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Weed composition and cover after three years of soil fertility management in the central Brazilian Amazon: Compost, fertilizer, manure and charcoal applications

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Soils of the lowland tropics in the central Brazilian Amazon are generally highly leached, acidic and nutrient-poor. Charcoal, combined with other soil amendments, might improve fertility but this, in turn, could lead to increased weed problems for agricultural production. This experiment was conducted to assess weed pressure and species composition on plots receiving various inorganic and organic soil amendments, including charcoal. Additions of inorganic fertilizer, compost and chicken manure resulted in increases in weed ground cover of 40, 22 and 53%, respectively, and increases in species richness of 20, 48, and 63%, respectively. When chicken manure was applied, dominance by a few weed species was reduced, such that different species were more evenly represented. Although charcoal additions alone did not significantly affect weed ground cover or species richness, a synergistic effect occurred when both charcoal and inorganic fertilizers were applied. The percentage ground cover of weeds was 45% within plots receiving inorganic fertilizer, 2% within plots receiving charcoal and 66% within plots receiving both amendments. Improvements in the fertility of nutrient-poor soils of the tropics might increase weed pressure and make the development of effective weed management strategies more critical. These effects on weed populations were observed nearly 2.5 years after the addition of charcoal, chicken manure and compost, and >1 year after the last application of inorganic fertilizer.

Keywords: charcoal, organic amendments, soil fertility, weeds.

INTRODUCTION

Soils of the lowland tropics in the central Brazilian Amazon can be categorized as largely acidic, containing few weatherable minerals and plant-available nutrients, and having organic matter that undergoes rapid decomposition because of exposure to a warm and humid climate (van Wambeke 1992). However, Amazonian Dark Earth (ADE) soils are highly fertile compared with other soils of the region (e.g. Oxisols and Ultisols), often containing as much as 4× more organic matter in the top 30 cm of soil (Zech *et al.* 1990; Glaser *et al.* 2001). The organic matter of ADE soils is, on average, comprised of 4× more black carbon (C) (but up to 70× more in some cases), than organic matter in other soils of the region (Glaser *et al.* 2001). These features of ADE have stimulated interest in the possible use of charcoal amendments to increase the quality and fertility of nutrient-impoverished tropical soils (Glaser *et al.* 2002).

Black C (charcoal) amendments can improve soil pH, cation exchange capacity, base saturation, and can add nutrients with the accompanying ashes, thereby improv-

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ing crop growth (Glaser *et al.* 2002). The use of charcoal amendments is a particularly appealing management option for enhancing the quality and nutrient status of soils of the humid tropics. Contrary to other organic amendments, such as manures and composts which are rapidly mineralized (Bol *et al.* 2000; Diels *et al.* 2004), charcoal is very stable in soil (Shindo 1991; Schmidt & Noack 2000) and a single application can be more effective in enhancing long-term soil fertility than the use of mulch (Glaser *et al.* 2002), thus mimicking the dynamics of the black, C-rich Amazonian Dark Earths (Lehmann *et al.* 2003a).

Weed pressure on the fertile and C-rich ADE can be a serious challenge to crop production (Major *et al.* 2003; Major 2004). Previous work relating soil fertility to weed density has provided mixed results and has revealed high variability in response between weed species, years and within individual fields (Hume 1982; Freyman *et al.* 1989; Andreasen *et al.* 1991; Everaarts 1992; Medlin *et al.* 2001; Walter *et al.* 2002). Theoretically, weed species richness is expected to follow a unimodal pattern along a productivity gradient, with the highest number of species occurring at moderate productivity levels (Grime 1979; Stevens & Carson 1999). In agricultural systems, inconsistent results have been reported on the effect of soil fertility on weed species richness (Heil & Diemont 1983; Tilman 1987; Pysek & Leps 1991; Suarez *et al.* 2001). However, discrepancies between the results of these studies might be related to the sampling of habitats that were either at the high or low range of the fertility gradient.

The objective of this study was to assess the effects of charcoal and other organic and inorganic soil amendments on weed species composition and above-ground biomass on a Xanthic Hapludox in the central Brazilian Amazon.

