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# Using agroforestry to improve soil fertility: effects of intercropping on *Ilex paraguariensis* (yerba mate) plantations with *Araucaria angustifolia*

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**Abstract** This study assessed the use of agroforestry to improve soil nutrient properties in plantations containing *Ilex paraguariensis* St. Hilaire (yerba mate). Intercropping within tree plantation systems is widely practiced by farmers around the World, but the influence of different species combinations on system performance still requires further investigation. *I. paraguariensis* is a major South American crop commonly cultivated in intensive monocultures on low activity clay soils, which are highly prone to nutrient deficiencies. Study plots were established in 20 plantations in Misiones, Argentina. These involved two species combinations (*I. paraguariensis* monoculture and *I. paraguariensis* intercropped with the native tree species *Araucaria angustifolia*) and two age classes (30 and 50 years old). Chemical soil samples were analysed to determine Ca, Mg, K, P, N, C and Al concentrations, effective CEC (eCEC) and pH at two soil depths (0–5 cm and 5–10 cm). In the younger plantations, the agroforestry sites had lower nutrient levels than *I. paraguariensis* monoculture sites. However, the monoculture plantations were more susceptible than agroforestry sites to a decline in soil nutrient status over time, particularly with respect to Ca, eCEC, N and C for both soil depths. P concentrations were below detection limits for all sites, potentially reflecting the high P-fixing capacity of the kaolinic soils of this region. While agroforestry systems may be better at maintaining soil quality over time, significant growth increase of *I. paraguariensis* was apparent only for the monoculture sites.

**Keywords** Soil quality · Tropical soil management · Agroforestry · Intercropping · Yerba mate · Argentina

## Introduction

While millions of farmers throughout the World practice traditional agroforestry, research on the subject focused primarily on system descriptions and empirical and methodological investigations prior to the establishment of the World Agroforestry Centre in 1977 (Nair 1998). Findings in the last two decades support the many potential benefits of agroforestry, including improved nutrient cycling (Nair et al. 1999), increased soil organic matter and microbial populations (Chander et al. 1998) reduced weed populations (Beer et al. 1998; Sileshi et al. 2007), increased abundance of birds (Cockle et al. 2005), and improved soil water-use efficiency (Anderson et al. 2009). These mixed systems also

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increase soil organic carbon concentrations, mitigate loss of soil carbon by erosion and decrease nutrient loss caused by removal of biomass through harvest or burning practices (Montagnini and Nair 2004; Mutuo et al. 2005). Agroforestry may lower the frequency of land abandonment by improving soil quality within plantations (Parrotta et al. 1997) and offer opportunities for conservation strategies, while also improving rural livelihoods (Garrity 2004).

In the tropics, many valuable agricultural products are cultivated in single species plantations. However, many of these species, especially those that are partially shade tolerant, function well in mixed-stratified plantations or agroforestry systems. *Ilex paraguariensis* St. Hilaire (yerba mate) is a major regional crop of South America, which is suitable for agroforestry because it tolerates partial shade and can therefore be grown in conjunction with overtopping timber trees (Eibl et al. 2000; Montagnini et al. 2006). Although research on *I. paraguariensis* in agroforestry systems is sparse, studies involving *Theobroma cacao* (cacao), *Coffea* spp. (coffee), and *Camellia sinensis* (tea) provide baseline insight into how these intermediate sub-canopy tree species may function within agroforestry systems. Studies of shaded coffee and cacao are abundant (Beer et al. 1998) and report the effects of shade on production (Zuidema et al. 2005), shade tree selection for optimum pest management and merchantability (Somarriba et al. 2001), below ground competition, microclimate and pest interactions, nutrient cycling and soil fertility (Aranguren et al. 1982; Babbar and Zak 1994; Nair et al. 1999; Beer 1988; Méndez et al. 2009), and shade effects on the chemical content of leaves and fruit (Esmelindro et al. 2004; Jacques et al. 2007). Similar research with tea reports the benefits of mixed systems for economic stability, soil erosion control and reductions in weed infestation for small-scale farmers (Saint-Pierre 1991; Li 2005).

Tropical kaolinitic soils are susceptible to erosion, nutrient deficiencies, low pH, soil moisture stress, and loss of soil biodiversity and organic matter. Initiating agroforestry in place of current monocultures may be inherently better at mitigating these susceptibilities (Juo and Franzluebbers 2004; Cardoso and Kuyper 2006). Plantation systems which incorporate a mixture of species on the same area of land may sustain soil fertility, increase the production lifespan of crop species, and provide benefits to land holders that may minimize the frequency of land abandonment and further settlement into forest areas. (Huijun and Padoch 1995; Beer et al. 1998; Laurance and Peres 2006).

