Plant productivity in cassava-based mixed cropping systems in Colombian hillside farms

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Abstract

In the Colombian hillsides cassava (Manihot esculenta Crantz) is cultivated because of its ability to produce high yields on acidic soils poor in nutrients. Farmers often plant mixtures of cassava cultivars, while bush-beans or maize are traditionally grown as cassava-intercrops. The objectives of this study were: (a) to determine if cassava or overall production can be improved by planting cassava cultivar mixtures or intercropping, (b) to assess the influence of soil properties on the dry matter production of cassava production systems, (c) to verify if soil cover can be increased by growing cultivar or species mixtures. On-farm trials were conducted at four locations in typical hillside environments with slopes up to 55% in the Southwest of Colombia from 1996 to 1998. Two cassava varieties contrasting in plant architecture (early branching variety, rich in apices versus erect, late branching variety, poor in apices) were grown as pure stands, as a variety mixture and each intercropped independently with upland rice or Canavalia brasiliensis. Rainfall during the trial period was only 76% of the long term average due to the 'El niño' phenomenon. The cassava cultivars produced tuber yields of 9.0 and 7.5 t ha\(^{-1}\) DM when planted in cultivar pure stands. Cassava growth and biomass production increased with increasing size of water stable aggregates and soil N content and decreased with increasing soil bulk density. In the cassava cultivar mixture, competition changed the pattern of biomass allocation, leading to a significantly lower harvest index compared to the mean of the pure stands (−6%). Intercropped C. brasiliensis significantly reduced cassava harvest index (−13%; mean of cassava/C. brasiliensis mixtures compared to mean of pure stands) as well as cassava (−53%) and total biomass production (−24%), while differences were not statistically significant in the cassava–rice systems probably because of the poor performance of rice. The strong reduction in cassava tuber yield in the

Abbreviations: ANOVA, analysis of variance; CIAT, Centro Internacional de Agricultura Tropical; coeff, coefficient; DAP, days after planting; DM (kg), dry matter; DMRT, Duncan’s multiple range test; p, error probability level; P < 0.1(*), error probability level of 10%; *P < 0.05, error probability level of 5%; **P < 0.01, error probability level of 1%; ***P < 0.001, error probability level of 0.1%; ns, not significant; r, coefficient of correlation (Pearson-r); R\(^2\), coefficient of determination; SBRA, stepwise backward multiple regression analysis; stdv, standard deviation; stdcoeff, standard coefficient; WSA, water stable aggregates

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cassava/C. brasiliensis systems was due to competition for water between cassava and the intercrop, aggravated by the lack of rain. The percentage of soil cover was slightly higher in all mixed cropping systems compared to the pure stands. In contrast to the mixture concept which seeks to increase productivity and soil cover compared to monocropping, the mixed cropping systems used in the studies in Rio Cabuyal reduced cassava tuber yield and total biomass production of the cropping systems compared to the cassava cultivar monocrops. When total soil cover was improved compared to the cassava cultivar pure stands it was paralleled by reductions in terms of cassava tuber yield.

Keywords: Cassava; C. brasiliensis; Upland rice; Cultivar mixture; Intercropping; Soil structure stability; Bulk density; Diameter of aggregates in air-dried soil; Soil cover

1. Introduction

Cassava (Manihot esculenta Crantz) is grown in the Colombian hillsides on acidic soils because tuber yield remains relatively high even under conditions of degraded land with low inputs (Braun et al., 1993; Olasantan et al., 1994). Erosion and nutrient depletion, especially of K (Howeler and Cadavid, 1990), are at the same time the reason for and the consequence of continuous cassava cultivation on steep slopes.

In Colombia, farmers often plant mixtures of cassava cultivars due to shortage of planting material or relative geographic isolation (Lozano et al., 1980). Gold and co-workers found that cultivar mixtures increased cassava yield by reducing herbivore load (Gold et al., 1989a, 1989b, 1990). Cassava with bush bean and maize intercrops may be grown where fertilizer is available for the intercrops (Zaffaroni et al., 1991; Mutsaers et al., 1993; Olasantan et al., 1996). Based on the principles outlined by Altieri (1994) and Risch et al. (1983) mixed cropping systems reduce susceptibility of crop(s) to pest (Ezulike and Igwatu, 1993; Gold, 1993) and disease attacks and the risk of total crop failure (Ahohuendo and Sarkar, 1995; Fondong et al., 2002). Such cropping systems can also improve soil cover and reduce erosion compared to monocrops directly (Francis, 1990; Evangelio et al., 1994; Leinhner et al., 1996; Ruppenthal et al., 1997; Howeler, 1998) or indirectly by increasing water infiltration and earth worm activity (Hulugalle and Ezumah, 1991; Hulugalle et al., 1994). Plants with different aerial and subterranean architectures growing on the same fields might increase the resource use efficiency for light, water, and nutrients (Mason et al., 1986a, 1986b, 1986c; Ikeorgu and Odurukwe, 1990; Sitompu et al., 1992). By suppressing weeds, intercrops utilize resources otherwise economically lost (Akobundu, 1981; Unamma and Ene, 1984; Zuofa et al., 1992; Olasantan et al., 1994). Both is relevant for cassava since it grows slowly in its initial development phase making limited use of the available resources (Mohankumar and Hrishi, 1978; Mutsaers et al., 1993). Systems with intercropped legumes additionally improve the fertility status of the soil by N-fixation or by pumping nutrients from deeper soil layers (Obiagwu, 1995; Leinhner et al., 1996; Lusembo et al., 1998). Mixed cropping systems can also improve labor efficiency (Odurukwe and Ikeorgu, 1994), enhance the diversity of the farmers’ diet and provide them with an additional income (Gold, 1993), though these advantages are disputed (Benites et al., 1993). Cassava cultivars and intercrop partners have to be carefully selected concerning early development, plant architecture, competitive ability and time to maturity. Only fast maturing species may be planted simultaneously with cassava (Kawano and Thung, 1982; Tsay et al., 1988; Cenpukdee and Fukai, 1991; Ezumah and Lawson, 1990; Muhr et al., 1995; Okeke, 1996; Okoli et al., 1996; Polthanne and Anan, 1999; Hernandez et al., 1999).

Little is known about the beneficial or detrimental effects of cultivar or species mixtures for cassava under on-farm conditions. The purpose of this study was to evaluate different cassava cultivation systems with respect to their effect on plant productivity. On-farm trials were conducted using two contrasting types of cassava cultivars intercropped with each other or rice or Canavalia brasiliensis as intercrop partners. The objectives were: (a) to determine if production can be improved through cropping system diversification (i.e. by planting a mixture of cassava varieties, or intercropping cassava with another crop), (b) to assess the influence of soil properties on cassava production,
(c) to determine if soil cover can be increased by growing more diverse systems.

