts of leaf litter and twig wood from inga. Inga + centrosema had the highest biomass at 35 t ha^{-1} and it was followed by pure inga with 24 t ha^{-1}. Addition of centrosema to colubrina nearly doubled the total biomass to 18.4 t ha^{-1} compared with pure colubrina. The amount of ash after burning was 1.98 t ha^{-1} in colubrina fallows which was higher than in natural (1.27 t ha^{-1}) and inga (about 1 t ha^{-1}) fallows. The lowest quantity of ash was in inga fallows because of

Table 5
Biomass removed from plots and burnt in situ at harvest, and nutrients recycled through the burnt biomass in different 3-year-old fallow systems at Yurimaguas, Peru

Fallow systems	Biomass (>2.5 cm) removed (t ha^{-1})	Biomass burnt (t ha^{-1})					Nutrients recycled through ash (kg ha^{-1})				
		Wood <2.5 cm	Tree foliage	Weeds + centrosema	Litter (tree + weeds + centrosema)	Total	N	P	K	Ca	Mg
Natural fallow	9.5	2.1	1.1	1.3	5.5	10.0	47	1.0	90	75	24
Inga	31.3	13.0	3.6	1.3	6.1	24.0	67	0.8	109	67	19
Inga + centrosema	38.1	15.7	3.9	4.0	11.1	34.7	53	0.6	95	54	16
Colubrina	22.4	2.8	1.2	1.9	3.6	9.5	39	1.0	142	85	23
Colubrina + centrosema	27.2	3.2	1.1	5.6	8.5	18.4	75	0.7	111	82	22
Centrosema	0.0	0.0	0.0	5.1	7.5	12.6	58	0.7	97	63	18
SED	7.81	1.70	0.35	0.86	1.55	2.22	23.4	0.2	27.5	17.4	4.6
LSD (0.05)	16.40	3.70	0.80	1.80	3.26	4.66	–	–	–	–	–

SED, standard error of difference of treatment means; LSD, least significant difference at 95% confidence level.

relatively higher amount of wood material that remained unburned compared with other fallows. Nutrient quantities recycled through ash of burnt biomass were highly variable among and within the different fallow systems; so few treatment differences were significant despite large differences in the total biomass burnt (Table 5). Obviously, burning was not uniform or complete, especially in the inga plots. However, no adjustment was made for the nutrients that remained in the unburned biomass, which slowly decomposed over seasons.

3.2. Soil changes following natural and planted fallows

Nitrogen leaching in the first year of fallow phase was very high under all the systems because of low nutrient retention capacity of the soil and inadequate root systems of the fallow vegetation. However, the amount of cumulated N leached in the last 2 years of the fallow period was small, varying from <2.6 to 13.6 kg N ha^{-1} or 9 to 48% of the total N leached (annual leaching data not presented). Leaching of ammonium relative to nitrate was very low under all systems (Table 6). Nitrate leached at 50 cm depth was lowest under natural fallow and at 100 cm it was lowest under both natural fallow and inga + centrosema. Nitrate leaching at 50 cm depth under all planted fallows was similar, which was 62–179% higher than under natural fallow. Nitrate leaching at 100 cm depth was low under pure centrosema and the trees combined with centrosema, representing a status similar to that under natural fallow. Greater N leaching under planted trees compared with natural fallow indicates lower root density of planted tree fallows.

Table 6
Total ammonium and nitrate leached beyond 50- and 100-cm depths over a 2.5-year period (October 1994–March 1997) under different fallow systems at Yurimaguas, Peru

Fallow system	Nitrogen leached beyond specified depths (kg ha^{-1})			
	50 cm		100 cm	
	NH_4	NO_3	NH_4	NO_3
Natural fallow	1.6	19.9	1.4	24.5
Inga	3.0	49.3	2.1	48.1
Inga + centrosema	2.0	38.2	2.6	22.0
Colubrina	1.3	32.3	1.7	46.0
Colubrina + centrosema	3.2	55.6	1.6	28.5
Centrosema	1.8	49.7	2.1	31.5
SED	0.54	10.42	0.56	6.89
LSD (0.05)	1.15	24.08	1.20	15.92

SED, standard error of difference of treatment means; LSD, least significant difference at 95% confidence level.

