

1 **Manioc peel and charcoal: a potential organic amendment for sustainable soil**
2 **fertility in the tropics**

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1 **Abstract**

2

3 In tropical areas, where crop production is limited by low soil quality, the development
4 of techniques improving soil fertility without damage to the environment is a priority. In
5 French Guiana, we used subsistence farmer plots on poor acidic soils to test the effect
6 of different organic amendments, bitter manioc peel (M), sawdust (Sw) and charcoal
7 (Ch), on soil nutrient content, earthworm abundance and yard-long bean (*Vigna*
8 *unguiculata sesquipedalis*) production. The peregrine *Pontoscolex corethrurus* was the
9 only earthworm species found. Pod production and plant growth were lowest in
10 unamended soil. The application of a mixture of manioc peel and charcoal (M+Ch)
11 improved legume production as compared with other organic mixtures. It combined
12 favourable effects of manioc peel and charcoal. Manioc peel improved soil fertility
13 through its low C:N ratio and its high P content, while charcoal decreased soil acidity
14 and exchangeable Al and increased Ca and Mg availability, thus alleviating possible
15 toxic effects of Al on plant growth. The M+Ch treatment was favourable to *P.*
16 *corethrurus*, the juvenile population of which reaching a size comparable to that of the
17 nearby uncultivated soil. The application of a mixture of manioc peel and charcoal, by
18 improving crop production and soil fertility and enhancing earthworm activity, could be
19 a potentially efficient organic manure for legume production in tropical areas where
20 manioc is cultivated under slash-and-burn shifting agriculture.

21

22 **Key-words** Organic farming, Slash-and-burn cultivation, Aluminum, Phosphorus,
23 Earthworm density, Legume, Soil nutrient content

24

25 **Introduction**

26

27 In the tropics, traditional shifting cultivation still supplies food to 300-500 million families
28 (Anonymous 1985). However, in some areas, under increasing population pressure

1 and lack of cultivable land, usually farmers shorten the fallow period (Seiler and
2 Crutzen 1980; Brady 1996). Biological soil functioning is rapidly perturbed when the
3 balance between plant needs, nutrient availability and decomposer activity is disrupted
4 by the shift from traditional slash-and-burn agriculture towards permanent cultivation
5 (Myers and De Pauw 1995; Lavelle 1997). Without cheap, reliable techniques to
6 maintain the fertility of acid soils under permanent cultivation, crop production rapidly
7 decreases and poverty increases among farmers.

8

9 Considering the cost of inorganic, synthetic fertilisers for poor local farmers, and
10 significant leaching losses in sandy soils poor in organic matter, new fertilising
11 techniques in the tropics increasingly rely on the management of soil biota, a key factor
12 in soil fertility (Lavelle et al. 1989; Beare et al. 1997). Methods using green waste and
13 soil fauna activity were developed to improve crop production by stabilising nutrients
14 and organic matter within soil biogenic structures (Sparovek 1998; Senapati et al.
15 1999).

16

17 Senapati et al. (1999) improved tomato production in Peru with composted
18 sawdust, reaching the same level as with inorganic fertilizers. Several studies,
19 reviewed by Glaser et al. (2002), showed that charcoal, through its positive effects on
20 soil physical and chemical properties, can improve microbial activity and crop
21 production. In the presence of the endogeic earthworm *Pontoscolex corethrurus*
22 (Glossoscolecidae, Oligochaeta), a species adapted to tropical cultivated soils (Lavelle
23 et al. 1987), we previously found that yard-long bean (*Vigna unguiculata sesquipedalis*
24 L.) production was improved by amendment with manioc peel and to a lesser extent by
25 charcoal. These two amendments, respectively, increased P availability and decreased
26 soil acidity (Topoliantz, unpublished doctorate thesis). In Latin America and Africa,
27 bitter manioc (*Manihot esculenta utilissima* Crantz) is widely cultivated for its tubers
28 (Guillaumet 1996), and their peel, produced in large quantity, provides a potentially

1 valuable green waste that can be used for vermicomposting despite its cyanide toxicity
2 (Mba 1983, 1996).

3

4 Tian et al. (1997) found that combining mulches of different quality could help to
5 synchronize nutrient supply with plant needs. The goal of our present study was to test
6 the combined effects of manioc peel, charcoal and sawdust on yard-long bean
7 production, in the true conditions of subsistence farming. Considering the whole
8 agroecosystem plant-soil-fauna, we also determined how mulches affected the soil
9 nutrient content and the earthworm populations as compared with unamended soil. The
10 trial was carried out in the local farming context in order to provide new cheap solutions
11 to improve crop yields in the tropics.