Before the start of the trial, two meetings were organized with farmers to define cassava cultivars, intercrops for cassava and experimental fields. Besides cassava, farmers were interested in upland rice and in *C. brasiliensis*. Rice is an important component of the farmers’ diet with some potential as a subsistence crop in Rio Cabuyal. The idea of planting upland rice as single row intercrop with cassava was to combine the production of a subsistence crop with the establishment of life barriers analogous to those formed with Vetiver grass (*Vetiver zizanioides*) which the farmers are already familiar with (Ruppfenthal et al., 1997). The farmers were interested in *C. brasiliensis* due to its supposed ability to repel leaf cutter ants (*Atta* sp.) (CIAT, 1996b). *C. brasiliensis* establishes very fast and provides early soil cover and suppression of weeds (CIAT Tropical Forages Program, Robinson Mosquera, pers. commun., 1995). Its strong roots may substantially reduce erosion during high-intensity rainfalls and especially tillage erosion at harvest. Since the plant may be cut back easily several times during the cassava cycle without losing its ability for re-growth, competition of cassava may be controlled (Akanvou et al., 2002). Even in low P soils *Canavalia* spp. are able to fix between 22 and 133 kg ha$^{-1}$ N from the atmosphere (Cadisch et al., 1993; Wortmann et al., 2000; Becker and Johnson, 1998).

2. Materials and methods

2.1. Experimental sites

Experiments were carried out for one cassava cropping cycle from November 1996 to January 1998 at four locations at altitudes between 1425 and 1625 m above sea level. Sites 1 (Julio) and 2 (Lizardo) were in the middle-upper, sites 3 (Jeremias) and 4 (Merardo) in the lower portion of the watershed of Rio Cabuyal, situated in Cauca Department in Southwest Colombia (2°47’N, 76°32’W). Selected characteristics of these sites are given in Table 1. The soils in Julio and Lizardo were classified as Typic Dystrandepts while the soils in Jeremias and Merardo were oxic Dystropepts (USDA, 1998). Selected physico-chemical characteristics of these soils are presented in Table 2. Available phosphorus content at all sites was extremely low and probably the most limiting nutrient for cassava production.

Based on the classification of life zones (Holdridge, 1967), Rio Cabuyal lies in the tropical premontane moist forest zone. The annual mean temperature and the annual mean precipitation are 20°C and 2066 mm, respectively. There are two dry periods, from June to August and from December to February (Gijsman and Sanz, 1998). Based on its environmental and socio-economic characteristics this watershed had been chosen as a representative pilot area for the hillside areas in Latin America (CIAT, 1996a).

2.2. Plant material and experimental set up

Two cassava cultivars with contrasting growth patterns were selected for the trials. They were the early branching CG 402-11 forming a large number of apices and the erect, late branching SM 526-3 which develops only a few apices. Both had produced high tuber yields, i.e. 8–10 t ha$^{-1}$ DM in variety trials under hillside conditions (Jaramillo, 1994). Upland rice var. Foffia 62 (origin Madagascar) × Shin-Ei 3 (origin Japan) with cycle length of 123 days was sown in a single row at a rate of 5 g m$^{-1}$ (equals one quarter of normal seed rate, i.e. 25 kg ha$^{-1}$ instead of 100 kg ha$^{-1}$). Based on previous results (Robinson, 1997; Jalloh et al., 1994; Dahniya et al., 1994) and taking into account soil and climatic conditions in Rio Cabuyal favoring cassava over rice, rice and cassava were planted at the same time.

*C. brasiliensis*, CIAT-Accession No. 17009, known to deal well with low-P conditions was sown in a single row at a distance of 80 cm in the row (three grains of *C. brasiliensis* per planting hole).

Cassava was fertilized at planting with 0.5 kg of chicken manure containing 1.8% N, 1.4% P, and 1.8% K (on a DM basis, CIAT analytical services) per plant as is traditionally done in this region. The respective amounts of nutrients on an area basis were 113 kg ha$^{-1}$ N and K, and 88 kg ha$^{-1}$ P. Intercrops did not receive additional fertilizer.

There were seven treatments (Table 3) replicated twice at each of the four locations in a randomized complete block design. Soil preparation and length of prior fallow periods were different between the experimental sites (Table 1). Sixteen rows of five
Table 1
Characteristics and plot history of trial sites

<table>
<thead>
<tr>
<th>Site name, slope range (average)</th>
<th>Soil classification</th>
<th>Usual agronomic practices and pest or disease incidence</th>
<th>Crops produced prior to trial (rest of time under spontaneous fallow); length of fallow period before experiment</th>
<th>Soil preparation for the experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Julio (1), 29–43% (37%)</td>
<td>Typic Dystrandept</td>
<td>Ploughing with oxen; fertilizer, chicken manure, 0.5 kg cassava per plant; ant and whitefly attack</td>
<td>June 1995–July 1996: cassava–bean intercrop. Fallow length: 3 months</td>
<td>Manual hoeing to 10 cm (only area of cassava planting)</td>
</tr>
<tr>
<td>Lizardo (2), 37–57% (44%)</td>
<td>Typic Dystrandept</td>
<td>Manual hoeing; fertilizer, chicken manure, 0.5 kg cassava per plant; yield losses through ant damage</td>
<td>September 1993–October 1994: cassava; November 1994–December 1995: cassava. Fallow length: 10 months</td>
<td>Ploughing with oxen to 15 cm</td>
</tr>
<tr>
<td>Jeremias (3), 16–31% (24%)</td>
<td>Oxic Dystropept</td>
<td>Ploughing with oxen; no fertilization</td>
<td>1989–1991: cassava. Fallow length: 5 years</td>
<td>Ploughing with oxen to 15 cm</td>
</tr>
<tr>
<td>Merardo (4), 14–37% (27%)</td>
<td>Oxic Dystropept</td>
<td>Ploughing with oxen; no fertilization</td>
<td>March 1994–April 1995: cassava. Five plots were last cultivated in 1990. Fallow length: 18 months/5 years</td>
<td>Ploughing with oxen to 15 cm</td>
</tr>
</tbody>
</table>

a USDA soil taxonomy (1998).