The fallow systems did not differ significantly in soil nutrient status at clearing of fallow biomass or after burning, so the results for these sampling periods were averaged over the systems for comparing with the initial soil nutrient status (Table 7). Changes in soil nutrients mostly occurred in the top 5 cm soil layer, except K, which was also found to have increased significantly at the 5–15 cm depth after burning. Changes during the fallow phase were negligible and whatever changes were after burning of the fallow biomass. Substantial changes in soil nutrient status cannot be expected within a short period of 3 years, particularly on low base status soils such as in the Amazon (Szott et al., 1999). Whereas total N, cations and extractable P increased following burning, exchangeable soil acidity and aluminum saturation decreased. The increase in soil N could be attributed to capture of N at depth, prevention of leaching and probably N contribution from biological nitrogen fixation in the case of leguminous plants. The cations increased probably due to recycling of these nutrients to soil surface through burning of fallow biomass (Table 5) (Szott et al., 1999). Phosphorus increase was probably due to the accumulation of P in the biomass of fallow systems via the symbolic association of fallow species with mycorrhizal fungi and its release into the soil on burning the residues (Ruiz, 1994).

The natural fallow recycled amounts of Ca and Mg similar to those recycled by planted fallows because less biomass and hence less nutrients were removed from the system. Substantial amounts of biomass (firewood and poles) and with it greater amounts of nutrients were removed from planted fallows, rendering nutrient recycling in these systems to be similar to that in natural fallow. Incomplete burning of biomass returned to soil in these systems also contributed to the lack of improvement in soil nutrients. However, planted fallows in combination with centrosema would still be preferable to natural fallow because of less nutrient depletion in the long run and the added value of the trees.

Soil bulk density (BD) following fallows decreased by about 7.5% primarily in the 0–10 cm depth, except after inga and centrosema fallows which did not cause

Table 7
Soil chemical properties[a] before and after different fallow systems at Yurimaguas, Peru

Parameter	Before fallow	At fallow clearing[b]	After burning[b]	SED	LSD (0.05)
0–5 cm					
Organic C (g k g^{-1})	14.1	12.1	14.9	0.58	–
Total N (g k g^{-1})	1.03	2.06	2.48	0.06	0.12
pH	4.7	4.6	4.6	0.07	–
Exchangeable Ca ($cmol_c$ l^{-1})	0.92	0.78	1.69	0.16	0.32
Exchangeable Mg ($cmol_c$ l^{-1})	0.34	0.35	0.70	0.11	0.23
Exchangeable K ($cmol_c$ l^{-1})	0.14	0.18	0.51	0.03	0.07
Exchangeable Al ($cmol_c$ l^{-1})	0.89	0.97	0.42	0.12	0.25
Extractable P (mg k g^{-1})	11	9	20	1.17	2.35
Al saturation (%)	45	45	15	5.1	10.3
5–15 cm					
Organic C (g k g^{-1})	9.5	8.7	8.7	0.40	–
Total N (g k g^{-1})	0.71	0.16	0.15	0.01	0.02
pH	4.6	4.4	4.0	0.02	–
Exchangeable Ca ($cmol_c$ l^{-1})	0.22	0.21	0.34	0.04	0.08
Exchangeable Mg ($cmol_c$ l^{-1})	0.11	0.10	0.13	0.01	–
Exchangeable K ($cmol_c$ l^{-1})	0.07	0.09	0.14	0.01	0.02
Exchangeable Al ($cmol_c$ l^{-1})	2.00	1.93	2.44	0.06	–
Extractable P (mg kg^{-1})	4	5	5	0.36	–
Al saturation (%)	82	85	83	2.11	–

[a] Analyses were based on the methods described by Hunter (1979).
[b] Values averaged over six fallow systems; SED, standard error of difference of treatment means.

any changes (Table 8). Bulk density values above 1.45 Mg m^{-3} are considered high for soils similar to that of this experimental site (Alegre and Cassel, 1999). Cumulative water infiltration increased by 100% or more following natural fallow, inga, inga + centrosema and colubrina fallows (Table 8). The initial cone index values at 0–5 cm depth increased significantly from 270 kPa before fallow to 1450 and 1100 kPa at 50 cm depth for inga and natural fallows, respectively (Fig. 1). As the roots of inga and trees in natural fallow were thick and/or very dense, they might have compressed the soil and increased resistance to penetrometer.

