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Senna siamea trees recycle Ca from a Ca-rich subsoil and increase the topsoil pH in agroforestry systems in the West African derived savanna zone

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Abstract

The functioning of trees as a safety-net for capturing nutrients leached beyond the reach of crop roots was evaluated by investigating changes in exchangeable cations (Ca, Mg, and K) and pH in a wide range of medium to long term alley cropping trials in the derived savanna of West Africa, compared to no-tree control plots. Topsoil Ca content, effective cation exchange capacity, and pH were substantially higher under *Senna siamea* than under *Leucaena leucocephala*, *Gliricidia sepium*, or the no-tree control plots in sites with a Bt horizon rich in exchangeable Ca. This was shown to be largely related to the recovery of Ca from the subsoil under *Senna* trees. The increase of the Ca content of the topsoil under *Senna* relative to the no-tree control treatment was related to the total amount of dry matter applied since trial establishment. The lack of increase in Ca accumulation under the other species was related to potential recovery of Ca from the topsoil itself and/or substantial Ca leaching. The accumulation of Ca in the topsoil under *Senna* had a marked effect on the topsoil pH, the latter increasing significantly compared with the *Leucaena*, *Gliridia*, and no-tree control treatments. In conclusion, the current work shows that the functioning of the often hypothesized 'safety-net' of trees in a cropping system depends on (i) the tree species and on (ii) the presence of a subsoil of suitable quality, i.e., clay enriched and with high Ca saturation.

Introduction

Trees in agroforestry systems in the tropics have been frequently hypothesized to recover nutrients and water from the subsoil because tree roots reach soil layers below the maximum rooting depth of annual crops (Grimme and Juo, 1985; Cadisch et al., 1997). The root safety-net zone is usually equated with that part of the soil profile from where trees recover substantial amounts of nutrients, not accessible to the associated food crop (Cadisch et al. 1997). Although trees will certainly recover some of their nutrients and water from the subsoil at certain times in the year, regular pruning of trees may change their root distribution and hence the relative amount of roots in the subsoil. Vanlauwe et al. (2002a), for instance, showed that *Senna siamea* (Lam.) H. S. Irwin & Barneby hedgerow trees that are regularly pruned, accumulate a relatively higher amount of roots in the topsoil, compared with trees that are less regularly pruned. Moreover, Aihou et al. (1999) and Tossah et al. (1999) observed that the subsoil fertility affected hedgerow tree biomass production of different species differently. In these reports, *Senna* produced less biomass on sites with a sandy profile than on sites with a heavier profile, while the biomass production of *Gliricidia sepium* (Jacq.) Kunth ex Walp and *Leucaena leucocephala* (Lam.)

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de Wit trees was less affected by the quality of the subsoil.

Technically, Integrated Soil Fertility Management (ISFM) advocates the combined use of organic inputs and fertilizer to enhance and/or sustain agricultural productivity (Vanlauwe et al., 2002b). In most environments in sub-Saharan Africa, enhancing the availability of organic resources is a major challenge. Inclusion of trees species in agricultural land has been one frequently tested option to improve the availability of organic resources as trees can potentially recover some of the nutrients and water leached beyond the crop rooting zone. On top of this, most leguminous trees can fix N from the atmosphere (Sanginga et al., 1995). In ISFM practices, the organic resources supply N but also fulfil a series of other functions such enhancing the soil available P status (Nziguheba et al., 2000), improving soil moisture conditions (Vanlauwe et al., 2001), or increasing the soil organic matter pool and/or its quality (Vanlauwe et al., 1998a, Cadisch and Giller, 2000).

Organic amendments can also increase soil pH based on their ash alkalinity or total base cation charge (Wong et al., 2000). This is an important attribute of organic resources in low input systems, which are still very common in sub-Saharan Africa, as removal of harvested products is leading to acidification (Van Breemen et al., 1983). Also in ISFM strategies this attribute is important as most commercially available N fertilizers in sub-Saharan Africa (SSA) are ammonium-based and consequently tend to decrease soil pH upon nitrification of the ammonium (Vanlauwe et al., 2001). Counteracting pH decrease is especially important in weakly buffered soils, as there are many in SSA. Wong and Swift (2003) described the biophysical principles governing the effects of organic matter in ameliorating soil acidity and discussed agroforestry systems that could be developed to exploit this phenomenon. Tang and Rengel (2003) stated that information on the effect of trees and shrubs on decreasing soil acidification in the field is limited.

The objectives of this paper are: (i) to assess the impact of hedgerow tree species on topsoil cation content for a wide range of trials in the West African derived savanna zone, (ii) to explore relationships between topsoil cation accumulation and subsoil properties, and (iii) to relate cation accumulation in the topsoil with changes in topsoil pH.

Materials and methods

Site characteristics

In this study, various medium to long term alley cropping trials were included, all established at sites in the derived savanna zone of West Africa (Jagtap, 1995) (Table 1). All trials were cropped at the time of sampling, except the Ibadan WB field trial, which was fallow since its establishment. All trials had at least the following treatments: a no-tree control, *Senna* alley cropping, and alley cropping with either *Leucaena* and/or *Gliricidia* (Table 1). *Senna* is a non-fixing leguminous tree, while *Leucaena* and *Gliricidia* are N-fixing leguminous trees.

Analysis of soil profiles from pits dug near the experimental sites under natural fallow showed that all but two of the sites had a clay accumulation horizon at about 40 cm soil depth (Figure 1). The Arenosol in Amoutchou and Cambisol on the non-degraded site in Niaouli did not show a substantial clay enrichment horizon. Soils with a clay accumulation horizon also showed a marked increase in soil exchangeable Ca and to a lesser extract Mg contents with depth (Figure 2). The exchangeable K content was below 0.2 $cmol_c$ kg^{-1} soil for all soil layers and sites (*data not shown*).