Table 2
Soil characteristics of experimental sites a, depth 0–20 cm

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Julio (1) Typic Dystrandept</th>
<th>Lizardo (2) Typic Dystrandept</th>
<th>Jeremias (3) Oxic Dystropept</th>
<th>Merardo (4) Oxic Dystropept</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand (g kg⁻¹ soil)</td>
<td>380 ± 30</td>
<td>410 ± 26</td>
<td>110 ± 46</td>
<td>220 ± 80</td>
</tr>
<tr>
<td>Clay (g kg⁻¹ soil)</td>
<td>310 ± 28</td>
<td>240 ± 13</td>
<td>660 ± 41</td>
<td>600 ± 92</td>
</tr>
<tr>
<td>Bulk density (g cm⁻³)</td>
<td>0.76 ± 0.05</td>
<td>0.69 ± 0.03</td>
<td>1.07 ± 0.04</td>
<td>0.95 ± 0.08</td>
</tr>
<tr>
<td>Air-dried aggregates (&lt;6.3 &gt; 2 mm), % (w)</td>
<td>42 ± 5.8</td>
<td>32 ± 5.8</td>
<td>71 ± 4.6</td>
<td>62 ± 2.7</td>
</tr>
<tr>
<td>Water stable aggregates, % (w)</td>
<td>91 ± 3</td>
<td>87 ± 3</td>
<td>93 ± 3</td>
<td>95 ± 2</td>
</tr>
<tr>
<td>Total N content (g kg⁻¹ soil)</td>
<td>4 ± 1.03</td>
<td>4.7 ± 0.94</td>
<td>1.9 ± 0.27</td>
<td>3.1 ± 0.86</td>
</tr>
<tr>
<td>OM content (g kg⁻¹ soil)</td>
<td>82 ± 12</td>
<td>116 ± 21</td>
<td>46 ± 7</td>
<td>72 ± 11</td>
</tr>
<tr>
<td>P content (Bray II) (mg kg⁻¹ soil)</td>
<td>1.94 ± 0.8</td>
<td>0.96 ± 0.3</td>
<td>3.1 ± 0.8</td>
<td>2.3 ± 0.5</td>
</tr>
<tr>
<td>K content (Bray II) (cmol kg⁻¹)</td>
<td>0.27 ± 0.08</td>
<td>0.28 ± 0.05</td>
<td>0.19 ± 0.05</td>
<td>0.26 ± 0.12</td>
</tr>
</tbody>
</table>

a Mean values ± standard deviation.
15–20 cm long cassava cuttings (approximately 10 nodes) were planted on contour at a distance of 0.8 m/C2 1.0 m in plots of 4.5 m/C2 17 m. At the same time intercropping species were manually sown in contour rows halfway between the cassava rows.

### 2.3. Methods

#### 2.3.1. Climate data

Rainfall and temperature data were collected on a daily basis at a CIAT experimental site in Pescador in the central part of Rio Cabuyal watershed at a distance of 2 and 4 km from the experimental locations in the middle-upper and in the lower part of the watershed, respectively (Jorge Rubiano, CIAT, pers. commun.).

#### 2.3.2. Cassava growth analysis

Commencing at 90 days after planting (DAP), cassava plant height, number of apices per plant and rate of leaf production per apex were measured bi-weekly on 10 plants per variety and plot over the whole cassava growing cycle, omitting the border rows.

#### 2.3.3. Biomass production of the different system components

Cassava was harvested 15 months after planting to determine fresh tuber yield and biomass per plot and per-cultivar. Dry matter production of cassava tuber and stem was measured on 3 kg subsamples after drying at 60 °C in an oven. At site Julio cassava yields were extrapolated based on yields of completely harvestable rows. At this site, between 4 and 28 plants per plot (12 plants on an average) of a total of 45 plants relevant for biomass measurement had been lost due to a massive pest attack (white grub, *Scarabaeidae* sp.).

*C. brasiliensis* was cut back twice before cassava harvest to reduce competition to cassava growth. Plant residues were left in the plots. Biomass fresh weight of *C. brasiliensis* was determined from samples from 2.5 m × 3 m, 3 and 6 months after planting, and from the whole plots at cassava harvest. Dry weight was determined after drying at 60 °C in an oven, on the basis of the sample from 2.5 m × 3 m for the intermediate cuts and on a subsample of 5 kg at harvest. Rice panicles were harvested 140 DAP.

#### 2.3.4. Chemical soil properties

Three bulk soil samples, 0–20 cm depth, were collected 2 weeks after planting along the diagonal of each plot (4.5 m × 17 m) in the interrows to avoid the fertilized zone. Soil samples were air-dried, sieved at 2 mm, and analysed to determine organic matter content (Nelson and Sommers, 1982), total N (Krom, 1980), 0.1 M HCl + 0.03 M NH4F (Bray II method) extractable P and K (Salinas and Garcia, 1985), 1 M KCl extractable Ca, Mg, Al (Thomas, 1982), 0.05 M HCl + 0.0125 M H2SO4 extractable zinc (Martens and Lindsay, 1990), soil texture (Bouyoucos, 1962) and pH H2O (Salinas and Garcia, 1985). Analyses were performed on each sample and averaged for each plot.

#### 2.3.5. Physical soil properties

Undisturbed soil cores, 5 cm in diameter and 2.5 or 5 cm in length, were taken 14 months after planting cassava at the four sites for the determination of soil physical characteristics. The following parameters were determined using the methodologies indicated in brackets: (1) compressibility (Klute, 1986; Culley, 1993), (2) hydraulic conductivity (Reynolds, 1993), (3) air permeability (Weeks, 1978), (4) total porosity and pore size distribution (Topp et al., 1993; Klute, 1986), (5) permeability *k* was indirectly determined with a DIK-5001 permeameter (Daiki Rika Kogyo Co., Tokyo, Japan).

Additional bulk soil samples, of 1 kg fresh soil, were taken 14 months after planting cassava from 0–5 and 5–20 cm depths with two replications per experimental plot. Samples were air-dried for 3 days.
for the aggregate analysis. Seven aggregate size classes were separated using an electric Sieve Shaker (CSC Scientific Company, Fairfax, VA, USA).

Aggregates with a diameter between 2 and 4 mm were subsequently used to determine the net weight of water stable aggregates (WSA) and the geometric mean diameter (GMD) of the WSA with the humid sieving technique (E. Amezquita, CIAT, pers. commun.) applying an apparatus similar to that described by Bourget and Kemp (1957).

2.3.6. Soil cover and soil erosion

Soil cover was assessed using a sighting frame as described by Elwell and Stocking (1974). Cover was expressed as a percentage of “covered” sights of the total number of 351 observations (i.e. nine frame lengths) per plot. Cover measurements were carried out bi-weekly until 200 DAP when the height of cassava plants made the use of the frame impossible. Total soil cover over the observation period, i.e. from planting until 200 DAP was estimated based on the area under the curve.

Eroded soil and runoff water were collected in a plastic-lined channel at the bottom of the plots. While the sites Julio and Lizardo (middle-upper watershed) were furnished completely with collection channels (i.e. one channel/plot, 14 channels per site), channels were dug only for one repetition per site (seven channels per site) at sites Merardo and Jeremias in the lower part. Excess water was pumped off when necessary and dry weight of eroded soil was determined (a) for the first 90 days and (b) for the total length of the cropping season. At the Julio site, soil cover and erosion measurements were discarded 90 DAP due to a massive pest attack (white grub, Scarabaeidae sp.) which caused the total loss of a substantial number of cassava plants in five plots at this site.