Table 8
Bulk density at two soil depths and cumulative infiltration during 120 s before the start and 2.5-years after the start of the fallows

Fallow systems	Bulk density (Mg m^{-3})		Cumulative infiltration (cm)
	0–10 cm	10–20 cm	
Before fallow (October 1994)	1.27	1.41	2.1
After fallow (March 1997)			
Natural fallow	1.17	1.39	4.2
Inga	1.27	1.44	4.1
Inga + centrosema	1.18	1.43	4.5
Colubrina	1.19	1.34	3.9
Colubrina + centrosema	1.16	1.32	2.8
Centrosema	1.26	1.43	2.7
SED	0.03	0.05	0.7
LSD (0.05)	0.06	0.11	1.5

SED, standard error of difference of treatment means; LSD, least significant difference at 95% confidence level

3.3. Products from tree fallows and crop yields

Inga produced pods within 2 years. However, total production in this study was low at 31,091 pods ha^{-1} in pure system and 26,805 pods ha^{-1} in inga + centrosema, because the trees were planted at narrower spacing than the desirable spacing of 5 m × 5 m for fruit production (Table 2). At the end of 3 years, inga produced 31.3 and 38.1 t ha^{-1} of fire wood in pure tree fallow and in combination with centrosema, respectively (Table 5). Colubrina trees produced 910 and 950 poles per hectare (Table 2) with a biomass of 22.4 and 26.5 t ha^{-1} in pure system and in combination with centrosema, respectively (Table 5). Both firewood and poles were removed from the respective plots. The natural fallow yielded only a total harvestable biomass

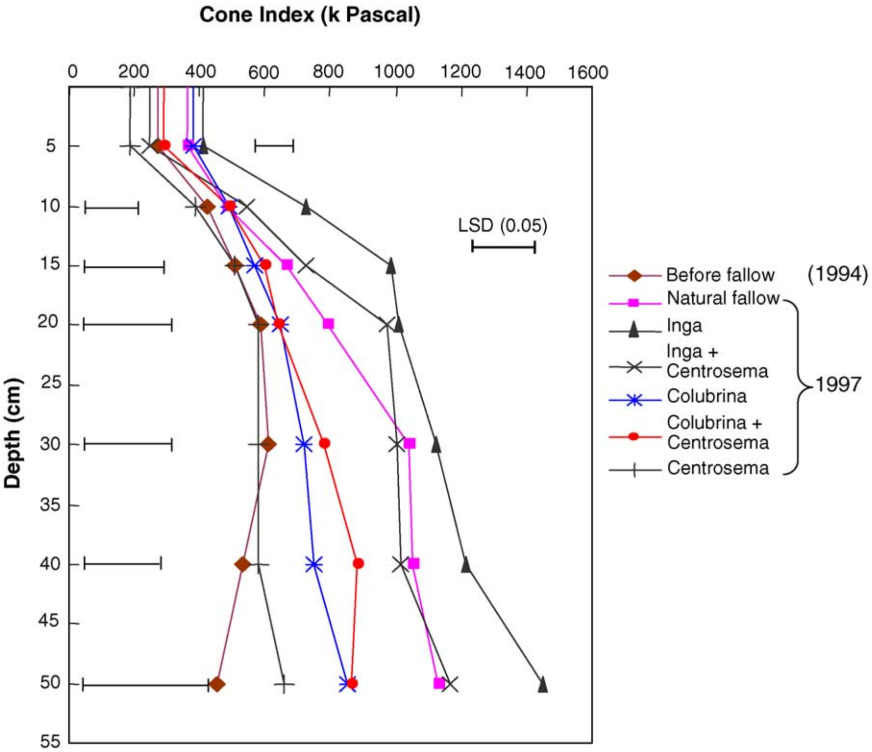

Fig. 1. Mechanical resistance at different depths in the 0–50-cm soil profile before (1994) and after different fallows (1997) at Yurimaguas, Peru. Bars at the left hand side are LSDs (0.05) to compare different systems at each soil depth and the bar at the lower right hand side is to compare the overall treatment means.

of 9.5 t ha^{-1}, comprising 7.8 t ha^{-1} of firewood and 220 small sized poles.