Only 7–8% of the original Atlantic Forest still exists and Misiones, Argentina contains the largest continuous expanse (Holz and Placci 2003; Galindo-Leal and Câmara 2003). Since fragmentation is a main threat to biodiversity within afforested areas, preserving the continuous reserves in Misiones is vital to ensure the unique ecological assets of the forest. The main agricultural crops in Misiones are yerba mate (167,722 ha), tobacco (26,380 ha) and tea (34,900 ha). Government subsidies also contribute to rapid increases in tree plantations (384,948 ha), which mainly include exotic species such as pine (*Pinus taeda* and *Pinus elliottii*), eucalyptus (*Eucalyptus camaldulensis*) and the native araucaria (*Araucaria angustifolia*) (Frangi et al. 2003). These species are managed intensively as monocultures and reductions in productivity due to loss of soil fertility may occur after only a few years (Moscatelli and Pazos 2000). Increasing demand for agricultural products and timber, combined with slash and burn agricultural practices, land abandonment, and selective forest timber harvests are the greatest threats to the primary Atlantic Forest (Galindo-Leal and Câmara 2003).

Argentina is the largest global producer of yerba mate (ca. 280,000 t $year^{-1}$) and export of the product contributes significantly to the country's GDP. Additionally, the product is becoming globally popular, with an estimated value of US $1 billion in 2004 (Heck and Mejia 2007). Research on the specific growing requirements of yerba mate is minimal, although it is one of the major plantation crops in Brazil, Paraguay, and Argentina. This study examined how monocultures of *I. paraguariensis* and mixtures with *A. angustifolia* in tree plantations affect available soil nutrients in 30 and 50 year old plantations.

## Materials and methods

### Site description

The climate throughout Misiones is defined by the Koppen System as subtropical and lacking a well-defined dry season. Annual precipitation is 1,700–2,400 mm and mean annual temperature is 21°C (Köppen 1918). Soils in Misiones originate from the Paraná plateau basaltic lavas formed in the early Cretaceous epoch. This basaltic material weathered to create the easily eroded and moderately fertile acidic soils found today (Stewart 1960; Faure 2001). The prominent soils types are Ultisols, with areas of Oxisols and Alfisols. Ultisols and Oxisols are traditionally the preferred soil type for *I. paraguariensis*, tea, *Vernicia fordii* (tung) and *Nicotiana tabacum* (tobacco) plantations, although soil nutrient concentrations decrease substantially after only a few years of crop production (Moscatelli and Pazos 2000).

The prominent "red soils" of Misiones are deep and clayey, contain sesquioxide and kaolinite, and are well drained and structured. Topsoil organic matter ranges from between 3 and 8% and the cation exchange capacity (CEC) ranges from 10 to 20 cmol $kg^{-1}$ (Fernández et al. 1997). Kaolinites are low activity clays with a low surface area, resulting in their relatively low CEC. The soils are low in organic matter, nitrogen, and phosphorus, making them poor to moderately suitable for tree plantations (Table 1) (Fernández et al. 1997). Additionally, marine carbonates deposited by atmospheric dust have a major role in calcium cycling in soils derived from silica-based parent material. This dust forms pedogenic carbonates, thereby providing much of the calcium present in these soils (Van der Hoven and Quade 2002).

## Species description

Two species native to the Atlantic Forest of Misiones and Southern Brazil are *Ilex paraguariensis* and *Araucaria angustifolia* (araucaria or Paraná pine). These species are commonly associated with each other, as well as with *Ocotea odorifera*, *Ocotea porosa*, *Cedrela fissilis*, *Podocarpus lamberttii* and *Dicksonia sellowiana* (Klein 1960; Alves da Silva et al. 1997). In the agricultural setting, *I. paraguariensis* is managed as a shrub and the leaves, twigs and stems are harvested annually. The species is most commonly planted in open plantations under native conditions, but it also grows in the forest understorey and midstorey. *A. angustifolia* is a dominant canopy species which grows to heights of 25–35 m and has a straight bole (Silba 1986). The species is valued for