2.4. Data processing and statistical analysis

Relative values of plant growth parameters for all treatments were calculated on a per site basis by dividing the observed value by the value for the respective cultivar grown in pure stand. The use of relative values allowed direct comparison of effects of competition on both cultivars in the different treatments.

Cassava top growth was assessed by repeatedly measuring the parameters plant height, number of apices per plant and leaf formation rate over the whole cultivation cycle. These data were depicted as graphs of the following function

\[ y = f(t_{\text{DAP}}) \]  

where \( y \) is the plant height, number of apices per plant or leaf formation rate of cassava.

In order to convert repeated measurement values into a single number, the area under the curve, i.e. the area between the \( x \)-axis and the graph of the respective function, was calculated for each of the three growth parameters. ‘Relative cassava top growth’ represents the mean value of the relative areas under the curve (i.e. value for the respective pure stand was set = 1) for the parameters plant height, number of apices per plant, and leaf formation rate.

Data were analysed using the Statistical Analysis Systems (SAS, 1988) and SYSTAT (SPSS, 1998) software. The former was applied to assess the effect of treatments and sites on cassava growth, biomass production of the cropping system components (i.e. cassava, rice, and \textit{C. brasiliensis}), and soil cover. SYSTAT was used to determine the effect of soil physico-chemical properties on cassava growth and on biomass production of the cropping system components.

Firstly, ANOVAs, Duncan’s multiple range tests and linear contrasts were performed separately for each of the four experimental sites (Gomez and Gomez, 1984) to assess the total treatment effect and to compare growth, production, and soil cover of the different treatments. Subsequently, the same statistical tools were applied carrying out a combined analysis over all sites for the growth and production data and over three sites for soil cover data (discarded at site Julio) to investigate differences between the experimental locations and site \( \times \) treatment interactions. ‘Site’ was considered as a fixed variable.

In the final step of data analysis, stepwise backward multiple regression analysis (SBRA) was used to simultaneously estimate the effect of selected soil parameters on growth and production of the tested cropping systems. The SBRA was carried out to replace the categoric variable ‘replication’ in the ANOVA by continuous variables of agronomic relevance.
In the SBRA model, the observed values for the dependent parameters are explained by \( k \) independent parameters and described by Eq. (2):

\[
y_{\text{obs}} = c_{\text{site}}(1+4) + c_{\text{treatment}}(1+7) + (\text{soil parameter}_1 \times c_1) + (\text{soil parameter}_2 \times c_2) + \cdots + (\text{soil parameter}_k \times c_k) + \text{error(residual)}
\]

\( y_{\text{obs}} \) is the observed value of the dependent variable, \( c_{\text{site}} \) and \( c_{\text{treatment}} \) are the category-specific constants, and \( c_k \) are the parameter-specific constants, respectively.

In order to pre-select the variables entered into the SBRA, data were subjected to a discriminant analysis. Thirty-four of 35 original soil parameters could be represented by 11 proxies based on significant pooled within-class correlations (\(|r| > 0.27, P < 0.05\)) (data not shown). Variables were only replaced if the per-site correlations were consistently positive or negative at all four experimental sites. Eleven proxies and the parameter ‘share of waterstable aggregates, 5–20 cm depth, which had no significant correlation (\( P < 0.05 \)) to any of the other parameters, i.e. 12 independent parameters in total were fed into the SBRA. Only two chemical properties were used as proxies, soil N and Ca content. The remaining main (P and K) and secondary plant nutrients (Mg and Zn) are highly correlated either to soil bulk density (5–20 cm) or to Ca content (data not shown). Original values of soil chemical parameters and the residual values of soil physical parameters were used as independent variables in the SBRA. Physical parameters had been measured at the end of the cropping cycle and were therefore corrected by subtracting the treatment effect from the original values, i.e. calculating the residuals from the ANOVA. Original values of growth and production parameters of the cropping systems were used as independent variables. Since cassava and cropping system growth and production were not only affected by the parameters used in the SBRA, but also by the parameters replaced by proxies (data not shown), the correlations which were relevant for the identification of the latter were taken into account for the discussion.

To simplify the discussion about the effect of the soil parameters replaced by proxies on production, parameter pairs not varying significantly between depth levels were merged into one variable per pair. The same was done where correlations between parameters were significant on both depth levels 0–5 and 5–20 cm, i.e. compressibility, % share of aggregates <1 mm in air-dried soil, mean diameter of WSA, % share of macro, meso, and micropores and bulk density.

SBRA defined the “significance” and the “relevance” of the effect of simultaneous changes of various soil parameters on cassava and cropping system growth and production (Hair et al., 1992; Jambu, 1991). “Significance” measures the change of \( y \) caused by a one unit change of \( x \) and is indicated in the form of a coefficient (i.e. regression slope) per parameter. “Relevance” is indicated in the form of a standard coefficient and measures the change of \( y \) relative to its standard deviation (stdv\( y \)) caused by a change of \( x \) by one standard deviation (stdv\( x \)) (Eq. (3))

\[
\frac{\Delta y}{\text{stdv}_y} = \frac{\Delta x}{\text{stdv}_x} \times \text{(standard coefficient} \pm \text{error term)}
\]

3. Results and discussion

3.1. Weather conditions and soil erosion

Climate in Rio Cabuyal during the trial period was influenced by the “El niño” phenomenon with rainfall being less than normal. While the average air temperature (19.7 °C) was close to the long term average of 20 °C, total rainfall during the cassava cropping cycle (November 1996 to January 1998) was 2800 mm, 76% of the long term average of 3700 mm for the same 15-month period (Fraiture et al., 1997). Only 5 mm of rain, 3% of the long term average, fell between July and August 1997 (between 240 and 300 DAP cassava; Jorge Rubiano, CIAT, pers. commun.). Leaf formation was reduced greatly at all sites after 240 DAP but increased again after 300 DAP as rainfall resumed (Fig. 1). Beside the reduction of total rainfall, the climate during the cropping cycle reported here was characterized by the absence of high-intensity rains (>100 mm h\(^{-1}\)). The estimated rates of total soil loss during the cropping cycle, i.e. 1.9 t ha\(^{-1}\) dry soil in the upper watershed (based on site Lizardo) and 0.6 t ha\(^{-1}\) dry soil in the lower watershed, respectively were about 10 times lower compared to those measured by other workers in the same area under similar soil conditions (Reining, 1992). Erosion data were not further analysed due to the lack of relevant rainfall events during the...
observation period and due to the pest attack leading to total cassava plant loss at site Julio.

### 3.2. Crop performance

Over all sites (including site Julio, where yields of plots with missing plants were extrapolated based on yields of complete rows (see Section 2.3.3), mean cassava tuber yields in the cultivar pure stands were 9.0 and 7.5 t ha$^{-1}$ DM for the cultivars CG and SM, respectively (Fig. 2). These yields were larger than the average tuber yield of a wide range of improved cultivars (5.1 t ha$^{-1}$ DM) grown under similar soil and fertilization conditions (Jaramillo, 1994). This sug-
gests that the lower rainfall in this cropping cycle had no negative influence on the tuber yield of the cultivars CG and SM.