In the first season immediately after clearing the fallows, all systems produced low yields of maize at less than 1 t ha^{-1} (Table 9). Maize after pure centrosema produced a significantly higher yield than after natural fallow or pure tree fallows. Centrosema combined with inga did not increase the subsequent maize yield, but centrosema together with colubrina increased maize yield by 74% compared with natural fallow. In the second season after clearing fallows, cowpea after pure centrosema, natural fallow and pure tree fallows produced similar yields at 0.64–0.78 t ha^{-1}, which were significantly greater than those after mixed fallows of trees + centrosema (Table 9). In the third season after fallows, rice produced about 1 t ha^{-1} after natural and pure centrosema fallows, but yielded significantly lower (0.51–0.80 t ha^{-1}) after tree fallows with or without centrosema. Cowpea yields in this study compared well with the regional average yield of 0.5 t ha^{-1}. However, rice yields only after pure centrosema and natural fallows and maize yields only after natural fallow compared favorably with the regional average yield of 1 t ha^{-1} for both these crops (INEI, 1997).

Table 9
Grain yields of crops after 3-year natural and planted fallows at Yurimaguas, Peru

Fallow systems	Maize kg ha^{-1}	Cowpea kg ha^{-1}	Rice kg ha^{-1}
Natural fallow	498	687	1110
Inga	577	690	720
Inga + centrosema	502	475	800
Colubrina	484	642	510
Colubrina + centrosema	867	404	590
Centrosema	926	782	1000
SED	183	111	145
LSD (0.05)	384	233	305

SED, standard error of difference of treatment means; LSD, least significant difference at 95% confidence level.

Table 10
Costs and net present value, benefit:cost ratio and returns to labor of different short-duration planted fallows at Yurimaguas, Peru over a 5-year period

Fallow systems	Labor used (no. of days)			Net cash flow for fallow phase[a] (USD ha^{-1})	Net cash flow for cropping phase[b] (USD ha^{-1})	Total net present value[c] (USD ha^{-1})	Benefit:cost ratio	Returns to labor (USD $workday^{-1}$)
	F	C	T					
Natural fallow	0	259	259	0	771	283	1.5	1.09
Inga	145	332	477	−652	2365	509	1.3	1.07
Inga + centrosema	182	332	504	−296	1736	392	1.2	0.78
Colubrina	115	256	371	−664	883	−89	0.9	−0.24
Colubrina + centrosema	154	258	412	−168	878	206	1.2	0.50
Centrosema	125	253	376	−53	672	123	1.1	0.33

F, fallow period; C, cropping period; T, total.
[a] Undiscounted sum of net returns for 1994–1996.
[b] Undiscounted sum of net returns for 1997–1999.
[c] A discount rate of 20% was used, the approximate bank rate for savings in Peru.

The low maize yields in this study were due to high aluminum toxicity and poor fertility of this low pH soil (Table 1). It appears that none of the fallow systems tested here sufficiently ameliorated the aluminum toxicity to raise crop yields. Low yields of all the crops following tree fallows were probably due to the overall low soil nutrient status and removal of substantial quantities of nutrients through the wood harvested from these systems (Table 9). Furthermore, as the non-harvested woody biomass did not burn completely, not all the nutrients in it were available for the crops. Rice yields after planted fallows were particularly low probably because roots of the surviving tree stumps exercised greater competition with the crop for growth resources than roots of any surviving trees in natural fallow. Pure centrosema appears to be the most appropriate short-term fallow for improving soil productivity and yields of food crops in the Amazon basin. But this system is not comparable with tree fallows combined with or without centrosema in terms of economic benefit.