**Table 1** Chemical soil characteristics for all treatments

| | Depth (cm) | $Al^{3+}$ ($cmol^+/kg^{-1}$) | $Ca^{2+}$ ($cmol^+/kg^{-1}$) | $Mg^{2+}$ ($cmol^+/kg^{-1}$) | $K^+$ ($cmol^+/kg^{-1}$) | eCEC ($cmol^+/kg^{-1}$) | Total nitrogen (%) | Total inorganic carbon (%) | pH |
|---|---|---|---|---|---|---|---|---|---|
| Monoculture: 30 year | 0–5 | 1.59 | 7.08 | 2.50 | 1.11 | 12.28 | 0.23 | 2.50 | 5.58 |
| Monoculture: 30 year | 5–10 | 1.84 | 5.99 | 1.44 | 0.75 | 10.03 | 0.19 | 1.89 | 5.27 |
| Agroforestry: 30 year | 0–5 | 2.26 | 6.29 | 1.82 | 0.58 | 10.95 | 0.20 | 2.35 | 5.44 |
| Agroforestry: 30 year | 5–10 | 2.69 | 3.60 | 0.91 | 0.35 | 7.54 | 0.16 | 1.63 | 4.99 |
| Monoculture: 50 year | 0–5 | 2.01 | 6.07 | 2.35 | 0.61 | 11.05 | 0.20 | 2.19 | 5.49 |
| Monoculture: 50 year | 5–10 | 2.31 | 4.04 | 1.36 | 0.39 | 8.10 | 0.17 | 1.81 | 5.19 |
| Agroforestry: 50 year | 0–5 | 1.34 | 9.56 | 2.78 | 0.64 | 14.31 | 0.26 | 2.87 | 5.83 |
| Agroforestry: 50 year | 5–10 | 1.45 | 5.83 | 1.68 | 0.42 | 9.38 | 0.19 | 1.92 | 5.43 |
| Forest control | 0–5 | 1.39 | 13.1 | 2.72 | 0.8 | 18.02 | 0.36 | 3.73 | 5.58 |
| Forest control | 5–10 | 1.34 | 8.92 | 1.86 | 0.63 | 12.76 | 0.25 | 2.48 | 5.37 |

Analysis of extractable $Al^{3+}$, $Ca^{2+}$, $Mg^{2+}$, $K^+$, eCEC, total nitrogen, total inorganic carbon and pH were performed following standard procedures for tropical soils (Hendershot and Duquette 1986; Kuo 1996; Sumner and Miller 1996; Thomas 1996) timber and, like *I. paraguariensis*, is often grown in plantations.

## Experimental design

The study was conducted on twenty plantations in the region of Monte Carlo in Misiones, Argentina. All sites contained 1–8 ha of *I. paraguariensis* on terrain on which the slope did not exceed 5%. Prior land use for all sites was primary or secondary forest with no previous agricultural history. Ten sites comprised monoculture *I. paraguariensis* plantations and ten were mixed systems of *I. paraguariensis* intercropped primarily with *A. angustifolia* (Fig. 1). To assess the effects of age, half of the plantations from each treatment were 30 years old and half were 50 years old. Plantation age and site history was determined by interviews with the landowners. No inorganic nutrient amendments were applied to any of the sites, but all site managers reported occasional use of the herbicide, glyphosate. One forest site, with no history of clearing, was sampled to provide baseline control values for soil nutrients typical of the region. All sites were situated at altitudes of 180–260 m.

On each plantation, four 10 $m^2$ circular plots were randomly chosen using unequal probability list sampling. To compare soil nutrient levels across treatments, six soil cores were taken using a 6-cm diameter corer for each of the four plots at two depths, 0–5 cm and 5–10 cm. Sampling was confined to the first 10 cm of the soil profile based on regional protocol for determining soil fertility for this soil type. One *I. paraguariensis* tree marked the centre of each circular plot and soil cores were taken at two points below the edge of the tree crown of the three central trees within rows. The six cores for each depth were air dried at room temperature, ground, sieved to 2 mm, homogenized and transported in polythene bags for analysis in Greeley laboratories, Yale University, USA. To determine plant competitiveness, root collar diameter (r.c.d.) was measured for *I. paraguariensis* and diameter at breast height and live crown height were determined for the intercropped species. Mortality of *I. paraguariensis* was determined by counting the number of dead trees in each plot.