12

13 **Materials and methods**

14

15 Site and soil amendment

16

17 The experimental study was conducted in French Guiana at Maripasoula ($3^{\circ}39'N$;
18 $54^{\circ}2'W$) in a local farmer's field (Topoliantz et al. 2002). The soil was an Oxisol with
19 58% sand, 14% silt, 24% clay, and 3% organic matter in the top 10 cm. Soil
20 preparation for legume culture was carried out according to local practices. In April
21 2001 the natural herb layer was cut and the soil was hoe-harrowed to 20 cm depth. At
22 the soil surface, rows of different organic mixtures composed of weakly composted
23 manioc peel (M), local home-made charcoal (Ch) and fresh sawdust from a local
24 sawyer (Sw) were applied at the rate of 100 L per row (67 L.m^{-2}). The chemical
25 composition of M, Ch and Sw is presented in Table 1. Equal volumes of organic wastes
26 were mixed together and were covered with soil to form mounds, as in traditional
27 practice. There were four mounds amended with M+Ch, M+Sw, Ch+Sw, and
28 M+Ch+Sw and a control mound made of non-amended soil (NoA), each 25 cm wide

1 and 6 m long, placed at 1 m distance from each other, parallel to the gentle land slope.
2 Lack of space and allowance for traditional methods of cultivation prevented us to
3 impose a randomized block design on the local farmer who kindly accepted to perform
4 the experiment on his own land.

5

6 Crop production and plant sampling

7

8 Four months after incorporating organic mixtures to the soil, i.e. in October 2001, seeds
9 of yard-long bean (*V. unguiculata sesquipedalis*) were sowed in the mounds, with pairs
10 of seeds in holes about 40 cm apart. Two months later, i.e. in December 2001, plants
11 were harvested by hand, paying attention to the root system, and the survival rate was
12 measured. Aerial parts were separated from root systems, shoots were dried in
13 newspaper and root systems were preserved in ethyl alcohol until laboratory analysis.
14 Legume nodules were isolated from roots, then all plant parts (shoots, pods, roots and
15 nodules) were dried at 105°C and weighed. Aphids present on root systems were
16 collected from the fixative and counted.

17

18 Earthworm sampling

19

20 Earthworms were sampled in the mounds at the time of crop harvesting (December
21 2001) according to the TSBF method (Anderson and Ingram 1993). Four soil blocks 25
22 cm x 25 cm x 30 cm were collected 2 m apart on the ridge of each mound, thus
23 totalling 20 samples. Earthworm individuals and cocoons were sorted by hand and
24 counted. Earthworms were also sampled with the same method under adjacent
25 uncultivated herb vegetation. Twelve samples were taken in four rows three-meter long
26 90 cm apart. All earthworm individuals were identified as *P. corethrurus*. They were

1 sorted according to their size, as juveniles (newly hatched individuals) and adults
2 (clitellate as well as non clitellate) before being replaced in the soil.

3

4 Soil sampling and analyses

5

6 In the gaps between the five mounds, a total of eighteen (4 x 4) soil samples were
7 taken for determining the composition of the original soil at the time of soil preparation
8 (April) and checking for gradients of soil fertility in the experimental field (Table 2). At
9 the time of harvest (December) eleven soil blocks per experimental mound, each 7 cm
10 x 7 cm area from 0-10 cm depth, were collected at different places of the ridges, thus
11 totalling 55 samples. The soil was air-dried before transport to the laboratory for
12 chemical analyses: organic C and N according to ISO 10694 and 13878, respectively
13 (Anonymous 1999), soil acidity (pH_{water} and pH_{KCl}), total P (P_{tot}) and available P (P_{av} ,
14 Olsen method), total K (K_{tot}), cation exchange capacity (hexamine cobalt extraction),
15 exchangeable K (K_{ex}), Mg (Mg_{ex}), Ca (Ca_{ex}), Na (Na_{ex}) and Al (Al_{ex}) according to Baize
16 (2000). The base saturation of the sorption complex (S/CEC, S=sum of exchangeable
17 K, Mg, Ca and Na) was calculated. Cyanide contents were measured according to NF
18 T90-107 (Anonymous 2001) in soil samples as well as in three samples of weakly
19 composted manioc peel which had been dried for 48h at 105°C.