Field trial establishment and management history

The establishment and management of the trials are described in sufficient detail in other reports (Aihou et al., 1999; Salako and Tian, 2001; Tossah et al., 1999; Vanlauwe et al., 2004) (Table 1). The years of establishment varied between 1986 and 1992. The hedgerow trees in all but one trial were regularly pruned and in the sites in Benin and Togo, fertilizer was applied to all treatments (Table 1). Average yearly biomass input in the various treatments, either as prunings or as litterfall during fallow periods was presented in the other reports and varied between 1840 and 9240 kg dry matter ha^{-1} $year^{-1}$ for the *Senna* treatment and between 940 and 7442 kg dry matter ha^{-1} $year^{-1}$ for the *Leucaena* or *Gliricidia* treatments (Table 2).

Soil sampling and analysis

Soils were sampled from the 0–10 cm layer at various times after trial establishment, always before residue and/or fertilizer application (Table 1). Various auger samples were taken per plot, bulked, air-dried, sieved

Table 1. Site characteristics, treatments considered, tree management history, fertilizer use, and soil sampling dates for the various trials

Site (country)	Soil type[a]	Rainfall, distribution	Trees planted	Treatments considered	Tree management history	Soils sampled[c]	Fertilizer usage[d]
Niaouli degraded field (Benin Republic)	Rhodic Ferralsol	1200 mm, bimodal	1989	Relative control[b], *Senna siamea*, *Leucaena leucocephala*, *Gliricidia sepium*	Pruned yearly since 1990	1996	150 kg cotton fertilizer (14N-23P-14K-5S-1B-0Ca) and 50 kg urea ha^{-1}
Niaouli non-degraded field (Benin Republic)	Ferralic Cambisol	1200 mm, bimodal	1989	Relative control, *Senna siamea*, *Leucaena leucocephala*, *Gliricidia sepium*	Pruned yearly since 1990	1996	Same as above
Glidji (Togo)	Rhodic Ferralsol	900 mm, bimodal	1991	Control, *Senna siamea*, *Gliricidia sepium*	Pruned in 1992 and between 1994 and 1996; fallow in 1993	1996	45 kg Urea-N, 26 kg TSP-P and 50 kg KCl-K ha^{-1}
Amoutchou (Togo)	Haplic Arenosol	1300 mm, unimodal	1992	Control, *Senna siamea*, *Gliricidia sepium*	Pruned in 1995 and 1996; fallow in 1993 and 1994	1996	Same as above
Sarakawa (Togo)	Ferric Acrisol	1200 mm, unimodal	1992	Control, *Senna siamea*, *Gliricidia sepium*	Pruned in 1995 and 1996; fallow in 1993 and 1994	1996	Same as above
Ibadan – D2 field (Nigeria)	Ferric Lixisol	1300 mm, bimodal	1986	Control, *Senna siamea*, *Leucaena leucocephala*	Pruned yearly since 1988	1999	None
Ibadan – WB field (Nigeria)	Ferric Lixisol	1300 mm, bimodal	1989	Control, *Senna siamea*, *Leucaena leucocephala*	Left fallow since establishment	2000	None

[a] Following FAO (1991).
[b] The relative control contains oil palm trees (Aihou et al., 1999).
[c] Soils were always sampled at the start of the first season of the year mentioned in the column.
[d] Fertilizer is applied only during the years when the trees are pruned.

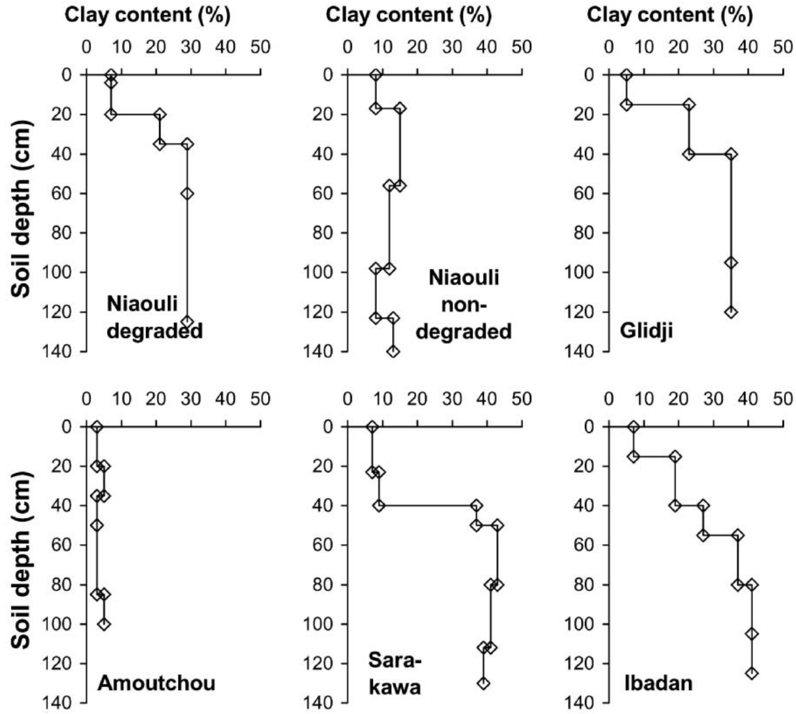

Figure 1. Clay content of the various soil layers up to 140 cm depth in the various target sites. The depth of each layer is visualised by a vertical line linking two subsequent data points, indicating the clay content of that respective layer. The data were obtained from profile pits under natural fallow near the trials.