MATERIALS AND METHODS

Experiment site

The research site was located at the Empresa Brasileira de Pesquisa Agropecuaria (EMBRAPA-Amazônia Ocidental), outside the city of Manaus, Amazonas, Brazil (3°8′S, 59°52′W; 40–50 m a.s.l.). The climate is humid–tropical, with a unimodal rainfall distribution peaking between December and May (211–300 mm month^{-1}; 75% of annual rainfall). The mean annual precipitation for the site is 2500 mm, with a mean air temperature of 26°C and mean atmospheric humidity near 84% (Ribeiro & Adis 1987). The soil at the site is classified as a Xanthic Hapludox (Soil Survey Staff 1997), which is derived from Tertiary sediments. It is very deep and clayey (59–72% clay), with low pH (3.9 in water) and available phosphorus (P) (4.8 mg kg^{-1}), and moderate levels of organic C (29.1 g kg^{-1}) and nitrogen (N) (1.7 g kg^{-1}) (Renck & Lehmann 2004).

After slashing a 12-year-old secondary forest in September 2000, remnant vegetation and roots were removed from the site, and a completely randomized block design was established with aluminum bands used at the edge of individual plots to control erosion and avoid cross-contamination of treatments (Steiner *et al.* 2004). Amendment treatments consisted of combinations of litter, burned litter, cattle manure-based compost, mineral fertilizer and lime, charcoal powder or charcoal pieces, and chicken manure, with each treatment replicated five times (Table 1). The treatments were applied to 2 × 2 m plots and to a depth of 10 cm.

Four crops were grown. Rice (*Oryza sativa* L.) was planted on 10 March 2001 and sorghum (*Sorghum bicolor* Moench) was planted on 15 October 2001 and 18 April 2002, the latter producing two harvests by ratooning. The last crop was harvested on 16 October 2002, and the site subsequently left to fallow. Although organic amendments (litters, chicken manure, compost) and charcoal were incorporated only at the onset of the experiment, mineral fertilizer applications were delayed and split (March 2001 and after the second harvest in April 2002) (Table 1). Organic amendments were added in proportions that achieved a 25% increase in total soil C content in the top 10 cm. During crop growth, weeds within experimental plots were removed by hand on a regular basis, but no weeds were removed after 16 October 2002.

Assessment of weed population

On 5 June 2003, all weeds present in each 2 × 2 m plot were identified and a visual estimate of percentage ground cover was obtained. Weeds were identified in the field by the primary author when possible, and when needed, dried specimens were identified using samples from the Instituto Nacional de Pesquisas da Amazônia (INPA), Manaus, Brazil, herbarium. Unidentified immature tree seedlings and sprouts were placed in a single group for statistical analysis.

Data analysis

Pearson's Moment Correlation coefficients were calculated for the treatments, soil fertility parameters and crop biomass data.

Table 1. Description of treatments on a Xanthic Hapludox in the central Brazilian Amazon

Treatment	Description	Carbon added (March 2001) (mg ha^{-1})	1st fertilization (March 2001)	2nd fertilization (April 2002)
C	Control	–	–	–
L	Litter	13	–	NPK2 + micro
L_B	Burned litter (+ fertilizer in 2002)	–	–	NPK2
F	Fertilizer (and lime)	–	NPK1	NPK3
C_M	Chicken manure	47	–	–
C_O	Compost†	67	–	–
C_C	Charcoal‡	11	–	–
C_O + F	Compost + fertilizer	67	NPK1	NPK3
C_C + F	Charcoal + fertilizer	11	NPK1	NPK3
$C_C{}^1/_2 + C_O{}^1/_2$	Charcoal + compost	5.5 + 33.5		–
$C_C{}^1/_2 + C_O{}^1/_2$ + F	Charcoal + compost + fertilizer	5.5 + 33.5	NPK1	NPK3
$C_C + C_O{}^1/_2$	Charcoal + compost	11.0 + 33.5	NPK1	NPK3
$C_C + C_O{}^1/_2$ + F	Charcoal + compost + fertilizer	11.0 + 33.5	NPK1	NPK3
$C_C + C_O{}^1/_2 + F_1$	Charcoal pieces	11.0 + 33.5		NPK2 + micro
$C_C + C_O{}^1/_2 + F_2$	Charcoal pieces	11.0 + 33.5	NPK1	NPK2

