USE OF THE AMAZONIAN TREE SPECIES *INGA EDULIS* FOR SOIL REGENERATION AND WEED CONTROL

B Lojka[1, *], D Preininger[1], P Van Damme[2, 3], A Rollo[1] & J Banout[1]

[1]*Institute of Tropics and Subtropics, Czech University of Life Sciences Prague, Kamycka 129, Prague 6–Suchdol, 165 21, Czech Republic*
[2]*Laboratory of Tropical and Subtropical Agriculture and Ethnobotany, Ghent University, Coupure Links 653, 9000 Ghent, Belgium*
[3]*World Agroforestry Center—ICRAF, GRP1-Domestication, PO Box 30677, Nairobi, 01000 Kenya*

Received March 2011

LOJKA B, PREININGER D, VAN DAMME P, ROLLO A & BANOUT J. 2012. Use of the Amazonian tree species *Inga edulis* for soil regeneration and weed control. Land for agriculture in the tropics is often cleared through slash and burn, which is a shifting cultivation system. However, shortening of fallow periods led to soil degradation, decreased yields and increased weed pressure. Our objective was to evaluate the effects of short-term tree fallow of *Inga edulis* on weeds and soil fertility. We compared four treatments, namely, (1) natural fallow, (2) planted fallow with *I. edulis,* (3) planted fallow with *I. edulis* + herbaceous cover crop kudzu (*Pueraria phaseoloides*) and (4) continuous cropping of cassava (*Manihot esculenta*). Tree and weed biomass amount and composition were determined at 3, 6, 9, 13, 17, 20, 24, 28 and 33 months after establishment, while soil samples at 17 and 25 months. The growth rate of *I. edulis* was slow when compared with other studies. However, improved fallows were able to significantly decrease aboveground weed biomass. Total biomass of improved fallows increased more rapidly than that of natural fallow and cassava cropping. There were no significant soil fertility differences between treatments and all fallows increased the organic matter in topsoil over time. Available P declined in all treatments but stocks of aboveground N, P and K increased more rapidly under improved fallows. Planted fallows using trees such as *I. edulis* have the potential to reduce growth of weed species and improve some soil fertility parameters but, on highly degraded soil, a longer time and possibly P fertilisation may be needed to achieve these increases.

Keywords: Agroforestry, *Imperata brasiliensis,* improved fallow, Peruvian Amazon, slash and burn farming

LOJKA B, PREININGER D, VAN DAMME P, ROLLO A & BANOUT J. 2012. Penggunaan spesies pokok Amazon *Inga edulis* untuk pemulihan tanah dan kawalan rumpai. Tanah pertanian di kawasan tropika sering dibersihkan dengan menebas dan membakar. Ini merupakan sistem pertanian pindah. Bagaimanapun, kala rang yang singkat mengakibatkan degradasi tanah, hasil tanaman yang berkurangan serta masalah rumpai yang semakin meruncing. Tujuan kajian ini adalah untuk menilai kesan jangka pendek rang pokok *Inga edulis* terhadap rumpai dan kesuburan tanah. Kami membandingkan empat ujian iaitu (1) rang semula jadi, (2) rang yang ditanam *I. edulis,* (3) rang yang ditanam *I. edulis* + tanaman penutup bumi kudzu (*Pueraria phaseoloides*) dan (4) penanaman berterusan ubi kayu (*Manihot esculenta*). Jumlah serta komposisi biojisim pokok dan rumpai ditentukan pada 3, 6, 9, 13, 17, 20, 24, 28 dan 33 bulan setelah ujian dimulakan, sementara untuk tanah, pada 17 dan 25 bulan. Kadar pertumbuhan *I. edulis* adalah perlahan berbanding kajian lain. Bagaimanapun, rang yang dipulihkan berjaya mengurangkan biojisim rumpai dengan ketara. Jumlah biojisim dalam rang yang dipulihkan meningkat lebih cepat daripada rang semula jadi dan rang tanaman ubi kayu. Tiada perubahan signifikan antara keempat-empat ujian dan lama-kelamaan, semua rang meningkatkan kandungan bahan organik dalam tanah atas. Fosforus tersedia menurun dalam semua ujian tetapi stok atas tanah bagi nitrogen, fosforus dan kalium meningkat lebih cepat di rang yang dipulihkan. Rang yang ditanami pokok seperti *I. edulis* berpotensi mengurang pertumbuhan spesies rumpai dan meningkatkan kesuburan tanah. Namun, di tanah yang rosak teruk, tempoh yang lebih lama serta pembajaan fosforus mungkin diperlukan untuk mencapai keputusan yang serupa.

INTRODUCTION

Shifting cultivation is one of the most frequently applied methods to open up new farmland in the tropics. Despite rapid economic development in many tropical countries, shifting cultivation is still practised by millions of farmers and has been blamed for causing deforestation and poverty (Mertz et al. 2008). Between 1999 and 2005, disturbance and deforestation rates

*E-mail: lojka@its.czu.cz

throughout the Peruvian Amazon averaged 632 and 645 km^2 $year^{-1}$ respectively. However, 64% of all damage was concentrated in the area around the Ucayali logging centre of Pucallpa and along the road network that emanated from it (Oliveira et al. 2007). Tropical deforestation is best explained by multiple factors rather than by single variables but in Peruvian Amazon the largest part of this deforestation is probably caused by small-scale farmers. In the region, farmers traditionally use natural fallow after a few years of cropping in order to renew soil fertility and control noxious weeds such as *Imperata brasiliensis*. However, increased population pressure in the Peruvian Amazon has reduced the fallow periods from 10–15 to 3–5 years (Fujisaka et al. 1999), leading to rapid soil degradation, decreasing yields and increasing weed pressure. These soils inherently have low fertility. High levels of acidity and aluminium content are limiting crop growth. Most nutrients are contained in the aboveground fallow biomass. Use of capital inputs such as fertilisers, pesticides and amendments is extremely limited.

It is evident that the shifting cultivation system is no longer sustainable. Thus, there is a need to find technologies that increase landuse to meet the needs of the growing population and reduce deforestation in the humid tropics (Alegre et al. 2005). Several studies confirmed that improved fallow systems based on leguminous trees could improve soil fertility more rapidly than natural fallow, and increase crop yields as well (Szott et al. 1999, Chirwa et al. 2004, Barrios et al. 2005, Hartemink 2005). These improved fallows can also have the potential to control noxious weeds (Ekeleme et al. 2004). *Inga edulis*, a tree locally known as guaba, is highly valued by farmers and can be used to improved fallow. High biomass production, ability to improve soil fertility and provide economically useful products (fruit and firewood) and its prevalence throughout the Amazon Basin has sparked the interest of scientists to further explore the potential of this species. Previous research with *I. edulis* suggested that this species could be successfully used in agroforestry systems (e.g. Weber et al. 1997, Pennington & Fernandes 1998).