20

21 Statistical analysis

22

23 Crop, earthworm and soil chemical data were statistically analysed (Glantz, 1997).
24 Differences between rows (six) and slope positions (three) in chemical properties of the
25 original soil were tested by two-way ANOVA without replication. The effects of
26 treatments (M+Ch, M+Sw, Ch+Sw, M+Ch+Sw and NoA) on crop, earthworm and soil
27 data were tested by one-way ANOVA (data were log-transformed when necessary) or
28 Kruskall-Wallis rank tests when assumptions of ANOVA were not fully satisfied even

1 after log transformation. Multiple comparisons among means or between groups were
2 done *a posteriori* using Tukey's test or Dunn's test following ANOVA or Kruskall-Wallis
3 rank test, respectively. The effect of treatments on plant survival was tested by χ^2 .
4 Relationships between nodules, pods, shoot, root and aphids were tested by
5 Spearman rank correlation coefficients. Comparisons of cocoon and earthworm
6 abundances between natural fallow and other treatments were made using Dunnett's
7 method. The chemical composition of the initial soil (between mounds) and that of the
8 non-amended mound (NoA) were compared by t-test.

9

10 Results

11

12 There were no detectable differences between the six rows (four rows between
13 mounds and two outside) in the 15 soil parameters which were measured on the initial
14 (uncultivated) soil (Table 2). Only two out of 15 parameters showed a (weak, although
15 significant at P 0.05 level) slope effect: the P content decreased from 198 to 160
16 mg.kg⁻¹ from up- to downslope and the base saturation was maximum downslope
17 (67%) and minimum at mid slope (48%). Given the absence of differences between
18 rows and because replication was achieved along the slope within each treatment, we
19 considered that treatments effects were not biased by spatial heterogeneity, despite
20 the absence of block design.

21

22 The survival rate of bean (number of shoots living at the time of harvest against
23 number of seeds planted) was only weakly affected by treatments ($\chi^2 = 9.38$, P=0.052),
24 although in NoA the observed survival rate was higher than in other treatments. Pod
25 production (per shoot) was higher in M+Ch than in Ch+Sw and NoA treatments where
26 it was nil or near nil (Fig. 1). The effects of treatments on other plant parameters are
27 presented in Table 3. The dry weight of shoots and the shoot:root ratio were higher in
28 the presence of amendments (M+Ch, M+Sw, Ch+Sw, M+Ch+Sw) but did not differ

1 among amendments. The shoot:nodule ratio was higher in M+Ch than in NoA and the
2 root:nodule ratio was not affected by treatments.

3

4 Aphid density (number of individuals per g of dry root, 4.2 in average) was not
5 affected by treatments ($H= 0.574$, $P= 0.97$).

6

7 Figure 2 shows the distribution of cocoons, juvenile and adult/subadult *P.*
8 *corethrurus* under each treatment and the natural fallow, at the time of harvest
9 (December). As a consequence of cultivation, a decrease was observed in juvenile
10 densities compared to the natural fallow, except under M+Ch amendment. Only M+Sw
11 decreased cocoon densities compared to the natural fallow. No general decrease and
12 no differential effect of treatments was observed in the adult/subadult population.

13

14 At the time of harvest, all soil nutrients except Na were significantly influenced
15 by treatments (Table 4). A higher pH_{water} was found in treatments using charcoal
16 (M+Ch, M+Ch+Sw and Ch+Sw) and the highest pH_{KCl} was observed in the M+Ch
17 treatment. Whatever the method used to measure pH, NoA was the most acidic. The
18 C:N ratio was highest in amendments containing sawdust (M+Sw, Ch+Sw, M+Ch+Sw).
19 Cation Exchange Capacity (CEC) was lowest in Sw+Ch and M+Sw+Ch treatments and
20 highest in NoA. In this latter treatment, we found the highest rate of exchangeable Al
21 and the lowest rate of exchangeable Mg, Ca and base saturation, the reverse being
22 observed in the M+Ch treatment.

23

24 When compared to the composition of the original soil (Table 1), NoA exhibited
25 a lower C:N ratio ($t= 4.7$, $P< 0.001$), pH Water ($t= 5$, $P< 0.001$) and pH KCl ($t= 3.5$, $P=$
26 0.001) and a higher exchangeable Al level ($t= -3.7$, $P< 0.001$). Most cyanide levels
27 were below the detection limit ($<0.1 \text{ mg.kg}^{-1}$) except for three samples in the M+Sw+Ch

1 treatment which showed a very low cyanide content (0.11, 0.11 and 0.12 mg.kg⁻¹) as
2 compared with manioc peel (3.6 mg.kg⁻¹).
3