† 80% biomass residue, 20% cattle manure, 500 g m^{-3} marble powder. ‡ Locally produced from secondary forest wood.
NPK1 (kg ha^{-1}): nitrogen (N) (30), phosphorus (P) (35), potassium (K) (50), lime (2100); NPK2 (kg ha^{-1}): N (55), P (40), K (50), lime (2800); NPK3 (kg ha^{-1}): N (55), P (40), K (50), lime (430); NPK2 + micro (kg ha^{-1}): N (55), P (40), K (50), lime (2800), zinc (7), boron (1.4), copper (0.6), iron (2.3), manganese (1.6), molybdenum (0.08).

A multivariate analysis of variance was performed using a model with fixed effects to evaluate the influence of charcoal powder and pieces, mineral fertilizer, compost, litter, burned litter and chicken manure on the percentage ground cover of weeds, weed species richness and dominance in the weed community. Dominance was assessed on a plot-by-plot basis using Simpson's index, C:

$$C = \sum_{i=1}^{s} (p_i)^2 \qquad (1)$$

where p_i = the percentage ground cover of species i divided by the total weed percentage ground cover in the plot, and s = the total number of species observed. The higher the value of this index, the less evenly distributed are the species in the sample; that is, there are dominant species. After inspection of the residual plots, percentage ground cover and species richness were logarithmically transformed to stabilize variance. The error rate on multiple comparisons was controlled using the Bonferroni *t*-statistic.

RESULTS AND DISCUSSION

Weed species composition

A total of 33 weed species were identified in the experimental plots (Appendix I). Twenty-seven percent of the species identified were members of the Poaceae family, with *Scleria melaleuca* Reichb. ex Schlecht. & Cham. and *Paspalum* cf. *conspersum* Schrad. ex Schult. the most abundant. Most species identified were herbaceous perennials.

Weed growth response to amendments

Addition of mineral fertilizer, chicken manure, compost and burned litter resulted in increases in percentage ground cover of weeds and weed species richness in treatment plots ($P < 0.05$; Table 2). As the burned litter treatment also received inorganic fertilizer, this treatment will not be discussed further. We will focus on the fertilizer amendment. Neither the addition of charcoal powder nor charcoal pieces alone to plots resulted in increases in weed cover or species richness. In contrast, the addition of charcoal alone significantly increased yields in the first crop (rice) compared with yields in unamended controls, although yields were very low (100 kg ha^{-1}) (Nehls 2002). The second crop grown, sorghum, did not benefit from charcoal-only additions. However, combined charcoal and inorganic fertilizer additions had a synergistic effect on sorghum yield, where the effect of the combined treatments was greater than the additive effect of charcoal and fertilizer (Steiner *et al.* 2004). A similar synergistic interaction ($P < 0.05$) between these amendments was observed for total weed

Table 2. Percentage weed cover and number of species (± standard error) in plots receiving different organic and inorganic fertilizer amendments

Treatment	Description	Coverage (%)	Number of species
C	Control	3.8 ± 1.3	2.6 ± 0.5
L	Litter	19.4 ± 9.0	3.6 ± 0.5
L_B	Burned litter (+ fertilizer in 2002)	36.1 ± 20.4	4.6 ± 0.4
F	Fertilizer (and lime)	44.7 ± 20.7	4.8 ± 0.6
C_M	Chicken manure	56.8 ± 14.3	7.0 ± 0.6
C_O	Compost†	26.1 ± 7.6	5.0 ± 0.3
C_C	Charcoal‡	1.9 ± 0.8	2.0 ± 0.4
C_O + F	Compost + fertilizer	61.4 ± 17.9	5.0 ± 0.5
C_C + F	Charcoal + fertilizer	66.0 ± 21.5	4.0 ± 0.7
$C_C{}^1/_2 + C_O{}^1/_2$	Charcoal + compost	8.7 ± 4.0	4.0 ± 0.9
$C_C{}^1/_2 + C_O{}^1/_2$ + F	Charcoal + compost + fertilizer	76.2 ± 11.1	5.4 ± 1.3
$C_C + C_O{}^1/_2$	Charcoal + compost	15.9 ± 7.7	4.7 ± 0.8
$C_C + C_O{}^1/_2$ + F	Charcoal + compost + fertilizer	55.6 ± 19.3	5.6 ± 1.3
$C_C + C_O{}^1/_2 + F_1$	Charcoal pieces	30.9 ± 18.2	4.6 ± 1.0
$C_C + C_O{}^1/_2 + F_2$	Charcoal pieces	48.0 ± 19.9	5.2 ± 0.6