On the average over all sites, the total biomass production of rice was only 0.1 t ha\(^{-1}\) DM. In contrast, rice grain yields for the same variety in intensively managed monocrop plots, grown in Rio Cabuyal at the same period in an earlier season and on soils comparable with the sites Julio and Lizardo, were between 1.6 and 2.3 t ha\(^{-1}\) DM (Quiros, 1996). We observed that rice grew well at site Julio with the lowest clay and the highest OM content among the experimental fields. The rice biomass production at site Julio was 200 kg ha\(^{-1}\) on average over the four cassava/rice plots, reaching 400 kg ha\(^{-1}\) in the best plot which is still 8–12 times lower compared to the rice variety trials described by Quiros (1996). The fact that the rice had been sown at a lower seed rate, i.e. 25 kg ha\(^{-1}\) instead of 100 kg ha\(^{-1}\), cannot explain the very low production. Since our results showed a reduced cassava production in the cassava/rice intercrop plots (see Section 3.4), we supposed a strong negative competition effect of cassava on rice. Conditions for rice growth were suboptimal in most experimental plots since the nutrient status was low, there was no additional fertilizer for the intercrops and clay content in the lower watershed was too high. Germination of rice was supposedly hindered by insufficient contact of the seeds with the soil at the sites where plots were ploughed with oxen (see Table 1). In addition, rice growth was severely hampered by repeated bird attacks at each of the four sites. The results showed that with low input practices typical for cassava plots most soil characteristics-soil preparation combinations allow for a negligible rice intercrop production only leading to grain yields 10–50 times lower compared to intensely managed monocrop plots. *C. brasiliensis* developed rapidly and covered the soil between the cassava rows. The legume performed best at site Julio with a P-concentration of only 1.9 mg kg\(^{-1}\) soil. Mean biomass production over all sites in Rio Cabuyal was 3.6 t ha\(^{-1}\) DM. There is no literature on *C. brasiliensis* production on soils comparable to Rio Cabuyal, but *C. brasiliensis* pure stands on the Cerrado soils in Brazil, when not cut back, produced 5 t ha\(^{-1}\) DM (Lathwell, 1990).

### 3.3. Site effect on cassava performance and soil cover over all cropping systems

Dry matter production of cassava shoots and tubers, relative cassava top growth and total biomass were very variable at each of the four sites. Cassava harvest index (average over all cropping systems) at site Lizardo was significantly lower compared to the sites Jeremias and Julio (Table 4). Per-cultivar analyses for CG and SM showed that at site Lizardo, SM tuber yield and harvest index were significantly lower compared to the other sites (Table 4), while the performance of CG did not differ significantly between the sites. This was due to heavy attacks of small ants (*Linepithema* sp.) on cultivar SM which reduced the rate of formation of leaves until 200 DAP at site Lizardo (Fig. 1). The ants acted as a competing

<table>
<thead>
<tr>
<th>Site</th>
<th>Cassava shoots (t ha(^{-1}) DM)</th>
<th>Cassava tubers (t ha(^{-1}) DM)</th>
<th>Harvest index(^{b}) (excl. fallen leaves)</th>
<th>Total biomass of cropping system (t ha(^{-1}) DM)</th>
<th>Relative cassava top growth(^{c})</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Plot Variety</td>
<td>Plot Variety</td>
<td>Plot Variety</td>
<td>Plot Variety</td>
<td>Plot Variety</td>
</tr>
<tr>
<td></td>
<td>CG SM</td>
<td>CG SM</td>
<td>CG SM</td>
<td>CG SM</td>
<td>CG SM</td>
</tr>
<tr>
<td>Julio</td>
<td>2.7a(^{d}) 2.9a 2.6a</td>
<td>7.2a 8.2a 6.4a</td>
<td>0.70a 0.71a 0.69a</td>
<td>11.6a</td>
<td>0.92a 0.87a 0.98a</td>
</tr>
<tr>
<td>Lizardo</td>
<td>3.6a(^{d}) 3.6a 3.8a</td>
<td>4.1a 5.2a 3.1b</td>
<td>0.50b 0.58a 0.42b</td>
<td>7.7a</td>
<td>1.03a 1.09a 0.99a</td>
</tr>
<tr>
<td>Jeremias</td>
<td>3.2a(^{d}) 3.4a 3.3a</td>
<td>7.9a 7.5a 8.5a</td>
<td>0.71a 0.70a 0.72a</td>
<td>12.0a</td>
<td>1.04a 1.08a 1.03a</td>
</tr>
<tr>
<td>Merardo</td>
<td>4.5a(^{d}) 5.6a 4.0a</td>
<td>7.2a 7.5a 7.4a</td>
<td>0.61ba 0.57a 0.65a</td>
<td>12.4a</td>
<td>0.91a 0.84a 1.02a</td>
</tr>
</tbody>
</table>

\(^{a}\) Averaged across all treatments.

\(^{b}\) Tuber yield/cassava biomass.

\(^{c}\) Relative area under curve, see Section 2.4 for explanations; no difference between pure stands by definition.

\(^{d}\) Numbers within a column followed by different letters are significantly different (differences between experimental sites, \(P < 0.05\), DMRT).
nutrient sink without affecting cassava shoot production, as previously observed by (Gold, 1993).

At site Lizardo, total soil cover over the observation period was significantly reduced compared to the sites Jeremias and Merardo. Four out of seven cover measurements between 100 and 200 DAP showed the same ranking of the locations (DMRT, $P < 0.05$, data not shown). Slower establishment and growth of C. brasiliensis at site Lizardo compared to Jeremias and Merardo explained these findings. At site Julio, cover measurements had been discarded 90 days DAP because of massive loss of cassava plants in several experimental plots.

3.4. Treatment effect on cassava and cropping system performance and soil cover across the four sites

As expected from the choice of cassava cultivars, cultivar CG in pure stand produced significantly more apices ($P < 0.001$) compared to cultivar SM (Table 5). Conversely, production of leaves was significantly higher ($P < 0.05$) in SM compared to CG. However, production parameters at harvest (tuber and shoot dry matter) did not differ significantly between CG and SM (Table 5, Fig. 2).

In the cultivar mixture, tuber and shoot dry matter production was lower and higher, respectively as compared to the mean of the pure stands (Table 5, Fig. 2). Linear contrast analysis showed a significant shift in biomass allocation from tubers to shoots, which was reflected in a lower harvest index for the cultivar mixture ($P < 0.10$) compared to the mean of the pure stands (Table 5).