4 **Discussion**

5

6 The development of aerial parts of *V. unguiculata sesquipedalis* L. was improved by
7 amending mixtures as compared with non-amended soil. When nutrients are scarce,
8 plants develop their root system at the expense of shoot growth (Taiz and Zeiger
9 1998). Nodulation was reduced by amendment, suggesting a poorer mineral N
10 availability in the unamended soil (Salisbury and Ross 1985). In the absence of
11 amendment we also observed a higher soil acidity compared with amended as well as
12 initial soil. A high level of Al, often observed at low pH in the soil solution (Nair and
13 Prenzel 1978), may be detrimental to cultivated plants by reducing root growth and
14 uptake of P, Mg and Ca by roots (Foy 1974). The amendments did not exert any
15 depressive effect on aphids, confirming that in this trial these sucking insects drain the
16 sap flow without affecting plant growth (Salisbury and Ross 1985).

17

18 Pod production was highest in treatments with manioc peel, especially when
19 supplemented with charcoal rather than sawdust. This result confirmed those obtained
20 in our previous bioassay (Topoliantz et al. 2002), in which manioc peel amendment
21 alone was the most productive treatment compared with charcoal, sawdust and non-
22 amended soil. We attribute the beneficial effect of manioc peel to a higher P
23 availability, the effect being reinforced in the presence of *P. corethrurus*, which
24 stimulates the mineralisation of microbial P (Barois et al. 1987; Brown 1995).
25 Phosphorus and K levels in manioc peel were estimated to 2.26 g kg⁻¹ and 10.3 g kg⁻¹,
26 respectively, thus higher than in charcoal (0.268 g kg⁻¹ and 5.05 g kg⁻¹) and far higher
27 than in sawdust (0.0633 g kg⁻¹ and 0.347 g kg⁻¹). However, at harvest time we did not
28 detect any increase in available P in the soil under manioc peel, except when manioc

1 peel were added together with charcoal and sawdust (Table 4). Given that pod
2 production was maximized under manioc peel amendment (Table 3) and that soil
3 collection for chemical analyses (Table 4) was done at harvest, we cannot discard that
4 at least part of the added P (38 g.m^{-2}) was mineralized then taken up by crop plants,
5 thus could not be detected in the soil. The negative effect of sawdust on pod production
6 (Table 3) could be due to N immobilization, which has been repeatedly reported to
7 occur in decaying wood (Swift 1977; Edmonds 1987).

8

9 At the time of harvest Al availability in the soil was lowest in the presence of a
10 mixture of manioc peel and charcoal (Table 4). Charcoal, by increasing pH, diminishes
11 mobile forms of Al (Tan 1982). We found that the soil amended with charcoal
12 presented also higher levels of exchangeable Ca and Mg. Several studies previously
13 showed that charcoal as well as its ashes increase the availability of P, K, Mg and Ca
14 and decrease that of toxic elements such as heavy metals (Fe, Mn and Zn) (Tryon
15 1948; Kishimoto and Sugiura 1985; Voundi Nkana et al. 1998). This effect can be
16 attributed to the porous nature of charcoal, rather than to a liming effect, given its
17 scarcity in nutrients when compared to manioc peel (Table 1). Charcoal exhibits a high
18 internal surface (Carcaillet and Thinon 1996) which increases in the course of time and
19 becomes progressively oxidised (Chan et al. 1999). Once chemically activated,
20 charcoal acts as a filter and retains positively as well as negatively charged mineral
21 ions in an exchangeable form (Holl and Horst 1997). Kishimoto and Sugiura (1985)
22 showed that charcoal also improved soil porosity and moisture holding capacity, which
23 led to better plant and root growth. In our study, lower soil acidity and toxic metals and
24 higher rate of macro-nutrients were observed when charcoal was combined with
25 manioc peel (with a high phosphorus content); this led also to better plant growth. We
26 suspect a synergistic effect of these two amendments due to the high surface area of
27 charcoal that confers a high sorptive capacity for chemical compounds (Titoff 1910;
28 Zackrisson et al. 1996; Wardle et al. 1998) and microbial communities (Pietikäinen et

1 al. 2000). Given the low content of swelling clays and organic matter in tropical Oxisols
2 (Brady and Weil 1999), the existence of a stable, solid component with strong sorptive
3 properties, such as charcoal (Skjemstad et al. 1996), would help to retain mineral
4 nutrients liberated during the decomposition of organic amendments.