This fast-growing, acid soil-tolerant, nitrogen (N)-fixing tree is traditionally used to shade perennial crops such as coffee and cocoa, provide firewood and charcoal, and produce sweet pulp suitable for human consumption (León 1966, Weber et al. 1997). Research has also shown that *I. edulis* is useful as a source of green manure in alley cropping and other agroforestry systems. The leaf litter protects the soil surface and roots of other plants, helps retain nutrients in the topsoil and helps control weeds and erosion (Lawrence 1993). Nitrogen content in fresh foliage reaches about 3.3% (Mendeléz et al. 1995). The highest biomass production rates for *I. edulis* were on acid soils at the experimental station near Yurimaguas, Peru, i.e. from 2 to 31 t ha^{-1} $year^{-1}$ (Szott et al. 1995).

The objective of this experiment was to evaluate the effects of short-term tree fallows of *I. edulis*, either alone or in combination with the leguminous cover crop kudzu (*Pueraria phaseoloides*), on reduction of weeds and replenishing soil fertility, compared with natural fallow and continuous cropping. We also quantified biomass production and nutrient accumulation potential during fallow.

MATERIALS AND METHODS

Experimental site, treatments and crop management

The experiment was conducted on-farm, 19 km from Pucallpa, along the main road to Lima (74° 25' W, 08° 25' S, 155 m above sea level), in the Peruvian Amazon. Mean annual precipitation is approximately 1600 mm; intense precipitation prevails during the wet months from February till May and from September till November. The soil is classified as a fine loamy Ultisol (Acrisol according to FAO/UNESCO classification system). It is acidic, infertile and low in organic C, N, P, Ca and Mg but high in Al saturation (Table 1).

The study was initiated in July 2006 on a field which was initially covered by grassy vegetation with a few shrubs, which had been used as extensive pastureland for at least 15 years. Original vegetation was cut manually and left *in situ*. Fallow and cropping treatments were established in August 2006. The study evaluated the following three fallow and one cropping systems: (1) natural fallow, (2) planted fallow with *I. edulis* (3) planted fallow with *I. edulis* + kudzu and (4) continuous cropping with cassava (*Manihot esculenta*). The four treatments were replicated four times in a completely randomised block design in 12 × 12 m plots. Plots were

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

Depth (cm)	pH	OM (%)	Available P (ppm)	Total K (ppm)	Sand (%)	Silt (%)	Clay (%)	Texture	CEC (me 100 g^{-1})	Exchangeable (me 100 g^{-1})					Saturation of base (%)
										Ca^{2+}	Mg^{2+}	K^+	Na^+	$Al^{3+} + H^+$	
0–10	4.7	1.83	4.7	82.3	51	41	8	Loam	7.72	1.21	0.29	0.24	0.22	1.55	25.2
10–40	4.6	1.00	2.6	39.3	46	38	16	Loam	8.68	0.67	0.17	0.15	0.19	2.55	14.6

Analysis methods: pH—1:1 water solution, OM (organic matter)—titrimetric dichromate redox method (Walkley & Black 1934), available P—modified sodium bicarbonate extraction (Olsen et al. 1954), total K and exchangeable cations (Ca^{2+}, Mg^{2+}, K^+ and Na^+)—Mehlich III extraction and atomic absorption spectrophotometry (Mehlich 1984), texture—hydrometer method (Day 1965), CEC (cation exchange capacity)—ammonium acetate (NH_4OAc) saturation (Chapman 1965), exchangeable cations Al^{3+} and H^+—exchange acidity (Peech 1965) separated by paths (1 m wide) to minimise interaction between them. After slashing, the plots of natural fallow were left for natural vegetation to regrow. *Inga edulis* was directly sown at 1 × 2 m (91 trees per plot), using three seeds per hole. The seeds were obtained from a nearby orchard. We have chosen kudzu as an accompanying herbaceous legume species because, although not native to the study area, it is traditionally used there by small farmers as a cover crop in tree plantations for soil fertility improvement, it withstands shade and smothers weeds effectively (Skerman et al. 1988). Kudzu was sown directly into three furrows between tree rows at a distance within lines of 30 cm. The seeds of both legumes were not inoculated by any N-fixing rhizobia strains. Before planting cassava, the plots were burned, as practised by farmers when preparing soil for planting. Cassava was planted by local stem cuttings at 1 × 2 m. We avoided burning during preparation of the other treatments because, based on our experience, planting was easier but it encouraged fast development of fire-resistant grassy weeds such as *Imperata*. Pure *I. edulis* and cassava plots were weeded with a brush cutter and machetes four times during the first year. The plots with kudzu and natural fallow systems were not weeded because we did not want to destroy establishment of kudzu vines while the natural fallow was the control treatment for comparison. No fertiliser was applied to the trees in the fallow systems nor to cassava plots. Natural vegetation that grew in the paths surrounding the plots was periodically mowed using a brush cutter.

Data collection and analysis

Herbaceous vegetation in the plots (hereafter referred to as weed) and its biomass was determined at 3, 6, 9, 13, 17, 20, 24, 28 and 33 months after establishing the experiment (always prior to weeding) by harvesting and weighing the weed biomass from three quadrants of 1 m^2 each per plot (randomised along a diagonal transect). Weeds in each quadrant were clipped at ground level, sorted according to species and counted. The density of each weed species, defined as number of plants per m^2, was recorded. Biomass of each species was bulked for each plot and oven dried at 106 °C for 24 hours for the determination of aboveground dry matter. From the same quadrants, plant roots and rhizomes (usually larger than 2 mm in diameter) were excavated by hand down to a depth of 30 cm, and total biomass for each plot was oven dried for belowground dry matter determination.

Inga edulis leaf and wood biomass production was assessed by measuring tree growth of 20 randomly selected trees (excluding trees at borders) per plot at the same time as the measurements of herbaceous vegetation. Tree height and main trunk diameter at 10 cm aboveground (D10) was measured by a pair of callipers. Biomass production was then calculated allometrically using the following biomass regression equations obtained in a previous study (Lojka et al. 2005):

$$\text{Wood biomass: DM (kg)} = 0.0466\ (\text{D10})^{2.3713},\quad r^2 = 0.924 \qquad (1)$$

$$\text{Leaf biomass: DM (kg)} = 0.1564\ (\text{D10})^{1.1817},\quad r^2 = 0.792 \qquad (2)$$

where DM = dry matter.

Cassava was planted once at the beginning of the experiment, harvested after about 12 months, planted again at the same plots and harvested again at 25 months after the trial initiation (i.e. after about 12 months after replanting). Total fresh biomass of tubers, stems and leaves from each plot was weighed and samples were taken for assessment of dry matter content of each plant part. Unfortunately, we could no longer evaluate the experiment because the experiment was destroyed by accidental fire shortly after the measurement at 33 months.