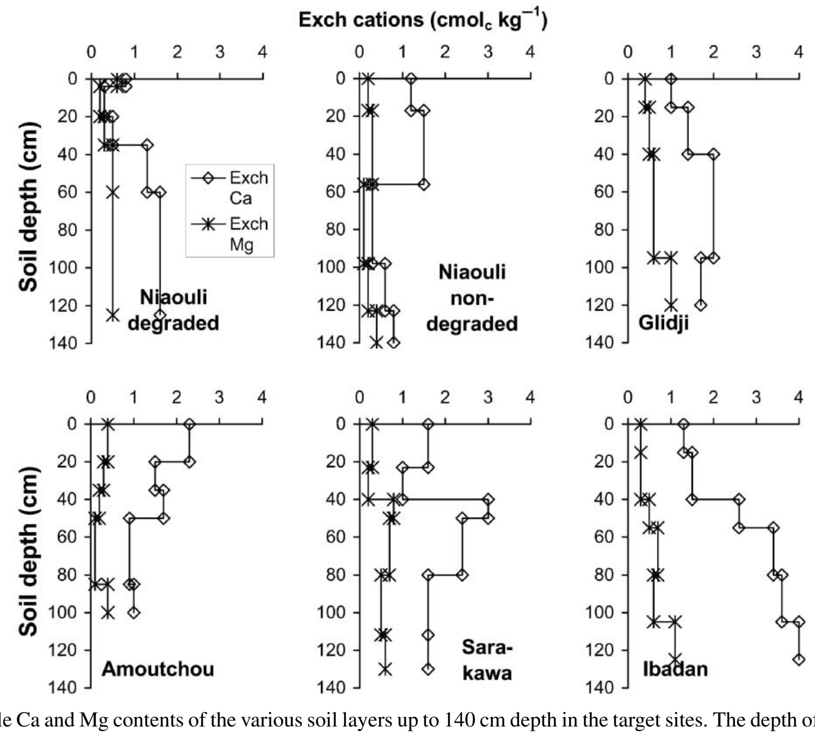

Figure 2. Exchangeable Ca and Mg contents of the various soil layers up to 140 cm depth in the target sites. The depth of each layer is visualised by a vertical line linking two subsequent data points, indicating the exchangeable Ca and Mg contents of that respective layer. The data were obtained from profile pits under natural fallow near the trials.

Table 2. Yearly organic input application rates in the various treatments with hedgerows

Site	Prunings or litterfall	Year of assessment	Treatment	Dry matter input kg DM ha^{-1} yr^{-1}	Reference
Niaouli degraded field	Prunings (2 per year)	Average of 1994 to 1996	*Senna* *Leucaena* *Gliricidia*	6030 2370 1750	Aihou et al. (1999)
Niaouli non-degraded field	Same as above	Same as above	*Senna* *Leucaena* *Gliricidia*	2480 2990 940	Aihou et al. (1999)
Glidji	Prunings (3 per year)	Average of 1995 and 1996	*Senna* *Gliricidia*	9240 2470	Tossah et al. (1999)
Amoutchou	Same as above	Same as above	*Senna* *Gliricidia*	1840 5450	Tossah et al. (1999)
Sarakawa	Same as above	Same as above	*Senna* *Gliricidia*	9750 4290	Tossah et al. (1999)
Ibadan – D2 field	Prunings (4 per year)	Average of 1991 to 1999	*Senna* *Leucaena*	5806 7059	Vanlauwe et al. (2004)
Ibadan – WB field	Litterfall	Average of 1992 and 1996	*Senna* *Leucaena*	7817 7442	Salako and Tian, (2001)

through 2 mm, and analysed for effective cation exchange capacity (ECEC), exchangeable Ca, Mg, and K content (IITA, 1982), and soil pH (soil:water 1:2.5). Details of the various soil sampling schemes are given in the reports mentioned above as are the soil data obtained at trial establishment.

Hedgerow samples, cation contents and ash alkalinity

The hedgerows in the cropped trials were pruned 2 to 4 times every year. Samples of first prunings (entire leafs with twigs smaller than 1 cm) of a single year were collected in all sites, except in Sarakawa, and their ash alkalinity was determined using the procedure proposed by Pierre and Banwart (1973). In summary, ash obtained from moistened and ground plant material, treated with 5 ml of a 25% solution of $Mg(NO_3)_2 \cdot 6H_2O$ was titrated with 0.5 N NaOH using methyl red as indicator (pH 5.3). The ash alkalinity was then calculated from the amount of base required to titrate carbon black samples minus the amount required to titrate the ash of the plant samples.

The individual cation contents of the prunings were not directly measured but the Organic Resource Database (ORD) (ftp://iserver.ciat.cgiar.org/webciat/ORD/) (Palm et al., 2001) was consulted to get reasonable estimates.

Mathematical and statistical analyses

The MIXED procedure of the SAS system (SAS, 1992) using 'treatment' as fixed factor and 'replicate' as random factor was used to determine the significance of the treatment effects, for each site separately. Significantly different means were separated with the PDIFF option of the LSMEANS statement. Regression analysis (SAS, 1985) was used to explore potential linear relationships between various attributes measured in this work.