5

6 In contrast, soils from treatments with a mixture of manioc and sawdust
7 exhibited at harvest the lowest pH and the same low base saturation as the complete
8 mixture of manioc, sawdust and charcoal. Thus the addition of sawdust to a mixture of
9 manioc and charcoal did not provide any benefit to legume production, even
10 suggesting a negative effect of the three amendments when combined. Fresh sawdust
11 is not palatable to saprophagous biota because of its low nutrient and high phenolic
12 content (Tian et al. 1993). Thus the addition of non-composted sawdust may inhibit
13 manioc peel decomposition. It seems that the positive effect of sawdust amendment on
14 soil nutrient content may appear later than that of manioc peel because of much slower
15 decomposition.

16

17 Only the mixture of manioc and charcoal did not depress earthworm densities.
18 In the natural fallow, *P. corethrurus* juveniles and cocoons were mostly present in the
19 upper 20 cm of the soil and adults tended to live more deeply (Topoliantz, unpublished
20 doctorate thesis). Fragoso (1985) already observed the same vertical distribution of *P.*
21 *corethrurus* during the dry season. Under cultivation, adults and juveniles were mostly
22 present at greater depths than in the fallow (Topoliantz, unpublished doctorate thesis),
23 suggesting some avoidance effect of mounded soil, which was lessened under mixed
24 manioc-charcoal amendment. Presumably earthworms burrowed deeper in order to
25 avoid desiccation of the superficial soil layers, especially in non-amended cultivated
26 soil. The manioc-charcoal mixture presented as many cocoons and juveniles as the
27 natural fallow, indicating that this amendment did not interfere with *P. corethrurus*
28 reproduction.

1
2 The cyanide content of our manioc peel was very low (3.6 mg.kg^{-1}) compared
3 with that reported by Mba (1983) in decomposed peel (168.5 mg.kg^{-1}). Thus in our
4 study this amendment did not produce cyanide toxicity in the soil. We also observed
5 that soil aggregates 0.2-0.6 cm (mostly earthworm faeces) were negatively correlated
6 with soil acidity (Topoliantz, unpublished doctorate thesis), indicating that charcoal,
7 which increased pH, favoured juvenile earthworm activity. Although *P. corethrurus* is
8 known to tolerate soil acidity (Lavelle et al. 1987), juveniles are apparently more
9 sensitive to this factor, and thus any treatment increasing pH will favour this peregrine
10 species which is able to ingest charcoal and mix it with the original soil (Topoliantz and
11 Ponge 2003).

12
13 Under conditions that can be managed by subsistence farmers the combination
14 of charcoal and manioc peel offers a cheap, reliable method to alleviate Al toxicity and
15 to increase the nutrient status of acid tropical soils, through the buffer and filter power
16 of charcoal and the input of P by manioc, thus improving legume production. It also
17 provides favourable conditions for earthworm reproduction, allowing the maintenance
18 of the fragile equilibrium between producers (plants) and decomposers (microbes, soil
19 fauna) under tropical agriculture. As manioc peel are rapidly decomposed by soil biota,
20 this amendment will have to be regularly added, whereas charcoal does not need to be
21 supply repeatedly, being persistent in the soil (Glaser et al. 2001). Farther, excess of
22 charcoal could even depress plant growth due to a too high alkalinity (Kishimoto and
23 Sugiura 1985).

24
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- 13

1 **Legends**

2

3 **Fig. 1.** Mean pod production of *Vigna unguiculata sesquipedalis* (yard-long bean)
4 according to treatments (M: manioc peel, Ch: charcoal, Sw: sawdust, NoA: non-
5 amended soil) with standard error. Numbers of replicates are shown in Table 2. Groups
6 significantly different are denoted by different letters. Kruskal-Wallis rank analysis ($H =$
7 18.5, $P < 0.001$) was followed by a posteriori Dunn's tests.

8

9 **Fig. 2.** Mean densities of cocoons, juveniles and adults/subadults of the earthworm
10 *Pontoscolex corethrurus* according to treatments (4 replicates each) and in the natural
11 fallow (12 replicates), with standars errors. Treatment effects were compared by one-
12 way ANOVA (F). Significance of F for each developmental category is indicated by
13 * $P < 0.05$, *** $P < 0.001$. Groups significantly different are mentioned by different letters.
14 One-way ANOVA was followed by comparisons between amendments and natural
15 fallow using Dunnett contrasts.