All plant parts (roots, stems, wood and leaves) of the most frequent weeds, *I. edulis,* kudzu and cassava were analysed three times during the experiment, namely, at 3, 17 and 33 months. Content of basic elements for one mixed random sample for each plant part was determined in the laboratory at the National Agricultural University La Molina, Lima. Plant nutrients were extracted using 100% H_2SO_4 and 30% H_2O_2, while Ca, Mg and K were determined using an atomic absorption spectrophotometer, N by micro-Kjeldahl, and P by the modified Olsen method (Chapman & Pratt 1973). Total stock of nutrients was calculated by multiplying dry matter production of each plant part for each species by its nutrient content.

Soil samples were collected for physical and chemical property analysis (pH, organic matter, cation exchange capacity (CEC), available P, K and Ca) before the start of the experiment and then after each cassava harvest at 17 and 25 months. Soil samples were taken from four plots (one in each quarter) before the start of the experiment and then separately from each plot once the experiment was established. Ten soil cores were randomly collected from each plot to a depth of 40 cm with a precision auger (5.0 cm in diameter) and bulked according to two horizons (0–10 cm: dark brown, 10–40 cm: yellow ochre) for each plot. Soil samples were then air dried, sieved and sent for laboratory analysis. All analyses were done following the methods described by Chapman and Pratt (1973).

Predictive Analytics Software SPSS was used for analysis of variance (ANOVA) using Levene's test for equality of variances and t-test for equality of means to find out the effects of the four different treatments on total weed density, weed dry matter growth and changes in soil properties. Statistical comparison of treatments was based on two-sided tests assuming equal variances using the least significant difference test at 5% level of probability. The tests were adjusted for all pair-wise comparisons using the Bonferroni correction.

RESULTS AND DISCUSSION

Growth and biomass production of *I. edulis*

Inga edulis and kudzu grew well after planting. After 33 months, total aboveground tree biomass increased in pure *I. edulis* fallow to 0.87 kg tree^{-1} compared with 0.50 kg tree^{-1} in mixed *I. edulis* + kudzu fallow, and wood accounted for less than half of this total (Table 2). It seemed that kudzu was competing with *I. edulis* and decreased the trees biomass, especially in the second half of the experiment. At 17 months, *I. edulis* trees experienced better growth in mixed fallow but grew better in pure fallow at 33 months (Table 2). Overall, the growth of *I. edulis* was slower compared with other studies (Szott et al. 1995 Neill & Revalo 1998, Alegre et al. 2005). In the current study, after 33 months of growth, average tree height reached 1.3 m and trunk diameter reached 2.5 cm in pure *I. edulis* fallow. In contrast, in an experiment in Yurimaguas, Peruvian Amazon, *I. edulis* trees reached 6.8 m in height and 6.5 cm in diameter after three years (Alegre et al. 2005). In another study in the Ecuadorian Amazon, *I. edulis* attained a height

Table 2 Tree growth parameters and dry matter production of *Inga edulis* trees at 3, 17 and 33 months after establishment

Parameter	Fallow	Month		
		3	17	33
Tree density (No. ha^{-1})	IE	5000	5000	5000
	I + P	5000	5000	5000
Diameter (D10) (cm)	IE	0.4 a	0.8 b	2.5 a
	I + P	0.4 a	1.0 a	1.8 b
Height (cm)	IE	30.6 a	73.2 b	134.0 a
	I + P	30.6 a	87.3 a	101.9 b
Leaf biomass (g tree^{-1})	IE	53.0 a	120.1 b	461.8 a
	I + P	53.0 a	156.4 a	313.3 b
Wood biomass (g tree^{-1})	IE	5.3 a	27.5 b	409.3 a
	I + P	5.3 a	46.6 a	187.8 b
Total biomass (g tree^{-1})	IE	58.3 a	147.6 b	871.1 a
	I + P	58.3 a	203.0 a	501.1 b

IE = pure *I. edulis,* I + P = mixed *I. edulis* + kudzu; D10 = trunk diameter at 10 cm aboveground; for each month and growth parameters, data followed by a different letter (in each column) are significantly different (p = 0.05) of 10.8 m and a trunk diameter of 13.8 cm at 31 months (Neill & Revalo 1998). Finally, the highest biomass production rate was reported for *I. edulis* planted on acidic soils at the same experimental station near Yurimaguas, where the trees reached as much as 31 t ha^{-1} at two years of age, but the average was however between 8 and 12 t ha^{-1} (Szott et al. 1995). In our experiment, *I. edulis* biomass reached only 4.4 and 2.5 t ha^{-1} for pure and mixed fallow respectively.

The slow growth in our experiment might be explained by adverse soil conditions and competition with noxious weeds because the experiment was established on low fertility, degraded and compacted soil (deforested for at least 15 years and used as low grade pasture), particularly relative to experiments in Yurimaguas that were established on recently cleared land. Furthermore, in all the experiments reported above, *I. edulis* seedlings were used to establish the improved fallow. However, in our experiment we used the same method as the local farmers, i.e. direct sowing. The discrepancies between results of this study and those reported elsewhere could also be due to the fact that, in the latter, *I. edulis* seedlings used for transplanting were about four months old and 50 cm high, giving them a competitive advantage for growth over weeds. In the current study, the seeds germinated well but initial plant development was very slow. Another possible reason could likely be the deficiency of symbiotic rhizobia and mycorhizal fungi in the soil, which was deforested for a long time. These symbiotic microorganisms are very important for adaptation of trees to adverse soil conditions (Fernandes 1998). Inoculation has been recommended for promoting symbiosis among *I. edulis* trees by rhizobia and mycorrhizal fungi (Fernandes 1998). The inoculum could be produced by collecting surface soil, nodules and fine roots from mature, nodulated *I. edulis* trees.

Weed growth

All treatments contained a high diversity of weed species. Altogether, 21 weed species were identified, 9 of which belonged to the Poaceae family (Table 3). Most dominant species included cashaucsha (*Imperata brasiliensis*, Poaceae), cola de caballo (*Andropogon bicormis*, Poaceae) and stylo (*Stylosanthes guianensis*, Fabaceae). All treatments were dominated by grass weeds at the beginning of the trial. Nevertheless, species richness increased during the first year under all treatments (Figure 1), which is a sign of natural succession and weed composition improvement. There were no significant differences between treatments but there was a significant increase in the number of species in the first year. Results also showed that all four treatments led to successful control of grass species. The most promising results in terms of *Imperata* control were obtained for improved fallow with *I. edulis* and *I. edulis* + kudzu (Figure 2). The number of weeds generally decreased with time but in the case of sachahuaca (*Baccharis floribunda,* Asteraceae), which is a local shrub species, the number increased.