Results

Cation content and ash alkalinity of the various prunings

Surprisingly, the standard error of the various measurements compiled in the ORD was low indicating that the estimated values are likely reasonably accurate. *Senna* leaves contained most Ca and least Mg and K, while *Gliricidia* leaves contained most Mg and *Leucaena* leaves most K (Figure 3). In all sites, except

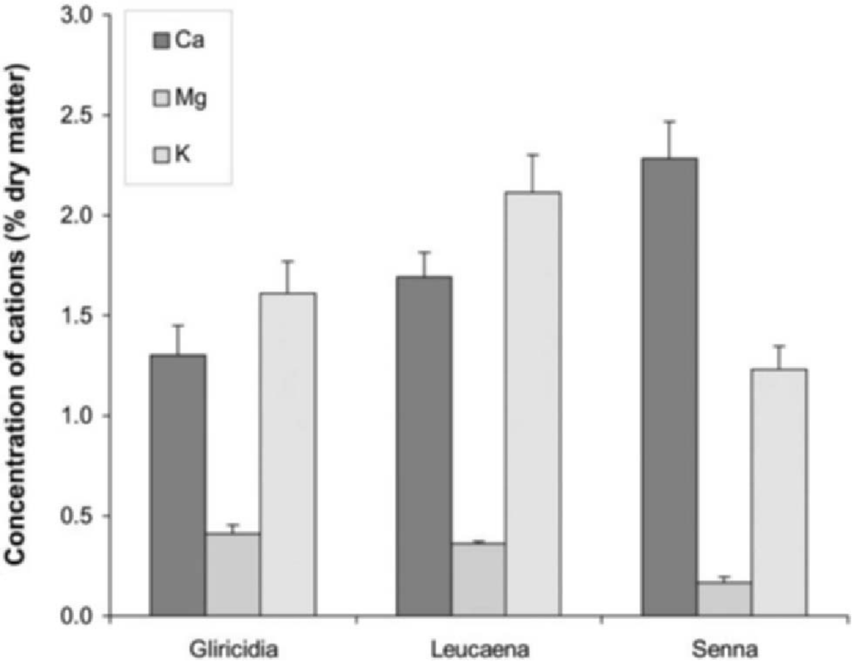

Figure 3. Estimated Ca, Mg, and K contents of *Senna*, *Gliricidia*, and *Leucaena* leaf residues, as extracted from the Organic Resource Database. All data currently in the database were used for the calculations. The number of entries used to calculate the presented values varied between 3 (*Senna* Mg content) and 19 (*Gliricidia* K content). The error bars are standard errors of the mean.

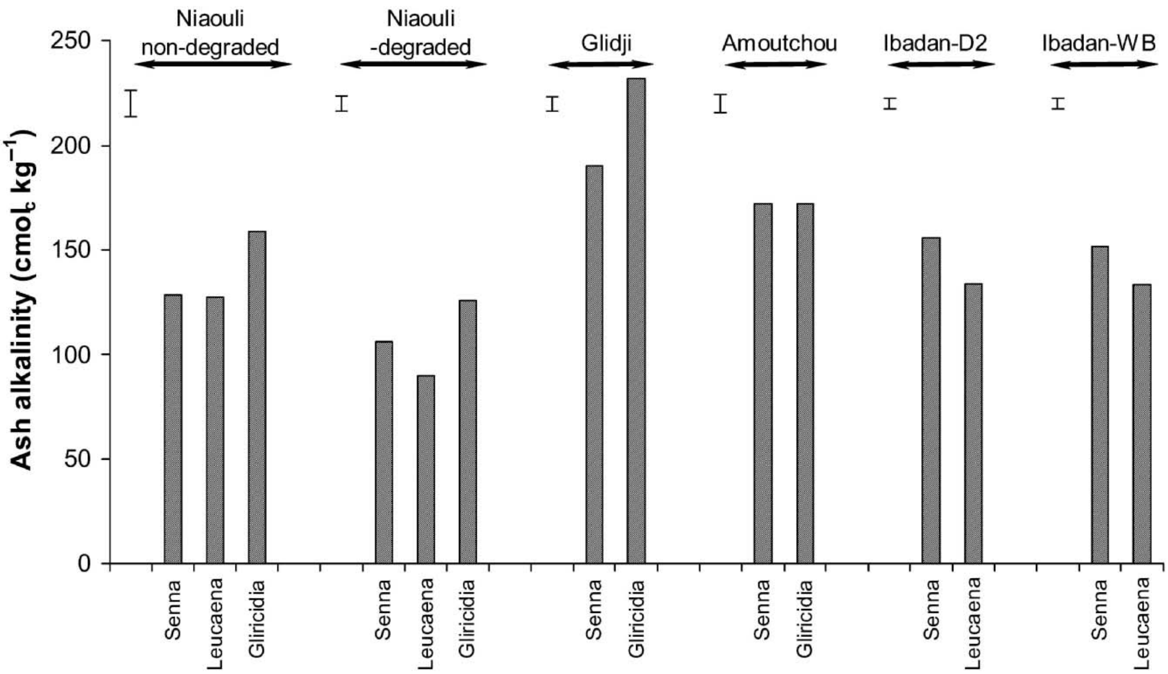

Figure 4. Ash alkalinity of the prunings obtained in the treatments used in this report. Data from Sarakawa were not available. Error bars are standard errors of the difference, calculated for each site.