† 80% biomass residue, 20% cattle manure, 500 g m^{-3} marble powder. ‡ Locally produced from secondary forest wood.

cover. The percentage ground cover of weeds was 45% on plots receiving inorganic fertilizer ($n = 5$), 2% on plots receiving charcoal ($n = 5$) and 66% ($n = 5$) on plots where both amendments were added.

When fertility parameters for soil samples collected on 22 October 2002 were used as predictors, no single factor was found to significantly influence total weed coverage. In fact, cations, P and pH values were highly correlated to each other ($P < 0.001$), but did not correlate well to C, N and C : N values. Cation concentrations and pH were significantly affected by most amendments used. However, P concentrations increased significantly only in plots receiving chicken manure, or fertilizer when the chicken manure treatment was removed from the analysis. In fact, this treatment lay outside the range of the other data. For these reasons, most concentrations of cations, P and pH were strongly correlated to total weed cover (Fig. 1). Increases in weed cover with rising fertility levels are consistent with the observed increase in crop yields and microbial activity before fallowing in this field experiment (Steiner *et al.* 2004). Pearson's Moment Correlation coefficient for total weed cover and total above-ground crop biomass of the last two crops grown was 0.82 ($n = 15$, $P = 0.0002$; Fig. 2), illustrating that on more productive plots, weed growth was increased more than seven months after plot abandonment.

Weed species response to amendments

While application of both inorganic and organic fertilizers significantly increased weed ground cover, the number of species within plots also significantly increased following the addition of inorganic fertilizer. These increases were even greater with the addition of chicken manure and compost ($P < 0.05$; Table 3). Simpson's index of dominance was significantly lower when chicken manure was applied ($P < 0.05$); that is, lower dominance was observed in these plots and a greater number of species were more evenly represented. Also, species richness was strongly and positively correlated to crop biomass for the last two crops grown (Pearson's Moment Correlation coefficient = 0.82, $P = 0.0002$; Fig. 2).

Of the 33 weed species on the site, only seven occurred on unamended control plots. Three species occurred only on plots amended with compost (*Sabicea amazonensis* Wernham, *Rolandra fruticosa* Kuntze and *Spermacoce ocymifolia* Willd. ex Roem. & Schult.), although their overall frequency was low. Weed species were grouped by life form in an attempt to identify trends in their response to the soil amendments used in this study. The ground cover of annual, grass and perennial species increased significantly only following fertilizer applications ($P < 0.05$), while the cover of legumes and sedges