Table 4 shows weed density and above- and belowground weed biomass under all treatments at different times after fallow initiation. As far as the number of individuals is concerned, there were no significant differences between treatments, except at nine months after fallow initiation when the number of weed individuals was highest in *I. edilis* + kudzu fallow, reaching almost 136 individuals m^{-2}. The number of weed individuals significantly decreased over time, partly as a result of effective control of the more numerous grass weeds such as *Imperata* (Figure 2) but no differences were found between treatments. There were significant differences in the biomass growth of weed but no clear trend of increase or decrease was observed (Table 4). It seemed that dry matter growth was mainly affected by the season of the year (wet or dry season) when samples were collected. As a consequence, we evaluated the differences between treatments for each date of sample collection separately. There were significant differences between treatments only at 9, 13, 17, 20 and 28 months of growth (Table 4). At 9 and 13 months, weeds of natural fallow and *I. edulis* + kudzu fallow had significantly greater biomass than *I. edulis* fallow and cassava fields. Aboveground biomass reached 524.6 g m^{-2} in the natural fallow compared with 130 g m^{-2} in the *I. edulis* fallow after 13 months. After 17 months, the mixed *I. edulis* + kudzu fallow (186.3 g m^{-2}) had the lowest weed biomass and was significantly less than that of natural fallow (382.5 g m^{-2}) which had the highest weed biomass. After 20 months, the lowest biomass was measured in pure *I. edulis* fallow (230.3 g m^{-2}) while the highest, natural fallow (385.4 g m^{-2}). Similarly after 28 months, the lowest weed biomass was observed in pure *I. edulis* fallow (140.4 g m^{-2})

Table 3 Weed species identified at experimental site across all treatments

Scientific name	Local name	Family
Aeschynomene americana		Fabaceae
Andropogon bicormis	Cola de caballo	Poaceae
Baccharis floribunda	Sachahuaca	Asteraceae
Brachiaria decumbens	Braquiaria	Poaceae
Coix spp.		Poaceae
Cyperus rotundus		Cyperaceae
Digitaria sanguinalis		Poaceae
Hyptis spp.		Lamiaceae
Imperata brasiliensis	Cashaucsha	Poaceae
Lantana camara	Sacha orégano	Verbenaceae
Ludwigia erecta	Clavito	Onagraceae
Panicum laxum		Poaceae
Paspalum conjugatum	Torourco	Poaceae
Paspalum spp.	Colchon sacha	Poaceae
Phyllanthus amarus	Chanca piedra	Euphorbiaceae
Pseudelephantopus spp.	Lengua de perro	Asteraceae
Pueraria phaseoloides	Kudzo	Fabaceae
Rottboellia cochinchinensis	Arrocillo	Poaceae
Scleria melaleuca	Cortadera	Cyperaceae
Sida rhombifolia	Pichana	Malvaceae
Stylosanthes guianensis	Stylo	Fabaceae

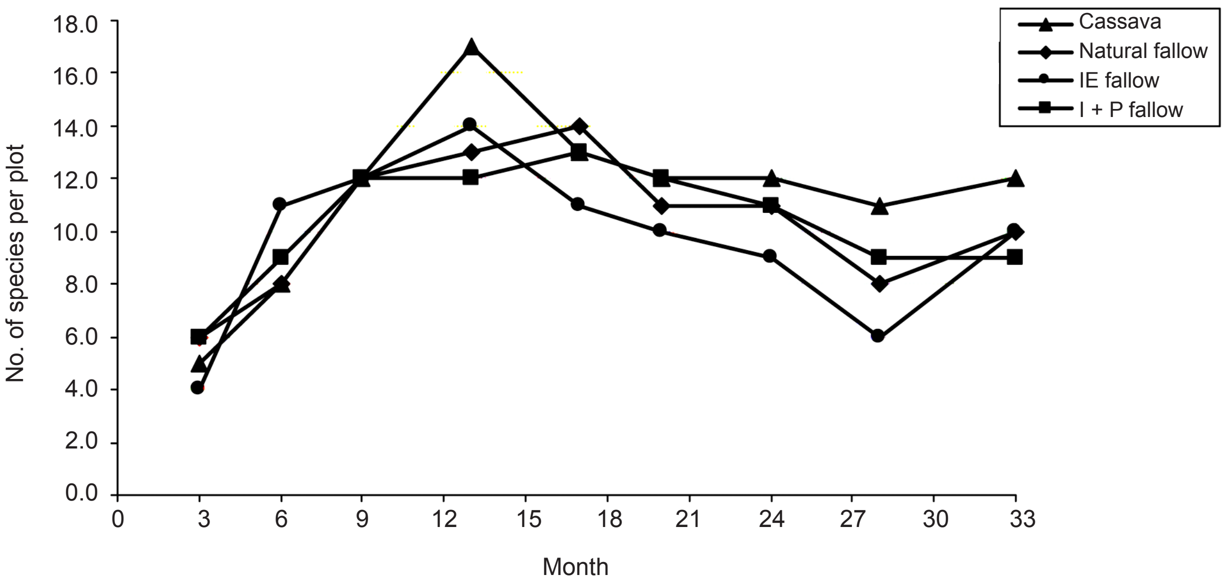

Figure 1 Number of weed species under different treatments plots over time; IE = pure *Inga edulis*, I + P = mixed *Inga edulis* + kudzu

and the highest, in natural fallow (380.8 g m^{-2}). As for belowground biomass, significant differences between treatments were only found at 17 months, where they were significantly lowest for *I. edulis* + kudzu fallow (142.1 g m^{-2}) and highest for the *I. edulis* fallow (315.0 g m^{-2}).

In most cases, tree fallows were able to significantly decrease weed biomass compared with natural fallow. In the study of Alegre et al. (2005), there was 130–190 g m^{-2} of total weed biomass under natural and pure tree fallows after 36 months. The values in our study were