Separate analyses based on DMRT for the cultivars CG and SM presented in Table 6 showed different reaction patterns of the cultivars when planted together in cultivar mixture. For cultivar CG, all parameters except for shoot biomass were slightly reduced, while cultivar SM increased shoot and total biomass production, formed more apices and grew taller compared to the respective pure stands (Table 6). The differences found when contrasting the cultivar mixture versus the mean of the pure stands (Table 5) were thus due to changes in SM shoot growth. The growth and production of aerial parts in cultivar CG planted in mixture with cultivar SM were more resilient compared to SM to the changed patterns of
Table 6
Per-cultivar analysis: comparisons among the four cropping systems containing the same cultivar (for cultivars CG and SM; mean across four sites)

<table>
<thead>
<tr>
<th></th>
<th>Cassava shoots (t ha⁻¹ DM)</th>
<th>Cassava tubers (t ha⁻¹ DM)</th>
<th>Harvest indexᵃ</th>
<th>Total biomass for cropping system (t ha⁻¹ DM)</th>
<th>Cassava plant heightᵇ</th>
<th>Cassava number of apices per plantᵇ</th>
<th>Cassava leaf formation rateᵇ</th>
<th>Relative cassava top growthᵇ</th>
</tr>
</thead>
<tbody>
<tr>
<td>CG-based systems</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CG pure stand</td>
<td>4.3ᵃᵈ</td>
<td>9.0ᵃ</td>
<td>0.67ᵃ</td>
<td>13.3ᵃ</td>
<td>2191ᵃ</td>
<td>220ᵃ</td>
<td>642ᵃ</td>
<td>1.00ᵃ</td>
</tr>
<tr>
<td>CG in cultivar mix</td>
<td>4.7ᵃ</td>
<td>7.9ᵃ</td>
<td>0.63ᵃ</td>
<td>12.6ᵃ</td>
<td>2171ᵃ</td>
<td>210ᵃab</td>
<td>636ᵃab</td>
<td>1.01ᵃ</td>
</tr>
<tr>
<td>CG/rice</td>
<td>3.6ᵃ</td>
<td>7.2ᵃ</td>
<td>0.67ᵃ</td>
<td>11.0ᵃ</td>
<td>2111ᵃ</td>
<td>202ᵃab</td>
<td>633ᵃab</td>
<td>0.99ᵃ</td>
</tr>
<tr>
<td>CG/C. brasiliensis</td>
<td>2.8ᵃ</td>
<td>4.3ᵇ</td>
<td>0.60ᵃ</td>
<td>9.7ᵃ</td>
<td>1842ᵃ</td>
<td>162ᵇ</td>
<td>597ᵇ</td>
<td>0.87ᵇ</td>
</tr>
<tr>
<td>SM-based systems</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SM pure stand</td>
<td>3.6ᵃᵇ</td>
<td>7.5ᵃ</td>
<td>0.65ᵃ</td>
<td>11.1ᵃᵇ</td>
<td>2000ᵃᵇ</td>
<td>50ᵃ</td>
<td>711ᵃᵇ</td>
<td>1.00ᵃᵇ</td>
</tr>
<tr>
<td>SM in cultivar mix</td>
<td>4.4ᵃ</td>
<td>7.5ᵃ</td>
<td>0.61ᵃᵇ</td>
<td>11.9ᵃᵇ</td>
<td>2247ᵃ</td>
<td>68ᵃ</td>
<td>696ᵃᵇ</td>
<td>1.17ᵃᵇ</td>
</tr>
<tr>
<td>SM/rice</td>
<td>3.3ᵃᵇ</td>
<td>6.9ᵃ</td>
<td>0.67ᵃ</td>
<td>10.3ᵃᵇ</td>
<td>1856ᵇ</td>
<td>52ᵃ</td>
<td>670ᵃᵇ</td>
<td>0.99ᵇ</td>
</tr>
<tr>
<td>SM/C. brasiliensis</td>
<td>2.5ᵇ</td>
<td>3.5ᵇ</td>
<td>0.55ᵇ</td>
<td>8.9ᵇ</td>
<td>1672ᵇ</td>
<td>41ᵇ</td>
<td>623ᵇ</td>
<td>0.87ᵇ</td>
</tr>
<tr>
<td>Cultivar mixtureᵉ</td>
<td>4.5ns</td>
<td>7.7ns</td>
<td>0.62(*)</td>
<td>12.2ns</td>
<td>2209ⁿˢ</td>
<td>139ⁿˢ</td>
<td>666ⁿˢ</td>
<td>1.09ⁿˢ</td>
</tr>
</tbody>
</table>

ᵃ Excluding fallen cassava leaves.
ᵇ Area under curve.
ᶜ Relative area under curve, see Section 2.4 for explications for explications.
ᵈ Treatments belonging to the same cultivar group followed by the same character are not significantly different.
ᵉ The cultivar mixture was compared to the mean of the pure stands: (*): linear contrast significant at $P < 0.1$. 
shading and competition for aerial space relative to the pure stands.

While competition for light in the cultivar mixture led to increased shoot production in both cultivars, the net effect was negative concerning total tuber yield. The harvest indices in both cultivars were decreased as compared to the pure stands. While tuber yield of cultivar SM grown together with CG was the same compared to the SM pure stand, the mentioned shift in assimilate distribution led to a reduction of tuber yield in cultivar CG as compared to the CG pure stand and to a reduction of total tuber yield in the cultivar mixture compared to the mean of the pure stands. The different reaction patterns of CG and SM confirmed the results of Kawano and Thung (1982). They found that the essential part of competition in cassava was for light. While competitive ability and spacing response (e.g., occupation of free space through formation of new apices and branches like in cultivar SM) were found to be strongly positively correlated, the correlation between competitive ability and harvest index was negative (Kawano and Thung, 1982). Our results concerning the mixture of two cassava cultivars with different competitive abilities may be explained in two ways. Firstly the majority of the total amount of assimilates produced by both cultivars was “drained” to the cultivar with the higher competitive ability and the lower harvest index, the productivity in terms of tuber yield decreased. Secondly there was a shift in assimilate distribution in both cultivars from the tubers to the shoots which was triggered in the “stronger” cultivar by the spacing response and in the “weaker” by the stress induced by the competing cultivar.

In all interspecies mixtures (i.e. cassava with C. brasiliensis or upland rice), cassava growth and production parameters were reduced compared to the pure stands (Tables 5 and 6). In combination with C. brasiliensis, all parameters in both cultivars were reduced compared to the respective pure stands, with significant differences for cassava shoot and tuber production, harvest index, total biomass production of the cultivation system, cassava plant height ($P < 0.05$), leaf formation rate and relative top growth ($P < 0.10$; Table 5). In addition, the number of cassava apices per plant in CG was significantly reduced in the presence of C. brasiliensis (Tables 5 and 6).