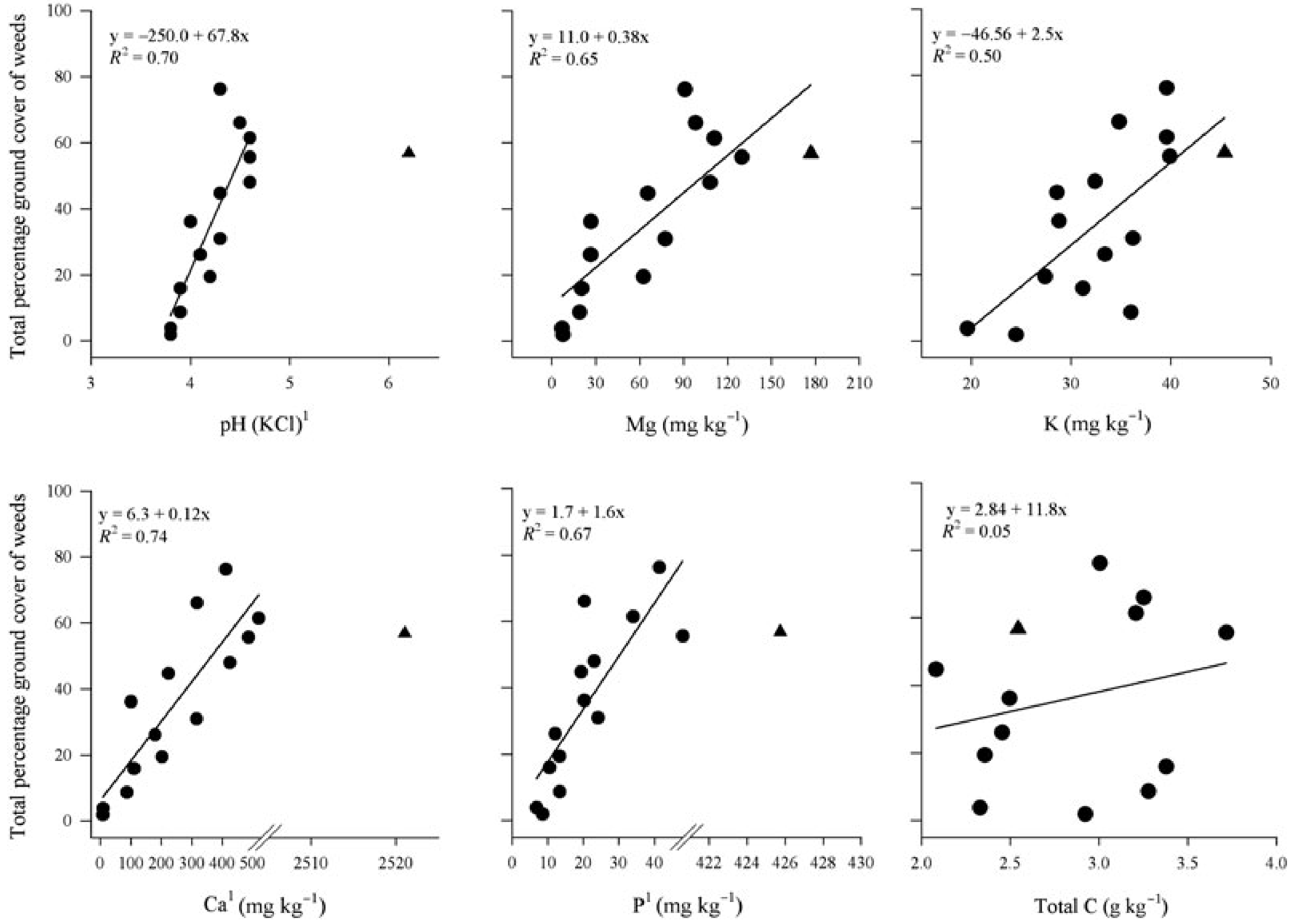

Fig. 1. Relationship between total percentage ground cover of weeds and soil parameters for plots amended with organic inputs and inorganic fertilizer (●). (1), the chicken manure treatment (▲) was omitted from the regression analysis. Mg, magnesium; K, potassium; Ca, calcium; P, phosphorus; C, carbon.

Table 3. Mean percentage ground cover and species richness of weeds for contrasts with and without fertilizer (F), chicken manure (C_M) and compost (C_O) applications. All percentage-increase values are significant ($P < 0.05$)

Treatment	N	Cover (%)	% increase between treatments	Number of species	% increase between treatments
+F	25	57.2	40	5.2	20
−F	25	17.1		4.2	
$+C_M$	5	56.8	53	7.0	63
$-C_M$	5	3.8		2.6	
$+C_O{}^1/_2$	5	15.9	14	4.7	57
$-C_O{}^1/_2$	5	1.9		2.0	
$+C_O$	5	26.1	22	5.0	48
$-C_O$	5	3.8		2.6	

was not influenced by any of the treatments. The perennial forb, *Spermacoce verticillata* L., occurred throughout the experimental area but was especially responsive to nutrient additions, with an average 13% cover ($n = 18$) on plots receiving inorganic fertilizer or chicken manure, and only a 5% cover ($n = 18$) on plots not receiving these amendments.