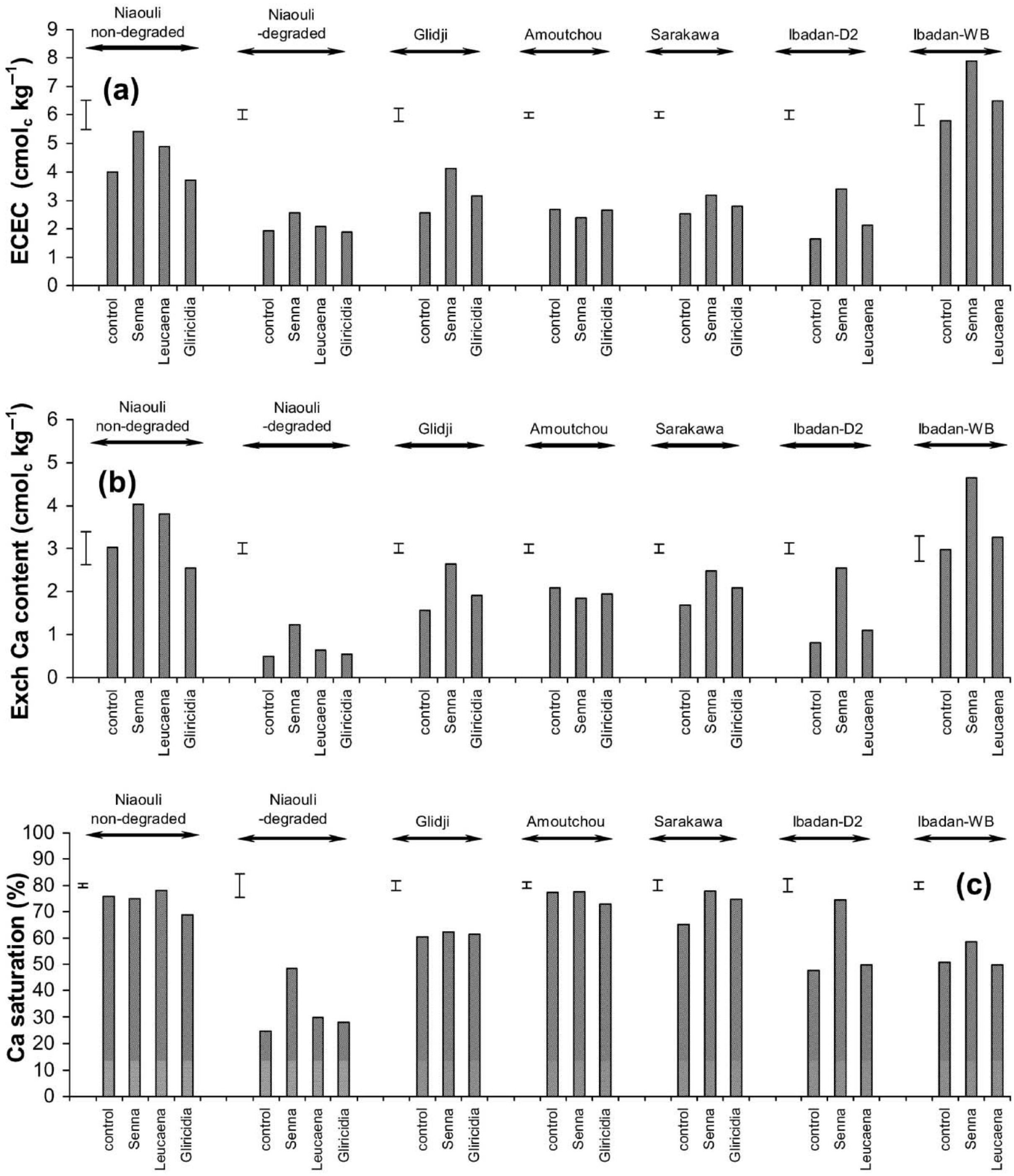

Figure 5. Effective cation exchange capacity (ECEC) (a), exchangeable Ca content (b), and Ca saturation of the ECEC (c) of the topsoil (0–10 cm) in the various trials included in this report. Error bars are standard errors of the difference, calculated for each site. Sampling times are given in Table 1.

in Amoutchou, the *Gliricidia* prunings had a significantly higher ash alkalinity than the *Leucaena* or the *Senna* prunings (Figure 4). In both Ibadan fields, the *Senna* prunings had a significantly higher ash alkalinity than the *Leucaena* prunings. Ash alkalinity was highest in Glidji, and lowest on the Niaouli degraded site (Figure 4).

Topsoil cation content and pH

The ECEC of the topsoil was significantly higher in the *Senna* than in the control and *Leucaena/Gliricidia* treatments in the Glidji and both Ibadan trials (Figure 5a). At the Sarakawa site, the *Senna* treatment had a larger ECEC than the control treatment. The exchangeable Ca content of the topsoil was significantly higher in the *Senna* than in the control and *Leucaena/Gliricidia* treatments in the Niaouli degraded field, in the Glidji field, and in both fields in Ibadan (Figure 5b). In the Sarakawa site, the *Senna* treatment contained significantly more topsoil Ca than the control treatment. In the Niaouli non-degraded field and the Amoutchou field, the treatment effect was not significant, although in the Niaouli field this was due to the high site variability. The *Senna* treatment contained between 1.2 and 4.5 $cmol_c$ Ca kg^{-1} (Figure 5a). Ca saturation was significantly higher in the Senna than in the other treatments in the Niaouli degraded and both Ibadan sites (Figure 5c). In Sarakawa, the *Senna* treatment showed a larger Ca saturation than the control treatment.

The exchangeable Mg and K contents of the topsoil were only significantly different between treatments in the Ibadan WB field (for both Mg and K) and in the Amoutchou field (for Mg alone) (*data not shown*). In both sites, the exchangeable K content was higher in the alley cropping than in the control treatment, while in the Amoutchou site, the *Gliricidia* treatment contained more exchangeable Mg than the two other treatments (*data not shown*).