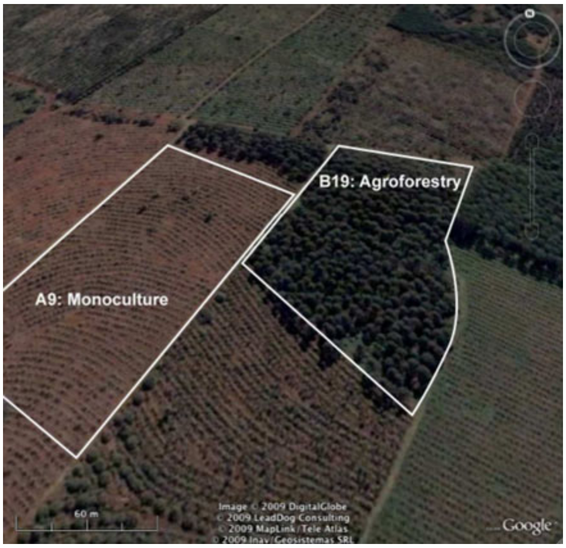


**Fig. 1** Satellite imagery obtained from Google Earth of two adjacent study sites

## Chemical analysis

The pH of air-dried soil samples was obtained using the 1:1 soil to deionized water method (Thomas 1996), while effective cation exchange capacity (eCEC) was determined by summation using the barium chloride compulsive exchange method. Samples were analyzed using an inductively coupled plasma mass spectrometer (ICP-MS Perkin-Elmer Optima 3000). Soil subsamples were dried at 105°C to determine dry weight, with 10% sample replication (Hendershot and Duquette 1986; Sumner and Miller 1996). This method gives results close to field conditions by avoiding the use of a buffering agent; as the eCEC of Ultisols and Oxisols may fluctuate depending on the pH, the unbuffered method gives less inflated results. Additionally, this method is better at capturing exchangeable aluminum ($Al^{3+}$) concentrations, an elemental form which is often present in soils with pH <5. Acid soils often contain significant levels of aluminum, as decreases in pH lead to the decomposition of aluminum silicate clays, releasing Al ions. While the overall concentration of aluminum may be very low, aluminum toxicity and reduced plant growth may become a concern for growers when 60% or more of the eCEC is occupied by exchangeable Al (Coleman et al. 1959; Kamprath 1972).

The Mehlich 1 method was used to extract exchangeable phosphorus, suitable for soils with a low pH (<6.5), low CEC (<10 meq 100 $g^{-1}$), and low organic matter (<5%) (Kuo 1996). Samples were analyzed using the ICP-MS. To determine nitrogen and inorganic carbon concentrations, soil was ground to 180 µm, dried at 105°C, and analyzed using a Thermo Electron Flash EA 1112 CHN analyzer (Thermo Electron Corporation, Waltham, MA). Calibration against the standard reference material, aspartic acid, showed a coefficient of variation of 0.1% or less for C and N concentrations for all samples.

### Data analysis

Differences in soil nutrient levels associated with treatment, age and the treatment*age interaction were analyzed using MANOVA in SAS (PROC GLM, Version 9.1, SAS Institute, 2002–2003). Wilks' $\lambda$ values are reported for all datasets. Data from the four replicates for each site were averaged for all analyses and tested for multivariate normality using chi-squared quantile plots of the raw data as well as the MANOVA residuals.

MANOVAs were run separately for soil depths of 0–5 and 5–10 cm. Analysis of soil characteristics (Ca, Mg, K, P, N, C and Al concentrations, eCEC and pH) were run separately from vegetative characteristics (r.c.d. in *I. paraguariensis* and mortality in *I. paraguariensis*). Multivariate contrasts were run using SAS for the following combinations: 30 year old monoculture vs. 30 year old agroforestry sites, 50 year old monoculture vs. 50 year old agroforestry sites, 30 year old monoculture vs. 50 year old monoculture sites, 30 year old agroforestry vs. 50 year old agroforestry sites.

Two-way ANOVAs were run in SAS to show individual nutrient responses to treatment and age. Boxplots of multivariate and univariate contrasts were created using R (Version 1.27, R Foundation for Statistical Computing 2008). To illustrate differences between multivariate contrasts, ordination (correspondence analysis) and discriminant analysis (score plots) were run in R. Principal components analysis was run in R to show the relationship of aluminum to other soil nutrients.

## Results

### Treatment effects on soil nutrient concentrations

Soil characteristics for the 0–5 cm depth differed significantly between sites as a result of the interaction between age and treatment ($P = 0.0162$), and for overall treatment effects ($P = 0.0215$). Nutrient concentrations for this horizon were significantly lower for the 30 year old agroforestry sites than for the *I. paraguariensis* monoculture sites ($P = 0.0026$). No significant treatment differences were seen for the 50 year old sites, possibly due to the initial difference in site quality found for the younger sites. At 5–10 cm depth, soil characteristics did not differ between treatments ($P = 0.2330$), but the 30 year old *I. paraguariensis* monoculture sites had significantly lower nutrient concentrations than the corresponding 50 year old sites ($P = 0.0050$) (Table 2).

**Table 2** MANOVA analysis of soil characteristics: extractable $Al^{3+}$, $Ca^{2+}$, $Mg^{2+}$, $K^{+}$, eCEC, total nitrogen and total inorganic carbon