An increase in species richness with nutrient addition is consistent with the generally observed unimodal rela-

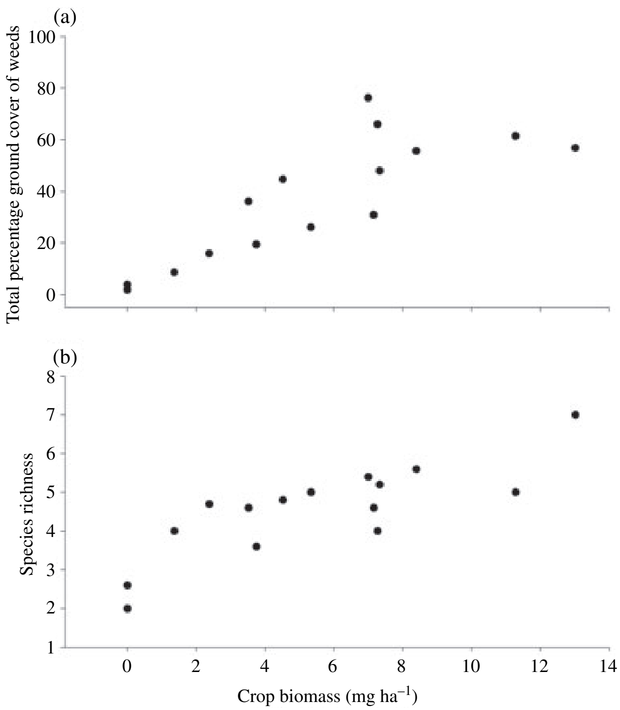

Fig. 2. Relationship between total above-ground crop biomass of the last two harvests and (a) weed percentage ground cover and (b) species richness, for 15 soil management treatments in the central Brazilian Amazon.

tionship of species density and productivity (Grime 1979). The organic amendments used improved the levels of plant-available potassium, calcium and magnesium and, consequently, soil reaction compared with inorganic fertilizer applications.

The compost used in this experiment was cattle manure-based. Although fresh cattle manure might contain large amounts of viable weed seeds, proper composting techniques commonly ensure that sufficiently high temperatures are attained to kill most, if not all, of these (Blackshaw & Rode 1991; Nishida *et al.* 1998). Also, the digestive process in chickens involves the physical grinding of seeds within the gizzard, which most likely results in the destruction of weed seeds. In fact, fresh or composted chicken manure has been found not to contain viable weed seeds (Parsons *et al.* 1993). If the composting process reached adequate temperatures (i.e. 65°C), neither the compost nor the chicken manure treatments would be expected to contribute weed seeds to the experimental plots. Therefore, the increase in number of weed species observed in plots receiving these amendments is likely to be related to increased soil fertility or to the contamination of amendments with weed seeds during processing and shipping. However, contamination is not likely because no weed species were systematically associated with these amendments in the field. In fact, plots that received compost or chicken manure had a greater abundance of species that were widespread at the experimental site.

Alternatively, seed dispersal might have been favored in plots where fertility was increased and where biomass production was greater. Weed seed-carrying insects, birds or small mammals might have been attracted to these plots, which offered better shelter and, possibly, more food. For example, at the landscape scale, Vulinec (2002) showed that seed-dispersing dung beetle communities were reduced as disturbance increased and biomass cover decreased in tropical forests of the Amazon.

Interestingly, 61% of the species reported in this study were not observed during a weed survey of 20 cropped plots on highly fertile Anthropogenic Dark Earth sites in the region (Major 2004). Although soil fertility might be important in determining species richness at a site, management is also crucial. The intensity of cropping, the length of fallow, weed management and crops grown all have an impact on potential species colonization and seedbank build-up, and can vary widely between fields (Major 2004).