Linear contrasts showed that despite the low rice production, cassava tuber production ($P < 0.10$) and harvest index (ns) of cultivar CG intercropped with rice were lower compared to the pure stand (Table 5). There were no such effects in the SM/rice system, possibly due to the more erect growth habit of SM compared to CG which reduced competition from the low growing rice. Generally spoken, reductions of cassava growth and production in the interspecific mixtures with rice or C. brasiliensis were more severe in cultivar CG compared to SM.

The decrease of total biomass production due to intercropping C. brasiliensis was likely due to strong interspecific competition for water induced by the higher evapo-transpiration rates of these systems compared to the cassava monocrop and aggravated by the dry summer of 1997. Our findings concerning the shift in assimilate distribution in the cassava plant support the results reported by Gold et al. (1989a, 1989b) and by Cock et al. (1979a), who found that under stress cassava favored top growth, first fulfilling the requirements of the energy producing structures before filling the storage tubers.

While this mechanism may reduce the production in terms of tuber yield, the plasticity of its above ground organs enables cassava to quickly respond to biotic and abiotic stresses such as pests and diseases, drought, and competition by weeds or intercrop partners.

Since the biomass production per unit nutrient and water uptake in cassava is higher compared to other crops (Howeler and Cadavid, 1990), the intercrop biomass was not sufficient to make up for the loss in total cassava biomass, not even in the case of the competitive C. brasiliensis.

Concerning soil cover at 100 DAP values were in between 45 and 63% depending on the cropping system (Fig. 3). Soil cover in both cassava/rice systems was significantly higher compared to the respective pure stands (linear contrasts, $P < 0.05$). Before the second cover measurement fields were weeded and C. brasiliensis was cut back, causing decreases in soil cover of between 13 and 35%, depending on the cropping system. Soil cover decrease after cutting the intercrop and increase through re-growth were most drastic in the CG/C. brasiliensis system, as the CG pure stand provided the least soil cover of all cropping systems.

Despite its erect growth, the SM pure stand provided better soil protection compared to the CG
pure stand at 150 and 194 DAP. This could be explained by its higher leaf production rate and larger individual leaf size. Due to the increased soil cover in the SM pure stand compared to the CG pure stand, differences in soil cover between the intercropping systems and the respective pure stands were larger and more frequent in the CG-based systems.

Based on the area under the curve, soil cover over the whole observation period was slightly higher in all mixed cropping systems compared to the respective pure stands and higher in the SM pure stand compared to the CG pure stand. However, the only significant difference measured was between CG/rice (57% total soil cover) and the CG pure stand (44% total soil cover) (linear contrast, \( P < 0.05 \), data not shown).

The gain in total soil cover in the CG/rice system compared to the CG pure stand was linked to a significant cassava tuber yield loss of 20% (linear contrast, \( P < 0.10 \)) (Table 6). In all other mixed cropping systems insignificant soil cover increases of between 10 and 13% were paralleled by cassava tuber yield losses of between 7 and 54% compared to the respective pure stands. Yield losses were highly significant for both cassava/\textit{C. brasiliensis} systems (Tables 5 and 6). The trade-off of reduced cassava tuber yield for increased soil cover, as observed in the mixed cropping systems is highly disadvantageous for farmers, especially for the cassava/rice and cassava/\textit{C. brasiliensis} systems. Besides the yield loss in cassava, the additional costs and time for seed and more careful soil preparation and weeding have to be taken into account. In contrast to the results presented here, Howeler (1998), working with farmers in Asia, has demonstrated that a combination of promoting more rapid growth of cassava through efficient fertilization, short-term cash intercrops, that mature before canopy closure and competition for moisture, e.g. peanuts, and erosion barriers lead to high yielding sustainable cassava-based systems.

### 3.5. Effects of soil physical and chemical characteristics on growth and production of cassava cropping systems

In a first approach, the stepwise backward multiple regression analysis (SBRA) had shown highly significant negative correlations between the dependent parameters and the clay content. The relevance of clay content had been up to three times higher compared to the second most important variable. Plotting of the residuals which were the basis for the regression calculations (original data reduced by site and treatment effects), i.e. dependent parameters versus clay content, revealed that these regressions were dominantly influenced by data from the experimental plots of site 4 (Merardo) (Fig. 4). Five plots at site Merardo had been under fallow for a longer period of time compared to the other plots of the same site before the start of the experiment (Table 1). These five plots had considerably lower clay contents than all others and cassava yields
were much higher than in other plots (Fig. 5). For this reason, the Merardo site was subsequently excluded from this analysis and the results of the SBRA are based on three sites and 42 observations (Fig. 3, Table 7). The SBRA showed that the N content of the 0–20 cm horizon, the mean diameter of WSA of the 0–5 cm horizon, and the bulk density of the 0–5 and 5–20 cm horizons, respectively, had a significant effect on one or more of the dependent variables and that eight regressions of soil parameters on dependent variables were statistically significant ($P < 0.05$) (Table 7). All these correlations showed similar trends at the three sites and were therefore further considered for the interpretation.

Soil parameters explained between 7 and 21% (measured as % share of the total sum of squares) of the

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**Fig. 4.** Regression lines over four and three (without site Merardo) experimental sites, respectively of clay content of soil (0–20 cm depth) on cassava stick production. $x = 0$ and $y = 0$, respectively are the means across all observations (56 and 42, respectively).

**Fig. 5.** Cassava tuber yield (residual, effect of cropping system subtracted) and clay content in plots with long (5 years, A) and short (18 months, B) fallow at experimental site Merardo (lower watershed).
Table 7
Relevance and significance of effect of soil parameters that significantly affected cassava and cropping system performance based on data of three experimental sites (without site Merardo)

<table>
<thead>
<tr>
<th>Independent (soil) parameters</th>
<th>N content, 0–20 cm (g kg⁻¹ soil)</th>
<th>Diameter of WSA, depth d = 0–5 cm (mm)</th>
<th>Bulk density, d = 0–5 cm (g cm⁻³)</th>
<th>Bulk density, d = 5–20 cm (g cm⁻³)</th>
<th>Percentage share of aggregates &lt; 1 mm in air-dried soil, d = 5–20 cm³</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Regression coefficient (b)</td>
<td>Beta (P)</td>
<td>Regression coefficient (b)</td>
<td>Beta (P)</td>
<td>Regression coefficient (b)</td>
</tr>
<tr>
<td>Cassava shoots (kg ha⁻¹ DM);</td>
<td>4479 ± 3529</td>
<td>0.35*</td>
<td>-6565 ± 5845</td>
<td>-1.10*</td>
<td>-6565 ± 5845</td>
</tr>
<tr>
<td>Total biomass of cult. system</td>
<td>11241 ± 8553</td>
<td>0.31*</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(kg ha⁻¹ DM); R² = 0.38/0.21³</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cassava plant height (cm); R² = 0.34/0.19³</td>
<td>1037 ± 968</td>
<td>0.30*</td>
<td>-458 ± 141</td>
<td>-0.87**</td>
<td>-458 ± 141</td>
</tr>
<tr>
<td>Cassava, number of apices P/plant; R² = 0.88/0.07³</td>
<td>17.3 ± 7</td>
<td>0.30*</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cassava leaf formation rate³</td>
<td>-418 ± 118</td>
<td>-1.60***</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* On a w/w basis.
* Beta: measures relative importance of the independent variables (Beta = b × Sᵢ/Sᵣ). Absolute values have to be taken. For example −1.10 is more important than 0.35. Values are to be compared within a dependent variable only. Confidence level: *P < 0.05; **P < 0.01; ***P < 0.001.
* R² value for model including categoric variables (site and treatment)/R² value for model with soil parameters only.
* New leaves per apex/21d.
total variability in growth and production parameters in cassava cropping systems (Table 7). Cassava tuber yield was not affected by the soil parameters at all.