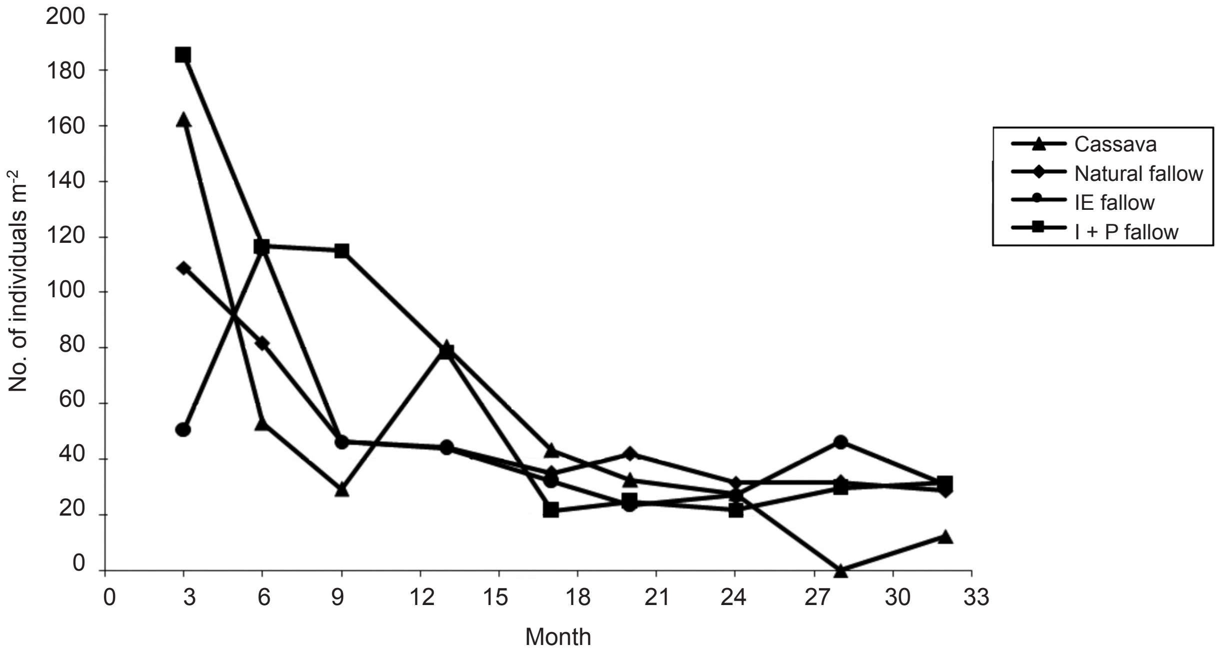

Figure 2 Occurrence of *Imperata brasiliensis* under different treatments over time; IE = pure *Inga edulis*, I + P = mixed *Inga edulis* + kudzu

Table 4 Weed density (number of individuals per m^2) and above- and belowground weed biomass (g m^{-2}) under different treatments

Treatment	Month								
	3	6	9	13	17	20	24	28	33
No. of individuals									
Cassava cropping	173.4 a	86.4 a	42.1 a	101.9 a	53.3 a	47.9 a	40.1 a	tr	21.5 a
Natural fallow	136.8 a	119.8 a	65.4 a	60.8 a	45.8 a	50.8 a	39.9 a	37.4 a	34.4 a
IE fallow	144.4 a	128.6 a	63.3 a	66.3 a	48.7 a	40.3 a	41.4 a	64.8 a	38.0 a
I + P fallow	193.3 a	141.3 a	135.8 b	91.1 a	24.0 a	27.5 a	24.1 a	31.8 a	40.9 a
Aboveground biomass									
Cassava cropping	162.3 a	257.7 a	60.2 a	130.8 a	245.6 b	316.9 b	246.4 a	tr	165.1 a
Natural fallow	246.0 a	326.1 a	296.1 b	524.6 b	382.5 c	385.4 c	285.8 a	380.8 c	164.2 a
IE fallow	180.9 a	234.7 a	150.8 a	130.0 a	304.2 b	230.3 a	196.7 a	140.4 a	117.1 a
I + P fallow	253.1 a	180.0 a	339.1 b	462.5 b	186.3 a	245.9 b	227.5 a	289.2 b	134.7 a
Belowground biomass									
Cassava cropping	139.8 a	138.7 a	120.8 a	77.1 a	271.9 b	103.5 a	120.4 a	tr	182.3 a
Natural fallow	134.1 a	139.8 a	140.8 a	104.6 a	265.4 b	80.1 a	117.0 a	190.4 a	131.7 a
IE fallow	128.0 a	154.6 a	165.8 a	90.0 a	315.0 c	100.7 a	111.2 a	130.8 a	129.0 a
I + P fallow	126.5 a	no	no	no	142.1 a	111.5 a	128.9 a	147.1 a	156.6 a

IE = pure *Inga edulis*, I + P = mixed *Inga edulis* + kudzu; for each date and indicator, treatments followed by a different letter are significantly different ($p < 0.05$); tr = trace (zero values), no = not measured at this time

much higher and varied between 180 and 650 g m^{-2}, although there was no significant difference between individual treatments (Table 4). As growth of *I. edulis* was slow, the trees had limited ability to shade the weeds out. Due to lower shade, weed control in this study was also lower than expected as shade was the major condition for efficient suppression of weeds under planted fallows. It has been reported that trees in natural fallows take three to four years or longer depending on their growth rates and canopy structure to establish a cover to significantly suppress weeds (Rao et al. 1998). In another study, *I. edulis* required 3.5 years to achieve a level of weed control similar to that achieved by the herbaceous legume *Centrosema* in 16 months (Szott 1987). Normally, *I. edulis* grows on poor, acidic and highly leached tropical soils (Neill & Revalo 1998, Szott et al. 1999). However, in this study the species showed slow growth and probably needed more time for development to effectively suppress noxious weeds.

Total biomass and contribution of trees

Total living biomass of trees, crops and weeds increased with time in *I. edulis* and *I. edulis* + kudzu fallows (Figure 3). At 3 and 17 between there were still no significant differences between treatments, but at 33 months, total living biomass reached 6114 kg ha^{-1} in *I. edulis* + kudzu fallow and 6817 kg ha^{-1} in pure *I. edulis* fallow. In cassava and natural fallow, maximum total mass was measured at 17 months (5455 and 6378 t ha^{-1} respectively) and then decreased to 3988 and 2965 t ha^{-1} respectively at 33 months.

Differences in biomass between treatments were mainly caused by differences in aboveground tree biomass accumulation (Table 5). The proportion of tree biomass to total aboveground biomass generally increased as time increased in tree fallows. In cassava and natural fallow treatments, we did not find any natural tree growth, except sachahuaca. Aboveground tree biomass reached approximately 2.5 t ha^{-1} in *I. edulis* + kudzu fallow and 4.3 t ha^{-1} in pure *I. edulis* fallow (with a tree density of 5000 individuals per ha) at 33 months. The proportion of aboveground legume biomass to total aboveground biomass in *I. edulis* + kudzu fallow increased from 16% at 3 months to 70% at 33 months. Also, in *I. edulis* fallow, the proportion of tree biomass increased from 14% at 3 months to nearly 79% at 33 months.