In this experiment, additions of inorganic fertilizer, compost and chicken manure increased weed ground cover and species richness. Although weed cover was responsive to fertilizer additions, species richness was most affected by organic amendments, such as compost and chicken manure.

Substantial increases in ground cover and species richness of weeds were observed nearly 2.5 years after the addition of chicken manure and compost, and >1 year after the last application of inorganic fertilizer. This is surprising considering the high rainfall patterns and nutrient-leaching rates of the region. However, crop residues were left on the plots and long-term nutrient cycling might have been enhanced where these amendments were applied and biomass production was increased. It is likely that increased weed biomass in the early stages of the trial led to increases in the seed bank.

Charcoal additions did not have a significant effect on weed abundance or species richness, but a synergistic effect of using combinations of charcoal and inorganic fertilizer on weed cover was observed. Charcoal-only additions did not directly contribute to nutrient inputs (with the possible exception of ashes) and, therefore, had limited effects on plant nutrition, while additions of charcoal together with inorganic fertilizer might have further increased nutrient availability by reducing leaching (Lehmann *et al*. 2003b).

We expect that improvements in the fertility of nutrient-poor soils of the tropics will increase weed pressure. When charcoal is combined with nutrient additions, weed pressure is likely to be intensified, unless crop and weed emergence patterns are modified, such that they result in a competitive advantage for the crop. Nonetheless, it is clear that as soil fertility management improves in these regions, effective weed management will become an even more important facet of agricultural production.

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APPENDIX I

Plant species observed on experimental plots of the central Brazilian Amazon, listed alphabetically by family.

Species	Family	Life form	Life history
Rolandra fruticosa Kuntze	Asteraceae	sh	p
Wedelia paludosa DC.	Asteraceae	f	p
Cecropia sp.†	Cecropiaceae	t	p
Cyperus cf. *diffusus* Vahl	Cyperaceae	s	p
Cyperus cf. *luzulae* Rottl. ex Willd.	Cyperaceae	s	p
Cyperus cf. *surinamensis* Rottb.	Cyperaceae	s	p
Cyperus flavus Boeck.	Cyperaceae	s	p
Rynchospora cf. *pubera* Boeck.	Cyperaceae	s	p
Euphorbia hirta Linn.	Euphorbiaceae	f	a
Phyllanthus niuri Linn.	Euphorbiaceae	f	a
Hyptis atrorubens Poit.	Lamiaceae	f	p
Marsypianthes chamaedrys Kuntze	Lamiaceae	f	a
Derris amazonica Killip†	Fabaceae Papilionoideae	wv	p
Desmodium adscendens DC.	Fabaceae Papilionoideae	f	p
Mimosa sp.†	Fabaceae Papilionoideae	f	u
Clidemia sp.†	Melastomataceae	sh	p
Mollugo verticillata Linn.	Molluginaceae	f	a
Digitaria cf. *horizontalis* Willd.	Poaceae	g	a
Panicum cf. *pilosum* Sw.	Poaceae	g	u
Panicum laxum Sw.	Poaceae	g	p
Panicum mertensii Roth	Poaceae	g	u
Paspalum cf. *conspersum* Schrad. ex Schult.	Poaceae	g	u
Paspalum decumbens Sw.	Poaceae	g	p
Paspalum multicaule Poir.	Poaceae	g	a
Poaceae sp.	Poaceae	g	u
Scleria melaleuca Reichb. ex Schlecht. & Cham.	Poaceae	g	p
Polypodiaceae sp.	Polypodiaceae	fe	p
Sabicea amazonensis Wernham	Rubiaceae	hv	p
Spermacoce ocymifolia Willd. ex Roem. & Schult.	Rubiaceae	f	u
Spermacoce verticillata Linn.	Rubiaceae	f	p
Solanum subinerme Jacq.	Solanaceae	f	p
Tree sprouts	Various	t	p
Vine	Unknown	u	u

† Identified from sterile specimen. a, annual; f, forb; fe, fern; g, grass; hv, herbaceous vine; p, perennial; s, sedge; sh, shrub; t, tree; u, unknown; wv, woody vine.