3.4. Economic analyses

There was no net income from any of the fallow systems in the first 15 months after establishment. Systems involving inga and/or centrosema did have returns through sale of inga fruits and centrosema seed from 15–18 months after establishment, but net cash flow was negative because of establishment costs in the fallow phases. Pure colubrina had the highest loss of USD 664 ha^{-1}, followed closely by pure inga with a loss of 652 ha^{-1} at the end of 27 months (1996) (Table 10). Mixed systems (inga + centrosema and colubrina + centrosema) had intermediate negative cash flows (USD −296 and −168 ha^{-1}), while pure centrosema was only slightly negative (USD −53 ha^{-1}). Natural fallow did not have any revenue in the fallow stage. In the cropping phase (1997–1999), net cash flow was high for inga (USD 2365 ha^{-1}) and inga + centrosema (USD 1736 ha^{-1}). This was fueled by the large output of fruit and firewood from inga, along with the high value of centrosema seeds. Natural fallow, colubrina, colubrina + centrosema, and centrosema were all grouped with net cash flow for the cropping phase ranging from USD 672 ha^{-1} to USD 883 ha^{-1}.

In principle, a positive net present value signals a feasible investment. The net present value (NPV) of natural fallow and pure centrosema over the 4.5-year study period was USD 283 and 123 ha^{-1}, respectively (Table 10). Colubrina + centrosema had an intermediate value (USD 206 ha^{-1}). The inga and inga + centrosema systems had the highest NPVs of USD 509 and 392 ha^{-1}. Pure colubrina had a negative NPV of USD 89 ha^{-1}. Natural fallow, however, had the highest benefit/cost ratio of 1.5, due to its lower costs relative to the more intensive planted fallow systems. All other fallows had lower benefit/cost ratios ranging between 0.9 (the negative NPV for pure colubrina fallow) and 1.3 (for pure inga fallow).

In the Amazon, labor is frequently the binding constraint faced by smallholders (Faminow et al., 1997a, 1997b). Labor use for natural fallow was lowest at 259 person-days, which translates to the highest return to labor, valued at USD 1.09 workday^{-1}. Other systems required substantially more workdays, and had resulted in lower returns to labor. Returns to workday are lower than the wage rate for all the six systems. This is not unusual since landowners accrue other benefits such as returns to other factors of production, such as land (e.g., realized through increased resale or rental value) and capital (e.g., returns to productive capital investments such as buildings and equipment, which will be unimportant for most small Amazon farms). In addition, full employment as hired labor income is unlikely across all seasons in each cropping year.

Farmers generally prefer systems that give regular income over the years, require less monetary inputs and are less sensitive to market fluctuations of input/output costs. This mostly explains why natural fallow continues to be the dominant land use in the Yurimaguas region. Labor costs of natural fallow were about 60% of average labor costs for the other five systems and 50% of the labor cost of inga + centrosema, the system with the largest NPV but also the most labor demanding. Given that labor is a major constraint in the Amazon region, returns to labor becomes an important criterion in judging the systems.

The baseline case utilized very conservative price and production parameters for the improved fallow systems. Table 11 shows the results of a sensitivity analysis of the financial measures of NPV and returns to labor under more optimistic conditions in a graduated manner. The first scenario recognizes that pole prices could be higher (USD 4.50 each) due to quality (girth and length), particularly for the systems with colubrina. A range of prices for poles are observed in the marketplace in Yurimaguas and this high-price case helps establish an upper bound on potential returns for the alternative systems under very optimistic conditions. Similarly, in the sensitivity analysis of centrosema and inga, effective yields are the parameters that are most uncertain and therefore utilized to establish bounds on financial returns. The NPVs for the two systems with colubrina increases to USD 1421 and 1782, and labor returns are much higher. Returns from natural fallow also increase, due to higher off-take value of poles. The second scenario presumes that centrosema seed yield is certain at 120 kg ha^{-1}, which increases the returns. The NPV of the mixed colubrina + centrosema system increases to USD 2476, and labor return is USD 6.01 workday^{-1}. Finally, the base case utilized an actual saleable yield of inga at 60% of total harvest, due to product losses and removal of small-sized pods. The last scenario relaxes this by assuming that all fruit is sold at the market price. Returns from the two inga systems increase but labor returns from the pure inga system remain below that from natural fallow.