Mean diameter of WSA of the top 5 cm of the soil was positively correlated to the production of cassava shoots, total biomass production of the cropping system, and cassava plant height.

Soil bulk density (5–20 cm depth) was negatively correlated to cassava shoot production, plant height and leaf production rate, while bulk density (0–5 cm depth) was negatively correlated to the number of apices per plant.

An increased total N content enhanced the number of apices per cassava plant.

Combining the results of the discriminant analysis (i.e. selection of the 11 proxies) with those of the SBRA suggested that soils with a low bulk density, a small size of aggregates in air-dried soil, a high percentage of macropores, a high water conductivity, a coarse texture, a high percentage of large WSA, high levels of pH, organic matter, N, Ca, Mg, and K increased plant growth and production compared to soils with the opposite characteristics.

The importance of aggregate stability for soil fertility and crop production has already been shown in a number of trials from the temperate and tropical zones (Karlen et al., 1992; Reining, 1992). These aggregates provide good growing conditions during phases of increased rainfall by preventing soil puddling and reducing soil erosion (Balesdent, 1997).

Soils with low bulk density and a high macropore/micropore ratio exert little physical resistance on tubers and increase cassava above ground growth and production due to a feedback mechanism described by Masle (1999) which reduces above ground growth as soon as root growth gets impeded.

Since bulk density was negatively correlated to both soil macroporosity and water conductivity (data not shown) the negative correlations observed between soil bulk density and cassava top growth parameters underlined the importance for cassava growth of both good aeration and rapid drainage of excess water as observed by Rehm (1991). The positive response of cassava above ground growth to increased N (increased number of apices with higher N level; Table 7) has been observed before by Howeler and Cadavid (1983), Olasantan et al. (1994, 1997) and in various field trials at CIAT (CIAT, 1992).

While our trial showed no significant correlation between cassava tuber yield and soil parameters, the farmers apply considerable amounts of nutrients in form of chicken manure (see Section 2), supposedly to increase tuber yield. In contrast to the Rio Cabuyal watershed where constant N supply is provided for by the high organic matter content of the soils, cassava yield was significantly improved by N applications in other areas poor in organic matter (Howeler and Cadavid, 1990). With respect to P and K, there are several reasons, why the regular application of fertilizer is important. K removal at cassava harvest in this experiment was between 100 and 150 kg ha\(^{-1}\) depending on cultivar and yield, so the amount of K fertilizer applied at planting (113 kg ha\(^{-1}\)) was hardly enough to make up for the loss at harvest. If cassava is planted for several crop cycles, K becomes the most limiting element (CIAT, 1992; Howeler and Cadavid, 1990). The application of P (88 kg ha\(^{-1}\)) was much higher than the removal (10–15 kg ha\(^{-1}\)), but the soil P content at all locations was below the critical level allowing for 95% of the maximum yield (Howeler and Cadavid, 1990), which fully justified the high P doses applied by the farmers.

In addition, the chicken manure used by the farmers had very high organic matter content (75% of DM). On the long run, this will help to improve aggregate stability and to reduce soil bulk density, which in turn will have a positive effect on crop growth and production and will decrease susceptibility to erosion.

4. Conclusions

Mixed cropping systems used in the studies in Rio Cabuyal reduced cassava tuber yield and total biomass production of the cropping systems compared to the cassava cultivar monocrops. When total soil cover was improved compared to the cassava cultivar pure stands it was paralleled by reductions in terms of cassava tuber yield. These findings were in contrast to the mixture concept which seeks to increase productivity and soil cover compared to monocropping by improving the use of natural resources and farmer inputs (Mutsaers et al., 1993). The results indicated that in terms of tuber production and soil cover plant-to-plant cassava cultivar mixtures are in fact no improvement compared to cultivar.
monocrops. They raised questions concerning the 'ideal' characteristics of a cassava cultivar and its partner crop planted in species mixtures. Based on our findings a cassava cultivar with low competition ability and high harvest index should be combined with a fast maturing intercrop. The plants' morphology and cassava branching type have to be taken into account. Though the contrasting morphologies of cassava cultivar SM and upland rice seemed to combine well in soils providing good growth conditions for rice, our experiment clearly showed that for the vast majority of soil characteristics-soil preparation combinations rice is not a suitable intercrop partner for cassava under the low input practices applied in Rio Cabuyal. Fast growing and highly competitive species with late maturity, e.g. *C. brasiliensis* should not be planted together with cassava right from the start of the cropping cycle. Other cropping systems different from cassava cultivar mixtures and intercropping systems need to be developed. Farmers in Rio Cabuyal are experimenting with cassava cultivated in strips between perennial barriers of grass and blackberry planted on the contour in order to reduce soil erosion (Müller-Sämann, 1997). In addition, cassava plantings consisting of different blocks of cassava varieties, would provide some of the potential advantages of more diverse cropping systems, but avoid the negative effects of strong intergenotype and interspecies competition observed in these experiments. Our results showed that – not depending on a specific cropping system – production is increased by the cultivation of improved and locally adapted cassava cultivars with adequate fertilization.

Nevertheless, it will not be possible to resolve all problems related to cassava monocropping with more diverse cassava cropping systems. In the Cauca department, improving of the fallow is another obvious option. Instead of intercropping *C. brasiliensis* with cassava, the legume could be cultivated in pure stands during the fallow period or it could be sown in fields going to the fallow period after the next cassava harvest as soon as the cassava crop is fully established. *C. brasiliensis* could play an important role as nutrient pump producing large amounts of green manure. These studies showed that taking advantage of the theoretical potential of species mixtures needs careful selection of the mixing partners for maximum complementarity. Cassava cultivars for species mixture plantings are not easily available and need to be selected under the same micro-environmental conditions (i.e. in species mixtures) they are thought to be cultivated in practice. Different management options and elements of production systems need to be combined and tested to improve overall productivity at the farm and at the landscape level. These studies also demonstrated that there is a need to test cropping systems at different locations with varying environmental conditions over an extended period of time.

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