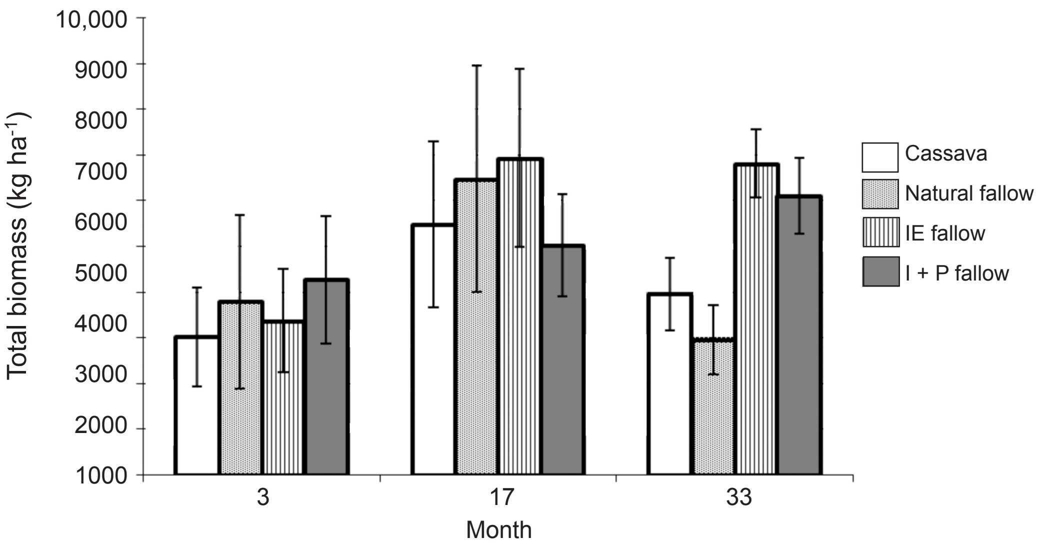

Figure 3 Total living biomass under different treatments at 3, 17 and 33 months; IE = pure *Inga edulis*, I + P = mixed *Inga edulis* + kudzu; bars indicate standard deviation

Table 5 Aboveground legume biomass contribution to total aboveground living biomass of tree fallows

Treatment		Month					
		3		17		33	
		%	kg ha^{-1}	%	kg ha^{-1}	%	kg ha^{-1}
IE fallow	*I. edulis*	13.9	292	19.5	738	78.8	4356
	Weed	86.1	1809	80.5	3042	21.2	1171
	Total	100.0	2101	100.0	3780	100.0	5527
I + P fallow	*I. edulis*	9.7	292	28.2	1015	55.1	2506
	Kudzu	6.3	191	20.2	727	15.3	696
	Weed	84.0	2531	51.7	1863	29.6	1347
	Total	100.0	3,014	100.0	3,605	100.0	4,549

IE = pure *Inga edulis,* I + P = mixed *Inga edulis* + kudzu

Belowground to aboveground biomass ratios in the tree fallows were relatively low and decreased over time to reach 0.23 and 0.34 for *I. edulis* and *I. edulis* + kudzu fallow respectively at 33 months (Table 6) when trees began to produce substantial amounts of aboveground biomass. In natural fallow and cassava, the ratio was higher and increased over time compared with the other two fallows. Fallow enriched with *I. edulis* can accumulate more aboveground biomass in the initial years than natural fallow (Szott et al. 1994).

Cassava yields

Cassava yield in the first year (harvest at 12 months after initiation) was very low (681.7 kg ha^{-1}). We assumed that this was mainly due to the low weeding frequency initially adopted in the test. Therefore, cassava was weeded more frequently in the following season to minimise weed competition. However, yield of the second harvest (25 months after initiation) was only 656.3 kg ha^{-1}. The extremely low cassava yields in our experiment were probably caused by poor soil fertility at the beginning of our trial. The area was severely degraded over a long period of time and a high occurrence of weeds caused high competition for nutrients. Although cassava is quite tolerant to low pH (Islam et al. 1980), low available phosphorus (P) in the soil and especially lower potassium (K) concentration can limit its growth and yield (Spear et al. 1978). Low cassava yield can also be probably due to the high underground water level. Although there were 91 cassava plants in each plot, only 61 and 52 plants were harvested in the first year and second respectively; mortality ranged from 33 to 43%.

Soil biophysical changes and nutrient stock

Soil samples taken on the same date were not significantly different between treatments except for pH, organic matter and available P content (Table 7). There was a decrease in soil pH after 17 months but the value increased after 25 months in all treatments and in both horizons. Organic matter content in 0–10 cm increased with time under all treatments. Fallows were able to increase organic matter by about 0.5% after two years (Table 7). Over the 25 months experiment, available P declined in all treatments in both horizons, with cassava cropping showing the highest decline (2.45 and 1.85 ppm in 0–10 cm and 10–40 cm horizons respectively).

Table 6 Ratios of root to aboveground biomass

Treatment	Month		
	3	17	33
Cassava cropping	0.86	1.07	1.06
Natural fallow	0.55	0.69	0.80
IE fallow	0.61	0.83	0.23
I + P fallow	0.42	0.39	0.34

IE = pure *Inga edulis*, I + P = mixed *Inga edulis* + kudzu; roots were sampled to a soil depth of 30 cm

Stocks of aboveground N increased with time in all treatments (Table 8). The increase was more rapid under tree fallows. Both tree fallows were able to accumulate much more N in aboveground biomass (especially during the second and third years). The average N concentration in *I. edulis* leaf, wood and root reached 2.1, 0.9 and 1.1% respectively, while in *Imperata* only 0.9 and 0.4 in stem and root respectively. After 33 months, *I. edulis* and *I. edulis* + kudzu accumulated as much as 76.1 and 81.8 kg N ha^{-1} respectively, which was several times higher than the values achieved by natural fallow or cassava. Aboveground P content also increased with time in all treatments and peaked at 17 months in cassava (2.7 kg P ha^{-1}) and natural fallow (2.6 kg P ha^{-1}). Tree fallows contained more aboveground P than natural fallow and cassava. The average P concentration in *I. edulis* leaf, wood and roots reached 0.09, 0.04 and 0.05% respectively, while *Imperata* 0.07 and 0.03% in stem and root respectively. At 33 months, treatment-related differences were mainly caused by greater P accumulation in *I. edulis* biomass. Consequently, aboveground P stocks were greater in the tree fallows. The amount of K in aboveground biomass at three months was about 10.0 kg ha^{-1} in all treatments. At 33 months, accumulation of aboveground K reached 8.4 kg ha^{-1} in the natural fallow and 47.0 kg ha^{-1} in *I. edulis* fallow. At that time, tree fallows contained significantly more K than natural fallow and cassava. In natural fallow and cassava monocropping, accumulation of K peaked at 17 months (results not shown).