| | Depth | *F* value | Num DF | Den DF | *P* value |
|---|---|---|---|---|---|
| *Source* | | | | | |
| Treatment effect | 0–5 | 4.07 | 6 | 11 | 0.0215** |
| Age effect | 0–5 | 3.69 | 6 | 11 | 0.0294** |
| Treatment*age effect | 0–5 | 4.42 | 6 | 11 | 0.0162** |
| Treatment effect | 5–10 | 1.61 | 6 | 11 | 0.2330 |
| Age effect | 5–10 | 2.97 | 6 | 11 | 0.0560* |
| Treatment*age effect | 5–10 | 1.75 | 6 | 11 | 0.1985 |
| *Contrast* | | | | | |
| Contrast 1 | 0–5 | 7.17 | 6 | 11 | 0.0026*** |
| Contrast 2 | 0–5 | 1.32 | 6 | 11 | 0.3275 |
| Contrast 3 | 0–5 | 6.11 | 6 | 11 | 0.0050*** |
| Contrast 4 | 0–5 | 2.00 | 6 | 11 | 0.1509 |
| Contrast 1 | 5–10 | 2.72 | 6 | 11 | 0.0717* |
| Contrast 2 | 5–10 | 0.65 | 6 | 11 | 0.6930 |
| Contrast 3 | 5–10 | 3.13 | 6 | 11 | 0.0482** |
| Contrast 4 | 5–10 | 1.59 | 6 | 11 | 0.2378 |

*Num DF* numerator degrees of freedom; *Den DF* denominator degrees of freedom; * $P \leq 0.10$; ** $P \leq 0.05$; *** $P \leq 0.01$

Contrast 1 = 30 year monoculture vs. 30 year agroforestry sites; Contrast 2 = 50 year monoculture vs. 50 year agroforestry sites; Contrast 3 = 30 year monoculture vs. 50 year monoculture sites; Contrast 4 = 30 year agroforestry vs. 50 year agroforestry sites

### Age effects on soil nutrient concentrations

Soil nutrient characteristics at 0–5 cm depth differed between sites as an overall result of age ($P = 0.0294$). Additionally, the 30 year old *I. paraguariensis* monoculture sites had significantly higher nutrient concentrations than the corresponding 50 year old sites. Overall soil nutrient concentrations for the 30 and 50 year old agroforestry sites did not differ significantly, suggesting that monoculture sites of *I. paraguariensis* are more prone to soil nutrient decline over time. Soil nutrient characteristics at 5–10 cm depth only differed significantly as an overall result of age ($P = 0.0560$) (Table 2).

## Age and treatment effects on individual nutrients

Soil nutrient concentrations at 0–5 cm depth were not significantly different for Ca, eCEC, N and C on the 30 year old sites, but differed significantly between treatments on the 50 year old sites ($P < 0.07$) (Table 2). The 50 year old agroforestry sites had greater concentrations of these nutrients than the corresponding *I. paraguariensis* monoculture sites. At both soil depths, the 50 year old agroforestry sites had significantly higher concentrations of Ca, Mg, eCEC, N and C than the 30 year old agroforestry sites, showing the positive effect of this treatment over time (Fig. 2). K concentrations were significantly greater on the 30 year *I. paraguariensis* monoculture sites than on the 50 year old sites ($P < 0.0001$), but no difference was found between agroforestry sites of different age (Table 3). Phosphorus levels were not included in the statistical analysis because concentrations were below detection limits at all sites.

## Relationship of aluminum to other soil nutrients

Principal components analysis showed very high correlations between all nutrients. Specifically, a