16

Table 1. Chemical composition of the different amendments (Topoliantz et al. 2002)

	Manioc peels	Wood charcoal	Sawdust
pH (H_2O)	6.72	9.60	5.31
Ashes (%)	31.9	3.80	2.35
Total C ($\text{g}.\text{kg}^{-1}$)	356	905	521
Total N ($\text{g}.\text{kg}^{-1}$)	24.2	5.64	5.13
C:N ratio ($\text{g}.\text{kg}^{-1}$)	14.71	160	102
Total P ($\text{g}.\text{kg}^{-1}$)	2.26	0.27	0.06
1 Total K ($\text{g}.\text{kg}^{-1}$)	10.3	5.05	0.35

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Table 2. Chemical soil composition of the initial soil in the upper 10 cm (means of 16 replicates \pm S.E.).

pH H ₂ O	4.75 \pm 0.05
pH KCl	3.84 \pm 0.03
Total C (g.kg ⁻¹)	20.6 \pm 0.8
Total N (g.kg ⁻¹)	1.34 \pm 0.04
C:N ratio	15.3 \pm 0.3
Total P (mg.kg ⁻¹)	179 \pm 6
Available P (mg.kg ⁻¹)	17.3 \pm 4.8
Total K (mg.kg ⁻¹)	944 \pm 47
Exchangeable K (mg.kg ⁻¹)	2.52 \pm 0.22
Exchangeable Ca (mg.kg ⁻¹)	21.3 \pm 1.9
Exchangeable Mg (mg.kg ⁻¹)	10.8 \pm 1.2
Exchangeable Na (mg.kg ⁻¹)	0.69 \pm 0.08
Exchangeable Al (mg.kg ⁻¹)	7.97 \pm 0.91
CEC (cmol _c /kg)	2.48 \pm 0.08
Base saturation (%)	55.7 \pm 3.9

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Table 3. Biological parameters of *Vigna unguiculata sesquipedalis* according to treatments (M: manioc peels, Ch: charcoal, Sw: sawdust, NoA: non-amended soil). Effects of treatments were tested by one-way ANOVA (F) or Kruskall-Wallis rank test (H). Significance levels are indicated by *P < 0.05, ** P<0.01, *** P < 0.001, N.S. not significant. Groups significantly different according to a posteriori multiple comparisons are denoted by different superscript letters. All weights and ratios are based on dry weights of plant parts

	M+Ch	M+Sw	Ch+Sw	M+Ch+Sw	NoA	Tested statistics
Number of shoots	9	7	7	5	13	
Shoot weight (g dry wt)	7.08±1.92 ^a	7.43±1.51 ^a	3.92±0.83 ^a	5.76±2.42 ^a	0.64±0.08 ^b	F = 18.6***
Shoot:root ratio (wt:wt)	7.92±0.52 ^a	8.12±0.69 ^a	7.78±1.34 ^a	8.73±1.17 ^a	3.84±0.35 ^b	F = 9***
Pod production:shoot ratio (wt)	0.31±0.08 ^a	0.11±0.08 ^{ab}	0±0 ^b	0.07±0.03 ^{ab}	0.08±0.04 ^{ab}	H = 14.3**
Pod production:root ratio (wt:w)	2.39±0.61 ^a	0.95±0.63 ^{ab}	0±0 ^b	0.67±0.28 ^{ab}	0.24±0.13 ^b	H = 17.9***
Shoot:nodule ratio (wt:wt)	2409±823 ^a	1046±373 ^{ab}	1300±891 ^{ab}	712±395 ^{ab}	384±82 ^b	H = 13.9**
Root:nodule ratio (wt:wt)	295±101	154±64	126±59	90.9±59.9	98.8±17.7	H = 9 N.S.

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Table 4. Nutrient contents of the soil at the end of the trial according to treatments (means of 11 samples \pm SEM). Otherwise as for Table 2.