Fallows enriched with *I. edulis* can increase stocks of N, P and K in the system (Szott & Palm 1996). Given the importance of soil organic matter for N and P availability, its dynamics can greatly affect, and are also affected, by fallow

Table 7 Changes in pH, organic matter (OM) and available phosphorus (P) under different treatments

Treatment	Month					
	0	17	25	0	17	25
Horizon	0–10 cm			10–40 cm		
pH						
Cassava cropping	4.67 a	4.26 b	4.54 ab	4.64 a	4.15 b	4.49 ab
Natural fallow	4.73 a	4.24 b	4.54 ab	4.60 a	4.02 b	4.50 a
IE fallow	4.80 a	4.10 b	4.65 a	4.56 ab	4.11 b	4.64 a
I + P fallow	4.73 a	4.09 b	4.58 a	4.50 a	4.13 b	4.45 ab
Organic matter (%)						
Cassava cropping	1.83 b	2.43 a	2.05 b	1.10 a	1.33 a	1.13 a
Natural fallow	1.83 b	2.13 ab	2.33 a	1.00 a	1.18 a	1.15 a
IE fallow	1.83 b	2.00 ab	2.25 a	0.90 a	1.28 a	1.13 a
I + P fallow	1.83 b	2.10 ab	2.30 a	1.00 a	0.90 a	1.15 a
Available P (ppm)						
Cassava cropping	4.93 a	2.08 b	2.48 b	3.08 a	1.00 b	1.23 b
Natural fallow	4.70 a	1.65 b	2.63 b	2.60 a	1.23 b	1.00 b
IE fallow	4.48 a	1.63 b	1.95 b	2.13 a	0.68 b	0.85 b
I + P fallow	4.70 a	2.23 b	2.80 b	2.60 a	0.75 b	0.90 b

IE = pure *Inga edulis*, I + P = mixed *Inga edulis* + kudzu; for each soil indicator, dates followed by a different letter (in rows) are significantly different ($p < 0.05$); there were no significant differences between treatments (in columns)

Table 8 Nitrogen stocks (kg ha^{-1}) in aboveground biomass under different treatments

Biomass component		Treatment			
		Cassava	Natural fallow	IE fallow	I + P fallow
			3 months		
Weed		13.2	20.6	14.6	20.5
Kudzu		0.0	0.0	0.0	8.0
Cassava		0.0	0.0	0.0	0.0
I. edulis	Leaf	0.0	0.0	5.5	5.5
	Wood	0.0	0.0	0.2	0.2
Total		13.2	20.6	20.3	34.2
			17 months		
Weed		21.2	33.3	26.7	15.7
Kudzu		0.0	0.0	0.0	30.5
Cassava		7.7	0.0	0.0	0.0
I. edulis	Leaf	0.0	0.0	12.4	16.2
	Wood	0.0	0.0	1.2	2.1
Total		28.9	33.3	40.3	64.5
			33 months		
Weed		16.7	14.3	10.1	11.6
Kudzu		0.0	0.0	0.0	29.4
Cassava		9.2	0.0	0.0	0.0
I. edulis	Leaf	0.0	0.0	47.8	32.4
	Wood	0.0	0.0	18.2	8.4
Total		25.9	14.3	76.1	81.8

IE = pure *Inga edulis*, I + P = mixed *Inga edulis* + kudzu performance, especially on highly weathered soils (Szott et al. 1999). Our results showed that *I. edulis* fallow increased soil organic matter through high biomass production. The value can further increase when *I. edulis* trees are slashed and the biomass left as mulch (Szott et al. 1995).

In contrast to the increase in soil organic matter, the observed decrease of available P in our trial was probably due to its accumulation in fallow biomass. Decreases in soil available P content during fallow can be stopped (Szott & Palm 1996) as available P, which is mineralised during the early fallow phase, tends to be conserved by vegetation growth (Szott et al. 1999). In our experiment, changes in soil nutrients mostly occurred in the top 10 cm soil layer, as reported also by Alegre et al. (2005), except for P, which also decreased significantly at depths of 10–40 cm. In the Philippine highlands, a *Gliricida* fallow system was able to increase soil available P over time (Grist et al. 1998). Soil available P could decline over time under *I. edulis* fallow, even though it was compensated by a P increase in the vegetation biomass (Szott 1987).

It seemed that on this highly weathered acidic soil, fast-growing, high biomass, long duration fallows based on trees and legumes could increase soil organic matter. However, since fallows have a limited ability to restore available P content, P fertilisers may be necessary to overcome P constraints in subsequent crop production to ensure long-term sustainability (Szott et al. 1999, Jama et al. 1998).

CONCLUSIONS

In our study, leguminous tree-based fallows showed the ability to control weed vegetation, to rapidly accumulate aboveground biomass and improve soil organic matter content. However, the degree of these positive achievements was lower than those reported in other studies. The most probable reasons were severely adverse soil conditions at the study site and also the method of *I. edulis* establishment from seed. Many studies confirm that *I. edulis* grows well on acidic soils and that it is suitable for weed control. Yet, due to certain limiting factors, *I. edulis* trees did not grow well in this study. However, during the course of our experiment, it was essential to follow the same farming methods practised by local farmers in order to obtain results of real conditions. Planted tree fallows using fast-growing trees such as *I. edulis* accumulate more vegetation biomass than natural fallow. However, in terms of weed control and soil fertility improvement, there were no clear differences between the different fallow and cropping systems. Under all treatments, a rather successful succession from pure grass weeds to a more diversified plant composition occurred over time. Yet, until the end of our trial, improved fallows did not show any ability to significantly control weeds compared with natural fallow or cassava cropping. *Inga edulis* trees were not able to suppress weeds by shading due to poor development of trees on severely degraded soil. The trees would probably need more time to demonstrate these abilities.

We conclude that planted fallows using economically valuable trees such as *I. edulis* have the potential to reduce weed growth and improve some parameters of soil fertility. However, on highly degraded soil, their effect needs a longer period of time and supplementary fertiliser may be required to optimise tree growth if inherent deficiencies of elements such as available P occur. In order to become effective, *I. edulis* would nevertheless require more extensive testing under a wider range of biophysical conditions, for example, on different soil types and under different farmer-management circumstances. This way, we can identify the social, cultural and economic conditions under which the tree fallows would become attractive to small farmers. Consequently, other economically valuable species need to be tested for planted fallows.

ACKNOWLEDGEMENTS

The research was conducted within the framework of the Czech Republic Development Cooperation in Peru No. 23/Mze/B/07-10 and was also supported by the Internal Grant Agency of the Institute of Tropics and Subtropics, Czech University of Life Science, Prague.

REFERENCES

Alegre JC, Meka RR, Arevalo LA, Guzman W & Faminow MD. 2005. Planted tree fallows for improving land productivity in the humid tropics of Peru. *Agriculture, Ecosystems and Environment* 110: 104–117.

Barrios E, Cobo JG, Rao MI, Thomas RJ, Amézquita E, Jiménez JJ & Rondón A. 2005. Fallow management for soil fertility recovery in tropical Andean agroecosystems in Colombia. *Agriculture, Ecosystems and Environment* 110: 29–42.