The topsoil pH was significantly higher in the *Senna* treatment than in the control and *Leucaena/Gliricidia* treatments in the Niaouli degraded field, and in the Ibadan D2 and WB fields (Figure 6). In the Sarakawa site, the *Senna* treatment had a significantly higher topsoil pH than the control treatment, while in the Glidji site, this was true for the *Gliricidia* treatment. In the Niaouli non-degraded field and the Amoutchou field, treatment had no significant effect on topsoil pH, although in the Niaouli field this was due to the high site variability (Figure 6).

Relationship between the topsoil cation content and soil profile and field management

A highly significantly linear relationship was observed between the excess Ca content of the topsoil relative to the no-tree control soil and the weighed Ca content of the 40–100 cm subsoil (Figure 7). Such relationship was not observed for the *Leucaena* and *Gliricidia* treatments as the Ca content of these treatments was not significantly different from the Ca content of the no-tree control treatments.

Discussion

In the studied trials, the *Senna* trees were recovering Ca from the subsoil and enriching the topsoil with Ca, but only at the sites with a Bt horizon and where exchangeable Ca content increased substantially with soil depth. Evidence for this can be found in the relative enrichment of the exchange complex with Ca relative to the no-tree control for the Niaouli degraded, Ibadan D2, and Ibadan WB sites (Figure 5c). Such enrichment can only occur if the trees recover part of their Ca from layers beyond the topsoil that have a relatively higher Ca saturation (Figure 2). After all, if these trees would recover most of their Ca needs from the topsoil, then the topsoil Ca content would be at most as high as the topsoil Ca content of the no-tree control treatment. Moreover, not only does the relative enrichment with Ca increase but also the total ECEC, as a result of higher topsoil C contents after long term application of *Senna* residues (Vanlauwe et al., 2004), indicating an even larger input of Ca from other than the topsoil layers. On the two sites without Ca enrichment in subsoil horizons (the Amoutchou and Niaouli non-degraded sites), the topsoil enrichment does not occur and tree biomass production was severely restricted (Table 2). *Senna* appears to be unable to compete with a crop (in the cropped alley cropping systems) or the weed vegetation (in the fallow plots) for topsoil nutrients. This is in sharp contrast with the *Leucaena* and *Gliricidia* trees. These trees are fast-growing and may thus more readily benefit from periods with high topsoil moisture content at early crop establishment, i.e., when the demand for nutrients by the food crop is relatively low. As the trials in Glidji and Sarakawa were established more recently, no significant enrichments of Ca can be observed yet, although a similar trend is developing.

The accumulation of Ca in the topsoil of the *Senna* treatments varied for the different sites and appeared to

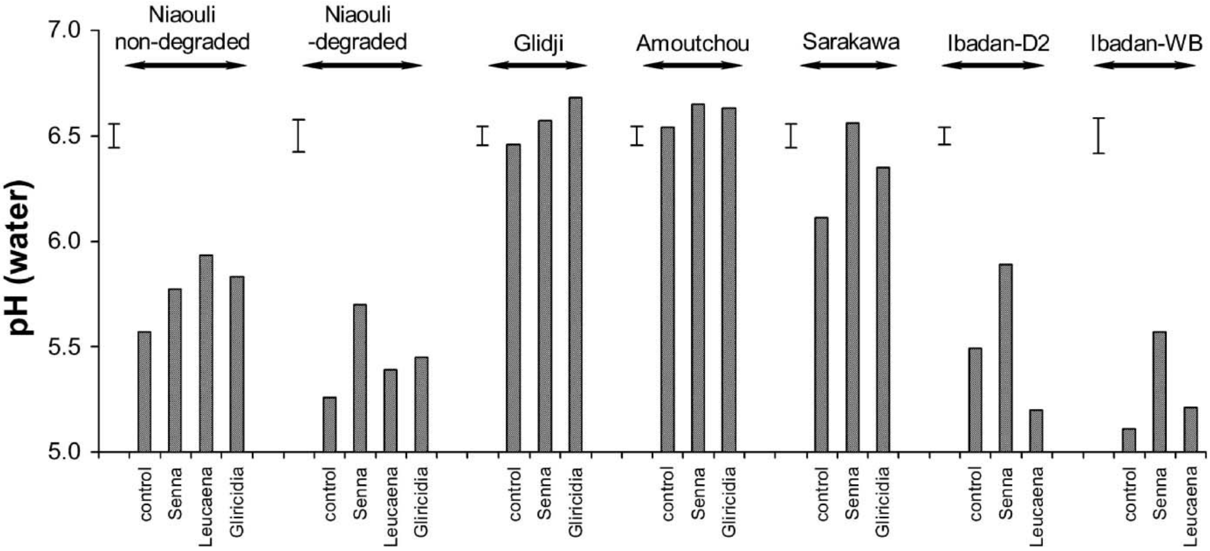

Figure 6. Soil pH in water of the topsoil (0–10 cm) in the various trials included in this report. Error bars are standard errors of the difference, calculated for each site. Sampling times are given in Table 1.