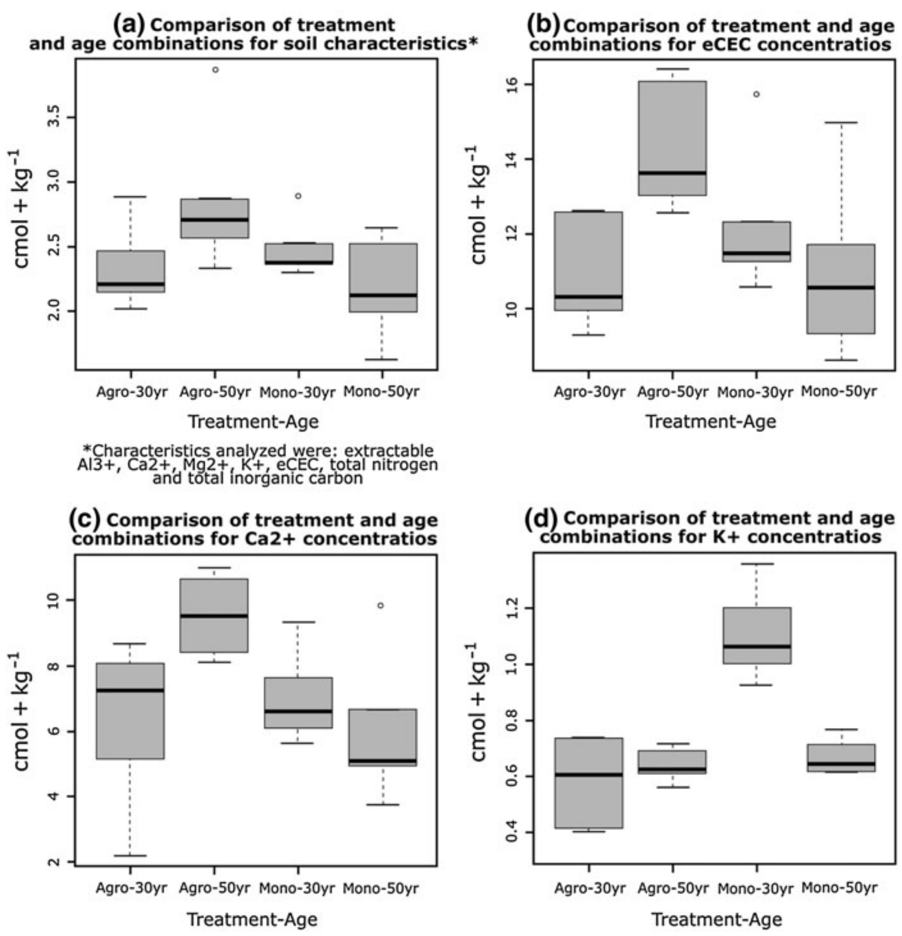


**Fig. 2** Boxplots comparing different treatment and age combinations for soil characteristics at soil depth 0–5 cm

**Table 3** Univariate contrasts of soil characteristics: extractable $Al^{3+}$, $Ca^{2+}$, $Mg^{2+}$, $K^{+}$, eCEC, total nitrogen and total inorganic carbon

| Contrast | Soil depth 0–5 cm | | | Soil depth 5–10 cm | | |
|---|---|---|---|---|---|---|
| | *F* value | DF | *P* value | *F* value | DF | *P* value |
| *Contrast 1* | | | | | | |
| $Al^{3+}$ | 1.11 | 1 | 0.3028 | 1.13 | 1 | 0.3045 |
| $Ca^{2+}$ | 0.38 | 1 | 0.5452 | 6.39 | 1 | 0.0224** |
| $Mg^{+}$ | 3.88 | 1 | 0.0664* | 3.20 | 1 | 0.0926* |
| $K^{+}$ | 21.67 | 1 | <0.0001*** | 9.61 | 1 | 0.0069*** |
| eCEC | 1.12 | 1 | 0.3660 | 4.01 | 1 | 0.0623* |
| N | 2.27 | 1 | 0.1510 | 5.87 | 1 | 0.0277** |
| C | 0.32 | 1 | 0.5808 | 3.12 | 1 | 0.0965* |
| *Contrast 2* | | | | | | |
| $Al^{3+}$ | 1.13 | 1 | 1.1400 | 1.17 | 1 | 0.2957 |
| $Ca^{2+}$ | 7.41 | 1 | 0.0151** | 3.56 | 1 | 0.0773* |
| $Mg^{+}$ | 1.55 | 1 | 0.2308 | 1.15 | 1 | 0.3004 |
| $K^{+}$ | 0.08 | 1 | 0.7746 | 0.06 | 1 | 0.8132 |
| eCEC | 6.72 | 1 | 0.0196** | 1.06 | 1 | 0.3184 |
| N | 6.82 | 1 | 0.0189** | 1.06 | 1 | 0.3189 |
| C | 6.76 | 1 | 0.0194** | 0.61 | 1 | 0.4453 |
| *Contrast 3* | | | | | | |
| $Al^{3+}$ | 0.44 | 1 | 0.5184 | 0.35 | 1 | 0.5638 |
| $Ca^{2+}$ | 0.62 | 1 | 0.4424 | 4.26 | 1 | 0.0556* |
| $Mg^{2+}$ | 0.17 | 1 | 0.6831 | 0.08 | 1 | 0.7783 |
| $K^{+}$ | 27.47 | 1 | <.0001*** | 7.70 | 1 | 0.0135** |
| eCEC | 0.95 | 1 | 0.3437 | 2.42 | 1 | 0.1396 |
| N | 1.89 | 1 | 0.1885 | 2.16 | 1 | 0.1606 |
| C | 1.40 | 1 | 0.2548 | 0.29 | 1 | 0.5985 |
| *Contrast 4* | | | | | | |
| $Al^{3+}$ | 2.13 | 1 | 0.1637 | 2.41 | 1 | 0.1401 |
| $Ca^{2+}$ | 6.52 | 1 | 0.0213** | 5.53 | 1 | 0.0318** |
| $Mg^{2+}$ | 7.84 | 1 | 0.0128** | 6.62 | 1 | 0.0204** |
| $K^{+}$ | 0.46 | 1 | 0.5074 | 0.32 | 1 | 0.5793 |
| eCEC | 7.14 | 1 | 0.0167** | 2.19 | 1 | 0.1585 |
| N | 7.54 | 1 | 0.0144** | 3.92 | 1 | 0.0653* |
| C | 3.93 | 1 | 0.0650* | 4.04 | 1 | 0.0615* |