Based on the three criteria of NPV, benefit/cost ratio, and returns to labor in the base case, the continued popularity of natural fallows relative to improved fallows is understandable. Tree fallows of pure inga or inga with centrosema appear to offer the next best option to farmers, but this must be tempered by the market opportunities that farmers confront. Inga is a staple fruit sold in local markets with inelastic demand that has minimal market potential for sales outside the region. Product bulkiness, perishability

Table 11
Sensitivity analysis of financial results under optimistic production and price levels

Fallow systems	Poles[a]		Poles ands centrosema[b]		Poles, centrosema and inga pods[c]	
	NPV (USD ha^{-1})	Net labor returns (USD workday^{-1})	NPV (USD ha^{-1})	Net labor returns (USD workday^{-1})	NPV (USD ha^{-1})	Net labor returns (USD workday^{-1})
Natural fallow	648	2.50	648	2.50	648	2.50
Inga	509	1.07	509	1.07	1144	2.39
Inga + centrosema	392	0.78	1087	2.16	1633	3.24
Colubrina	1421	3.83	1421	3.83	1421	3.83
Colubrina + centrosema	1782	4.32	2476	6.01	2476	6.01
Centrosema	123	0.33	818	2.17	818	2.17

[a] Poles sold at a price of USD 4.50 each due to better quality.
[b] Poles sold at price of USD 4.50 each and centrosema seed harvest averages 120 kg ha^{-1} with certainty.
[c] Poles sold at price of USD 4.50 each and centrosema seed harvest averages 120 kg ha^{-1} with certainty and inga fruit sales equal to harvest amount with no product loss due to deterioration and small size.

and distance to markets are other key marketing constraints. Most rural families produce primarily for on-farm consumption. As a result, widespread adoption of inga plantations could satiate cash markets in local urban centers, thereby lowering prices and returns to adoption.

In the sensitivity analysis, colubrina and colubrina mixed with centrosema appear to have potential financial viability for farmers, provided that centrosema seed production occurs and pole prices are high. But centrosema systems might also hold greater appeal to farmers, relative to inga systems, when considering market conditions. Not only do centrosema systems require less labor than the inga systems, but they also produce products for markets that are likely to be more stable in the face of widespread adoption and increased production. Demand for legume seed in the region is strong, particularly in the western Brazilian Amazon. Mixed fallows of tree + centrosema also offer the possibility of integrating livestock into the system and increase the scope for higher income (Arevalo et al., 1998).

4. Conclusions

Planted tree fallows using fast growing trees such as inga and colubrina accumulate more biomass than the natural fallow over a 3-year period. Addition of centrosema cover to the planted trees smothers weeds and has potential to add N into the systems through biological nitrogen fixation. Tree fallows with or without a centrosema cover crop may not increase or may even reduce yields of crops in the subsequent seasons compared with natural fallow. Only the pure centrosema fallow is appropriate for increasing the yields of subsequent cereal crops. However, planted tree fallows with inga, which produces fruit, firewood and charcoal in 3 years, or with colubrina, which produces poles in 3 years, are potentially more profitable, with higher returns to labor and capital invested than natural fallow or pure centrosema if farmers have access to profitable market opportunities for these products. Such profitable tree fallow systems have potential to reduce deforestation in the Amazon, and land being not a constraint there three, or even more years of fallow phase may not be a limitation for practicing these new land use systems.

Market opportunities for inga fruit and firewood in the Peruvian Amazon are generally sensitive to transportation costs (especially due to product weight and bulkiness) and distance to urban centers. Centrosema seed is a potentially viable cash product for farmers, due to its easy transport and increased utilization of legumes in Amazon pastures. Some farmers in the Peruvian Amazon specialize in charcoal production (generally land-constrained households, with sufficient family and/or communal labor along with ready access to urban markets; Coomes and Burt, 2000). Thus, the financial benefits for farmers from improved planted tree fallow systems should take into account commodity supply chains for the various products. They should also be evaluated across a range of conditions, for example, on different soil types and under different farmer-management circumstances in order to identify the social, cultural and economic conditions under which the tree fallows will be attractive to farmers in the Amazon region. Also, inga and colubrina may not be the best species for all agroclimates in the Amazon, so there is a need for testing other economically valuable species for planted fallow technology.

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