be related to the Ca content of the clay accumulation horizon (Figure 7) whereby sites without clay accumulation horizon (Amoutchou, Niaouli non-degraded) did not show any significant Ca accumulation in the topsoil. Care has to be taken, however, when interpreting this relationship as the sites with the highest subsoil Ca content were also initiated earliest (Table 1, Figure 2). The excess Ca content of the *Senna* treatment appeared to be related closely to the total estimated amount of dry matter added since trial establishment (Figure 8a) while the yearly dry matter input was related to the subsoil Ca content (Figure 8b). The latter figure suggests that subsoil Ca contents below 1.5 $cmol_c$ kg^{-1} seem to restrict *Senna* biomass production. *Senna* trees are often depicted as strong competitors for nutrients based on observations of roots present as far as 15 m away from the tree base (Hauser, 1993). However, as previously stated by Aihou et al. (1999) and Tossah et al. (1999), if the *Senna* trees really would recover a substantial amount of their nutrients through sideward exploitation of the topsoil then the biomass produced by the *Senna* trees on the poor soils (Amoutchou, Niaouli non-degraded) would have been most likely higher than the observed values, because of the presence of more fertile plots in the vicinity of the *Senna* trees in both these sites. Otherwise stated, competition for nutrients between *Senna* and crops would only occur in situations where no benefits from the alley can be expected due to poor biomass production, in turn caused by lack of subsoil nutrient reserves.

The stocks of exchangeable Ca content of the topsoil depend on the Ca application rates (organic matter, fertilizer, and atmospheric deposition), the conversion to exchangeable forms, the ECEC of the topsoil, and the removal of Ca with harvested products and through leaching losses beyond the topsoil. While estimated Ca application rates in the *Leucaena* and *Gliricidia* treatments varied between 12 and 125 kg Ca ha^{-1} yr^{-1}, this did not result in an accumulation of Ca in the topsoil relative to the no-tree controls. This is certainly not the result of substantial differences in Ca removal, as Ca removal with maize grains is usually not exceeding 2 kg ha^{-1} per crop (Wichmann, 1998). Delays in conversion of Ca from residue-bound into exchangeable forms also can not explain the lack of increase in the exchangeable Ca pool as *Leucaena* and *Gliricidia* prunings are known to release over 80% of their initial Ca content within 100 days under field conditions (Tian et al., 1992). As the ECEC of the control and *Leucaena/Gliricidia* treatments is also not significantly different, this indicates that either all Ca applied is leached beyond the topsoil or that most of the Ca taken up by the *Leucaena* or *Gliricidia* aboveground biomass is recycled from the topsoil. As for leaching, this would require an equal amount of anions to leach, where nitrate would be the predominant one, most of it derived from the residue applications. Previous studies looking at N recovery of ^{15}N labelled

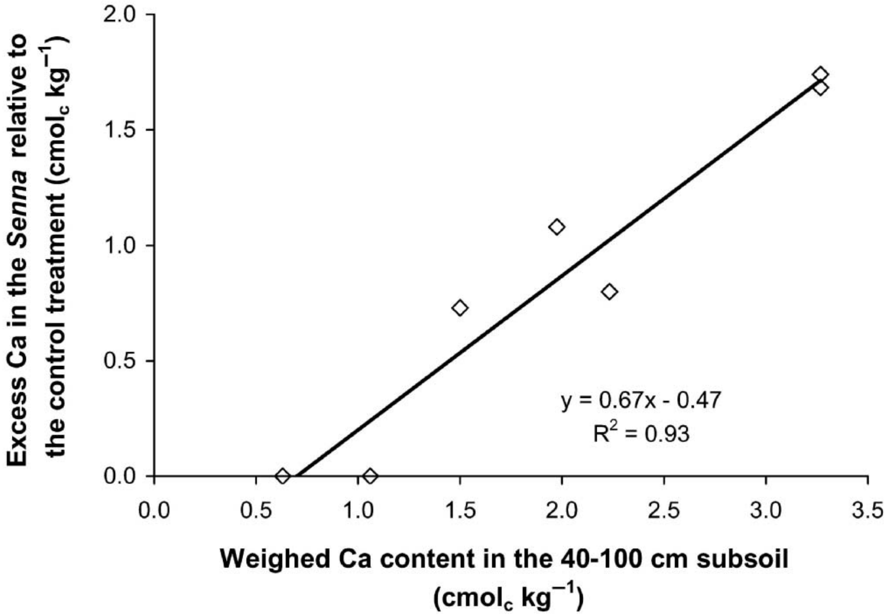

Figure 7. Relationships between the difference in Ca content between the *Senna* and the no-tree control treatments and the weighed Ca content of the 40-100 cm subsoil. Weighing was done by considering the Ca content and the depth of the soil layers between 40 and 100 cm. Note that for the sites where the *Senna* treatment did not contain a significantly different amount of Ca than the control (i.e. the Amoutchou and the Niaouli non-degraded site), the excess Ca content was set to 0.

Leucaena residues have shown that recovery of applied residue N was nearly 100% at 53 and 120 days after application, of which 5%, respectively, 3% was found in the mineral N pool of the top 100 cm of soil (Vanlauwe et al., 1998b; Vanlauwe et al., 1998c). This indicates that short-term leaching of freshly applied *Leucaena*-N is limited. However, N leaching may be delayed, and the total N balance in such systems is a better indicator for the amount of N lost. The *Leucaena* topsoil (0–15 cm) was observed to contain about 400 kg N ha^{-1} more than the no-tree control (Vanlauwe et al., 2004) and this appears to be less than half of the amount of N added through N fixation during a 12-year period (about 7 ton dry matter ha^{-1} yr^{-1} applied as prunings – Table 2 – with a minimal N content of 3.5% and a minimal proportion of N derived from fixation of 50% gives about 1400 kg N ha^{-1}). During that same period an estimated 250 kg N ha^{-1} was removed through maize grain harvests, indicating that indeed substantial losses of *Leucaena*-N may have occurred. Considering all the above, the fact that the topsoil Ca enrichment was not observed for the *Gliridicia* and *Leucaena* treatments is likely the result of a combination of topsoil recovery of Ca by those trees and leaching losses. Leaching of nitrate derived from applied residue N is likely going to be less in the *Senna* treatment due to its less favourable organic resource quality (Vanlauwe et al., 1997) and the fact that the tree does not fix N, therefore *Senna* trees are likely mining the subsoil Ca content rather than recycling Ca leached beyond the root zone of the companion crops or weeds.