*Num DF* numerator degrees of freedom; *Den DF* denominator degrees of freedom; * $P \leq 0.10$; ** $P \leq 0.05$; *** $P \leq 0.01$

Contrast 1 = 30 year monoculture vs. 30 year agroforestry sites; Contrast 2 = 50 year monoculture vs. 50 year agroforestry sites; Contrast 3 = 30 year monoculture vs. 50 year monoculture sites; Contrast 4 = 30 year agroforestry vs. 50 year agroforestry sites

positive relationship existed between all soil properties (Ca, Mg, K, N, C, pH) except aluminum, which had a negative association (Fig. 3).

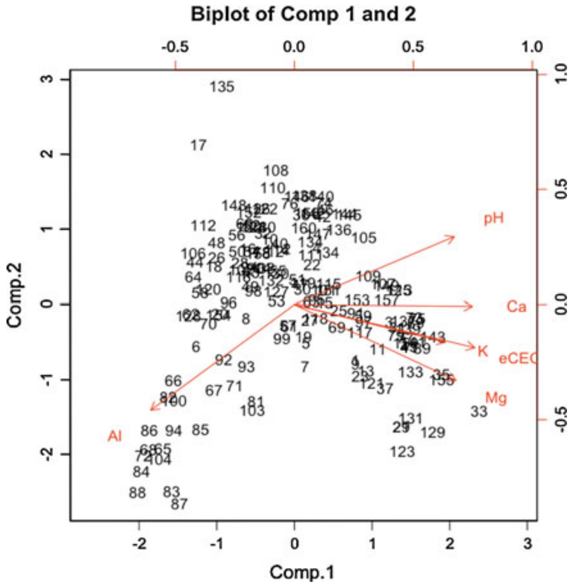


**Fig. 3** Principal components analysis scores for soil characteristics at soil depth 0–5 cm: extractable $Al^{3+}$, $Ca^{2+}$, $Mg^{2+}$, $K^{+}$, eCEC and pH

## Growth parameters and plant mortality

Vegetative properties differed significantly between sites as an overall result of the difference in their age ($P = 0.0004$), but there was no overall effect of treatment ($P = 0.\ 2558$) or treatment × age interaction ($P = 0.\ 3834$). Mortality in *I. paraguariensis* increased significantly on both monoculture and agroforestry sites over time ($P < 0.03$), but there was no overall difference between treatments. r.c.d. in *I. paraguariensis* increased significantly with age on the *I. paraguariensis* monoculture sites ($P = 0.0222$) (Table 4).

## Discussion

Soil nutrient concentrations were affected by intercropping *A. angustifolia* with *I. paraguariensis*. The interactive effects of intercropping and age support the use of these mixed plantation systems for soil quality management. The use of agroforestry to increase soil fertility is well documented by other studies (Aranguren et al. 1982; Fassbender et al. 1990; Nair et al. 1999), which support the results of the present study.

**Table 4** MANOVA analysis of vegetative characteristics: *I. paraguariensis* mortality and r.c.d

| | *F* value | DF | *P* value |
|---|---|---|---|
| Source | | | |
| Treatment effect | 1.50 | 2 | 0.2558 |
| Age effect | 13.94 | 2 | 0.0004*** |
| Treatment*age effect | 1.02 | 2 | 0.3834 |
| Contrast | | | |
| Mortality | | | |
| Contrast 1 | 0.38 | 6 | 0.5472 |
| Contrast 2 | 2.92 | 6 | 0.1067 |
| Contrast 3 | 13.15 | 6 | 0.0023*** |
| Contrast 4 | 6.41 | 6 | 0.022** |
| r.c.d. | | | |
| Contrast 1 | 0.25 | 1 | 0.6263 |
| Contrast 2 | 1.13 | 1 | 0.3027 |
| Contrast 3 | 6.41 | 1 | 0.0222** |
| Contrast 4 | 0.94 | 1 | 0.3467 |

*Num DF* numerator degrees of freedom; *Den DF* denominator degrees of freedom; ** $P \leq 0.05$; *** $P \leq 0.01$

Contrast 1 = 30 year monoculture vs. 30 year agroforestry sites; Contrast 2 = 50 year monoculture vs. 50 year agroforestry sites; Contrast 3 = 30 year monoculture vs. 50 year monoculture sites; Contrast 4 = 30 year agroforestry vs. 50 year agroforestry sites