Chapman HD. 1965. Cation exchange capacity. Pp 891–901 in Black CA (ed) *Methods of Soil Analysis, Part 2*. American Society Agronomy, Madison.

Chapman HD & Pratt PF. 1973. Métodos de análisis para suelos, plantas y agues. Editorial Trillas, Mexico DF City. (In Spanish)

Chirwa TS, Mafongoya PL, Mbewe DNM & Chishala BH. 2004. Changes in soil properties and their effects on maize productivity following *Sesbania sesban* and *Cajanus cajan* improved fallow systems in eastern Zambia. *Biology and Fertility of Soils* 40: 20–27.

Day PR. 1965. Hydrometer method of particle size analysis. Pp 562–563 in Black CA (ed) *Methods of Soil Analysis, Part 2*. American Society Agronomy, Madison.

Ekeleme F, Chikoye D & Akobundu IO. 2004. Changes in size and composition of weed communities during planted and natural fallows. *Basic and Applied Ecology* 5: 25–33.

Fernandes ECM. 1998. Nodulation and nitrogen fixation in the genus *Inga*. Pp 41–52 in Pennington TD & Fernandes ECM (eds) *The Genus Inga Utilization*. The Royal Botanic Gardens, Kew.

Fujisaka S, Escobar G & Veneklaas E. 1999. Plant community diversity relative to human land uses in an Amazon forest colony. *Biodiversity and Conservation* 7: 41–57.

Grist P, Menz K & Nelson R. 1998. *Gliricida* as improved fallow. Pp 133–147 in Menz K, Magcle-Macandog DB & Rusastra WI (eds) *Improving Smallholder Farming Systems in* Imperata *Areas of Southeast Asia: Alternatives to Shifting Cultivation*. ACIAR Monograph No. 52. ACIAR, Canberra.

Hartemink A. 2005. Nutrient stocks of short-term fallows on a high base status soil in the humid tropics of Papua New Guinea. *Agroforestry Systems* 63: 33–43.

Islam AKMS, Edwards DG & Asher CJ. 1980. pH optima for crop growth: results of a flowing solution culture experiment with six species. *Plant and Soil* 54: 339–357.

Jama B, Buresh RJ & Place FM. 1998. *Sesbania* tree fallows on phosphorus-deficient sites: maize yield and financial benefit. *Agronomy Journal* 90: 717–726.

Lawrence A. 1993. *Inga edulis:* a tree for acid soils in the humid tropics. *NFTA Highlights 93–04*. Nitrogen Fixing Tree Association, Morrilton.

León J. 1966. Central American and West Indian species of *Inga*. *Annals of the Missouri Botanic Garden* 53: 256–369.

Lojka B, Preininger D, Lojková J, Banout J & Polesný Z. 2005. Biomass growth and farmer knowledge of *Inga edulis* in Peruvian Amazon. *Agricultura Tropica y Subtropica* 38: 44–51.

Mendeléz G, Szott LT & Ricse A. 1995. Mineralización de nitrógeno de material foliar de especies de *Inga*. Pp 130–141 in Evans DO & Szott LT (eds) *Nitrogen Fixing Trees for Acid Soils: Proceedings of Workshop*. 3–8 July 1994, Turrialba.

Mertz O, Wadley RL, Nielsen U, Bruun BT, Colfer CJP, De Neergaard A, Jepsen MR, Martinussen T, Zhao Q, Noweg GT & Magid J. 2008. A fresh look at shifting cultivation: fallow length and uncertain indicator of productivity. *Agricultural Systems* 96: 75–84.

Mehlich A. 1984. Mehlich-3 extraction: a modification of Mehlich-2 extraction. *Communication in Soil Science and Plant Analysis* 15: 1409–1416.

Neill AD & Revalo N. 1998. Silvicultural trails of mahagony (*Swietenia macrophylla*) interplanted with two *Inga* species in Amazonian Ecuador. Pp 141–150 in Pennington TD & Fernandes ECM (eds) *The Genus* Inga *Utilization*. The Royal Botanic Gardens, Kew.

Oliveira PJC, Asner GP, Knapp DE, Almeyda A, Galván–Gildemeister R, Keene S, Raybin RF & Smith RC. 2007. Land-use allocation protects the Peruvian Amazon. *Science* 317: 1233–1237.

Olsen S, Cole C, Watanabe F & Dean L. 1954. *Estimation of Available Phosphorus in Soils by Extraction With Sodium Bicarbonate*. USDA Circular No. 939. US Goverment Printing Office, Washington DC.

Pennington TD & Fernandes ECM. 1998. *The Genus* Inga *Utilization*. The Royal Botanic Gardens, Kew.

Peech M. 1965. Exchange Acidity. Pp 905–913 in Black CA (ed) *Methods of Soil Analysis, Part 2*. American Society Agronomy, Madison.

Rao MR, Nair PKR & Ong CK. 1998. Biophysical interactions in tropical agroforestry systems. *Agroforestery Systems* 38: 3–50.

Skerman PJ, Cameron DG & Riveros F. 1988. *Tropical Forage Legumes*. FAO Plant Production and Protection Series. FAO, Rome.

Spear SN, Asher CJ & Edwards DJ. 1978. Responses of cassava, sunflower, and maize to potassium concentration in solution. I. Growth and plant potassium concentration. *Field Crops Research* 1: 347–361.

Szott LT. 1987. Improving the productivity of shifting cultivation in the Amazon Basin of Peru through the use of leguminous vegetation. PhD dissertation, North Carolina State University, Raleigh.

Szott LT, Palm CA & Davey CB. 1994. Biomass and litter accumulation under managed and natural tropical fallows. *Forest Ecology and Management* 67: 177–190.

Szott LT, Ricse A & Alegre J. 1995. Growth and biomass production by introductions of *Inga edulis* in the Peruvian Amazon. In Evans DO & Szott LT (eds) *Nitrogen Fixing Trees for Acid Soils: Proceedings of Workshop*. 3–8 July 1994, Turrialba.

Szott LT & Palm CA. 1996. Nutrient stocks in managed and natural humid tropical fallows. *Plant and Soil* 186: 293–309.

Szott LT, Palm CA & Buresh RJ. 1999. Ecosystem fertility and fallow function in the humid and subhumid tropics. *Agroforestery Systems* 47: 163–196.

Weber JC, Sotelo–Montes C & Chávarri LR. 1997. Tree domestication in the Peruvian Amazon Basin—working with farmers for community development. *Agroforestry Today* 9: 4–8.

Walkley A. & Black IA. 1934. An examination of Degtjareff method for determining soil organic matter and a proposed modification of the chromic acid titration method. *Soil Science* 37: 29–37.