	M+Ch	M+Sw	Ch+Sw	M+Ch+Sw	NoA	Tested statistics
pH H ₂ O	4.88 \pm 0.03 ^a	4.62 \pm 0.05 ^b	4.81 0.06 ^a	4.88 \pm 0.04 ^a	4.40 \pm 0.04 ^c	F = 21.3***
pH KCl	4.00 \pm 0.04 ^a	3.74 \pm 0.02 ^{cd}	3.84 \pm 0.03 ^{bcd}	3.87 \pm 0.02 ^b	3.67 \pm 0.02 ^d	F = 21.3***
Total C (g.kg ⁻¹)	21.4 \pm 1.2 ^{bc}	29.1 \pm 2.2 ^{ab}	26.0 \pm 2.8 ^{abc}	32.5 \pm 3.2 ^a	19.6 \pm 0.6 ^c	F = 5.8**
Total N (g.kg ⁻¹)	1.27 \pm 0.08 ^{ab}	1.45 \pm 0.06 ^a	1.07 \pm 0.05 ^b	1.36 \pm 0.07 ^a	1.46 \pm 0.03 ^a	F = 7.7***
C:N ratio	16.6 \pm 0.4 ^{bc}	19.9 \pm 1.1 ^{ab}	23.8 \pm 1.7 ^a	23.5 \pm 1.5 ^a	13.4 \pm 0.1 ^c	H = 37.2***
Total P (mg.kg ⁻¹)	171 \pm 11 ^{ab}	175 \pm 7 ^{ab}	159 \pm 21 ^b	167 \pm 8 ^{ab}	212 \pm 15 ^a	H = 16.8**
Available P (mg.kg ⁻¹)	14.9 \pm 0.7 ^{bc}	17.6 \pm 0.8 ^{ab}	13.0 \pm 0.7 ^c	18.1 \pm 0.8 ^a	15.0 \pm 0.5 ^{bcd}	F = 9***
Total K (mg.kg ⁻¹)	736 \pm 31 ^{bc}	836 \pm 39 ^b	673 \pm 41 ^c	891 \pm 58 ^b	1091 \pm 28 ^a	F = 15.7***
Exchangeable K (mg.kg ⁻¹)	2.67 \pm 0.20 ^b	5.05 \pm 0.33 ^a	2.59 \pm 0.30 ^b	4.66 \pm 0.45 ^a	2.20 \pm 0.11 ^b	F = 21.2***
Exchangeable Ca (mg.kg ⁻¹)	24.4 \pm 1.3 ^a	15.5 \pm 0.6 ^b	17.7 \pm 0.6 ^b	16.5 \pm 1.0 ^b	16.4 \pm 1.6 ^b	F = 10.3***
Exchangeable Mg (mg.kg ⁻¹)	4.59 \pm 0.37 ^{ab}	4.99 \pm 0.36 ^a	3.49 \pm 0.27 ^b	4.31 \pm 0.26 ^{ab}	2.23 \pm 0.14 ^c	F = 14***
Exchangeable Na (mg.kg ⁻¹)	0.77 \pm 0.06	0.73 0.04	0.69 \pm 0.07	0.73 \pm 0.09	0.56 \pm 0.06	F = 1.9 N.S.
Exchangeable Al (mg.kg ⁻¹)	3.84 \pm 0.23 ^c	6.34 \pm 0.41 ^b	4.98 \pm 0.32 ^{bcd}	5.79 \pm 0.61 ^b	12.7 \pm 0.6 ^a	F = 60.2***
CEC (cmol _c /kg)	2.42 \pm 0.11 ^{ab}	2.53 \pm 0.08 ^{ab}	2.17 \pm 0.09 ^b	2.31 \pm 0.13 ^b	2.71 \pm 0.08 ^a	F = 4.2*
1 Base saturation (%)	70.0 \pm 1.6 ^a	53.6 \pm 1.9 ^b	58.6 \pm 1.8 ^b	58.8 \pm 3.3 ^b	39.6 \pm 2.3 ^c	F = 23.3***