While the Ultisols of the Misiones region are well suited for *I. paraguariensis* plantations (Moscatelli and Pazos 2000), inherent site quality varies and not all sites produce desirable yerba mate yields. Plantation owners situated on particularly poor sites may therefore be inclined to diversify by using agroforestry methods to obtain the economic benefits gained by growing the multiple products. This study may support this practice of diversification on poor sites as, at both soil depths, the 30 year agroforestry sites had lower soil nutrient levels than the 30 year *I. paraguariensis* monoculture sites, while there were no significant differences between treatments on the older sites. This initial difference of soil quality on younger sites may contribute to why significant differences between treatments were not seen on the older sites. We would otherwise expect to see a treatment difference as nutrient concentrations decreased over time on the monoculture sites but remained constant on the agroforestry sites. Plantation owners reported fewer harvests of *I. paraguariensis* on 50 year old plantations due to declining plant productivity, perhaps providing an explanation of why the positive effects of intercropping on soil nutrient status is significant only once *I. paraguariensis* production begins to decline. Additionally, *I. paraguariensis* and *A. angustifolia* may have competed more vigorously on the 30 year old agroforestry sites, thereby causing more severe depletion of soil nutrients. This study supports previous findings (Parrotta et al. 1997) that agroforestry systems may provide an opportunity for soil remediation on degraded land, and also suggests that monoculture plantations are more susceptible than mixed systems to declining soil nutrient status over time (Ewel et al. 1991; Nair et al. 1999; Cardoso and Kuyper 2006; Méndez et al. 2009).

Increased nutrient cycling due to greater litter fall is one of the potential benefits of agroforestry systems for improving soil quality (Glover and Beer 1986; Aranguren et al. 1982). As demonstrated in this study, the increasing individual nutrient concentrations over time on agroforestry sites support the use of these mixed systems for soil quality improvement. When comparing the 30 year old sites at a soil depth of 0–5 cm, *I. paraguariensis* monocultures had significantly higher concentrations of Mg and K, whereas no difference was seen at 50 year old sites. Additionally, a comparison of the 50 year old sites show significantly higher concentrations of Ca, eCEC, N and C on the agroforestry sites, while no difference between treatments existed on the younger sites. Thus, even with uneven baselines on the younger sites, there was a trend for the mixed land use system to improve or maintain soil quality, whereas nutrient concentrations were depleted over time on the *I. paraguariensis* monocultures sites. At a soil depth of 5–10 cm, the concentrations of all of the individual nutrients were greater on the younger monoculture sites than on the corresponding agroforestry sites. Previous research involving agroforestry systems containing *Coffea* spp. supports the finding that Ca and K concentrations decreased over time on the *I. paraguariensis* monoculture sites whereas Ca, Mg, N, and C concentrations increased on the agroforestry sites (Aranguren et al. 1982; Babbar and Zak 1994). The intercropped *A. angustifolia* trees on the 50 year old sites were more mature and thus likely to deposit greater amounts of organic matter and provide more soil cover and shade to protect against erosion and soil moisture loss (Nair et al. 1999).

While aluminum is often an issue in tropical soils, the present study revealed no significant differences in aluminum concentrations in any of the treatment x age combinations. However, the negative correlation of aluminum concentration with those for all other nutrients is consistent with our understanding of how aluminum functions within soil (Juo and Franzluebbers 2004).

The clayey kaolinic soils of Misiones have high P-fixing capabilities, which may explain why P concentrations were below detection limits for all sites. P-fixation is generally associated with soils that have a high clay content and are rich in iron and aluminum oxides as phosphorus slowly becomes available to plants by solubilization (Sanchez et al. 2003; Juo and Franzluebbers 2004). The methods used in the present study to determine P concentration were only suitable for the detection of exchangeable P and, given the lack of available P in these soils, further studies might consider using other methods to determine total P concentration. Due to the deficit of available P at all the sites in this study, agroforestry may not be a viable technique for improving soil P status; further research is required to determine whether crop production is adversely affected as a result.

Analysis of r.c.d. in *I. paraguariensis* showed an increase over time at the monoculture sites. This finding may reflect the increased shading at the older agroforestry sites, which may have reduced plant growth by limiting light supplies. No significant difference existed between treatments for r.c.d. in *I. paraguariensis* on the 30 year plantations. Given that biomass production in *I. paraguariensis* is typically in decline after 30 years, the negative effects of these mixed systems on productivity may not be considered a huge threat by farmers. Furthermore, this study shows that the agroforestry systems were better than monocultures of *I. paraguariensis* in maintaining soil nutrient levels over time, so growers must consider the potential for these systems to improve security though protection of land quality. Niche markets for products grown using agroforestry practices are expanding and may provide the economic incentives necessary for these systems to be successful (Lawson 2009). For the yerba mate-agroforestry system to become prevalent in Misiones, plantation owners must feel confident that this land use scheme will provide both ecological and economic incentives.

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