Excess uptake of cations over anions is associated with release of protons and decrease in soil pH for plants having a relatively large cation/anion uptake (Tang and Rengel, 2003), as is the case with the current species (Figure 4), while the amounts of alkalinity produced during decomposition of organic residues at or near the soil surface is related to the excess cation content of these residues (Tang and Yu, 1999). One of the major processes increasing soil pH after application of organic resources is through the decarboxylation of organic anions, associated with cations in plant materials (Yan et al., 1996). In the current work, soil pH in the *Senna* treatments was observed to increase in the sites with a clay enrichment horizon relative to the control and *Leucaena* or *Gliricidia* treatments. This further supports the hypothesis that *Senna* withdraws most of its nutrients from the subsoil as otherwise the increases in soil pH, likely caused by the decomposition of cation-rich residues, would have been counteracted by proton release in the topsoil

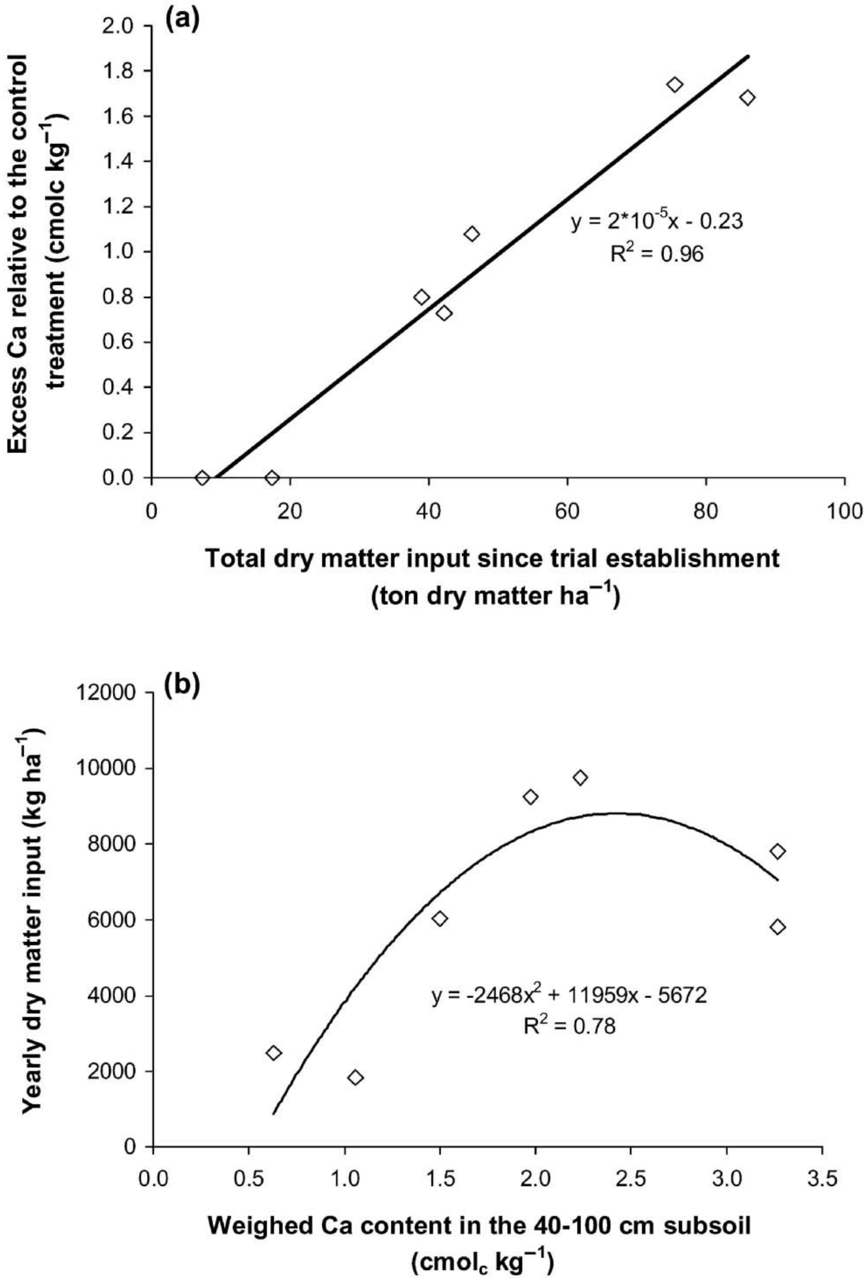

Figure 8. Relationships between the excess Ca in the *Senna* relative to the control treatment and the total *Senna* dry matter input since trial establishment (a) and between the yearly dry matter application (prunings or litterfall) and the weighed Ca content of the 40–100 cm soil layer (b) for the various sites. Weighing was done as explained in the caption of Figure 7.

caused by cation uptake, as observed for the *Leucaena* or *Gliricidia* treatments. Obviously, subsoil recovery of Ca by the *Senna* trees can lead to subsoil acidification and decline in tree biomass production although the latter has not been observed till date for the *Senna* trees on the Ibadan D2 field, continuously maintained since 1986 (Vanlauwe et al., 2004).

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