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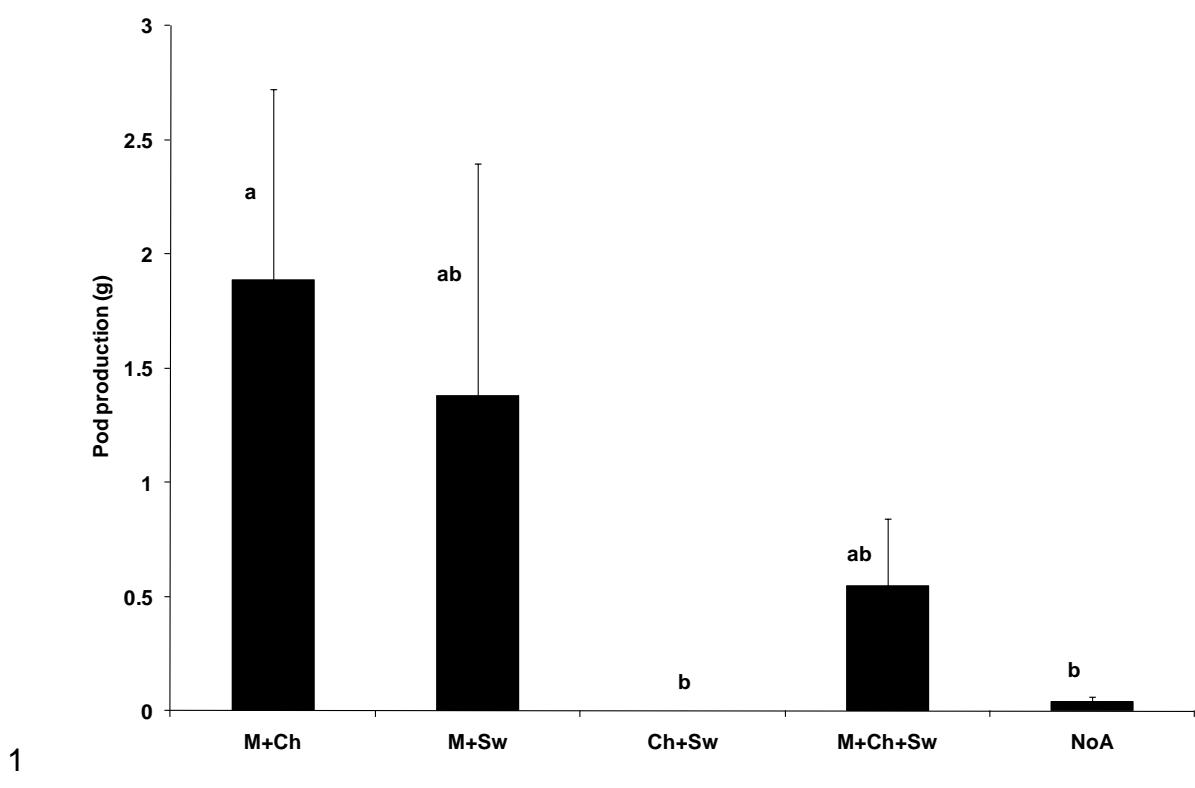
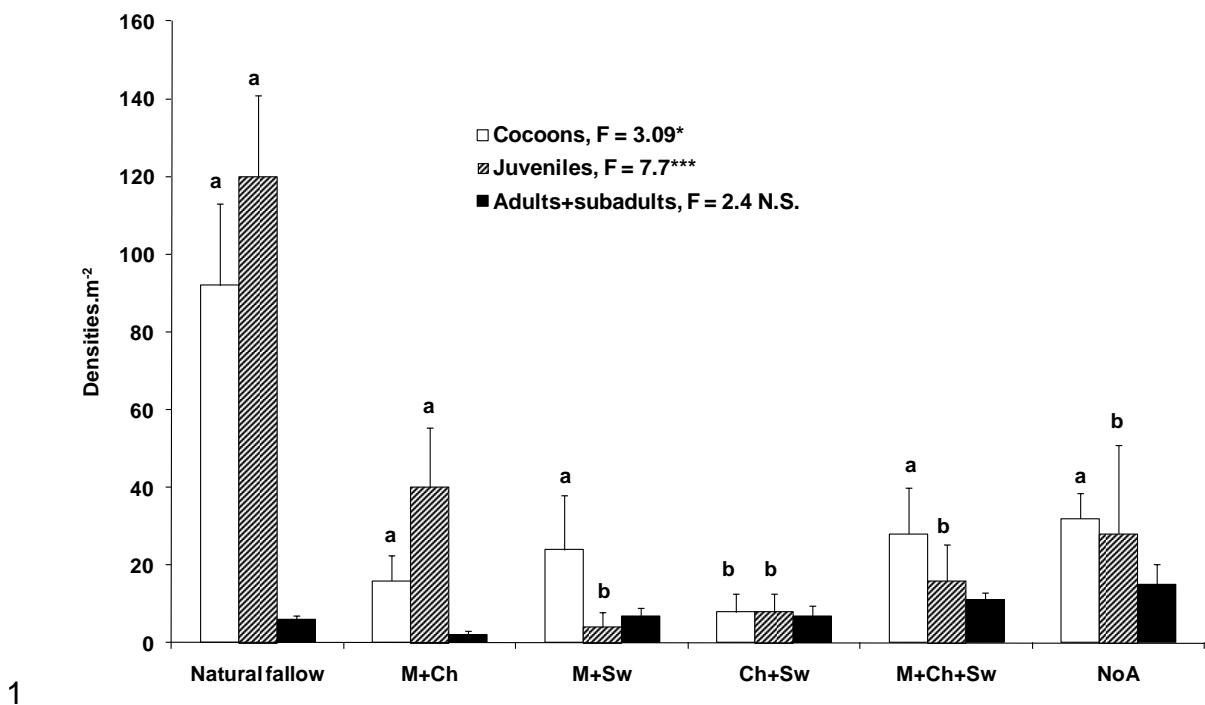


Fig. 1

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1

2 Fig. 2