Rehabilitation of degraded lands in Misiones, Argentina

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This article reports on the status of plantation forestry in Misiones (North-East Argentina) and describes results from recent experiences on land restoration projects using indigenous tree species. The findings of this research are already being used in community forestry projects in the region, which include open mixed and single-species plantations and enrichment planting in degraded secondary forests.

Balfourodendron riedelianum (Rutaceae, "guatambú blanco"), 13 year-old, grew best on site 3, the most fertile, in a private property near the town of Santiago de Liniers, in comparison with growth in the most degraded site. The growth of this species was better at this site than in other trials in the region where *B. riedelianum* has been tested in enrichment plantings.
Photo F. Montagnini.

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RÉSUMÉ

RÉHABILITATION DE SOLS DÉGRADÉS À MISIONES, ARGENTINE

Misiones, province d'Argentine, couvre moins de 1 % de la superficie du pays mais abrite 40 % de sa biodiversité et produit 70 % de son bois. Suite au défrichage des forêts, de nouvelles utilisations des terres s'imposaient. Nous présentons les résultats de projets de réhabilitation des terres intégrant des essences indigènes. Des essais (1990-1991) ont permis de tester *Ilex paraguariensis* en plantations mixtes et en agroforesterie. La meilleure croissance sur sol pauvre était obtenue avec *Enterolobium contortisiliquum* et *Astronium balansae*. Les résultats pour *Balfourodendron riedelianum*, très prisée dans la région, étaient excellents en sol fertile, sous réserve d'une bonne gestion. L'association de ces essences avec *I. paraguariensis* semble appropriée, puisque les récoltes d'*I. paraguariensis* permettent une rentabilisation rapide des investissements. Des essais d'enrichissement (1988-1990) dans des zones forestières surexploitées ont donné, sept ans après la plantation, les meilleurs résultats avec *Bastardiopsis densiflora, E. contortisiliquum, Nectandra lanceolata, Ocotea puberula* et *Peltophorum dubium*. Dans la réserve Guaraní, les meilleures essences au bout de treize ans étaient *O. puberula, B. densiflora* et *Cordia trichotoma*. Ces essences ont également des effets bénéfiques pour le sol, et peuvent améliorer les forêts dégradées. L'intégration d'essences à rotation plus courte (palmier *Euterpe edulis*) accélère la rentabilisation. Ces résultats sont utilisés pour encourager la plantation d'arbres dans le cadre de projets de sylviculture communautaire. Les chercheurs fournissent conseils et assistance ainsi que des plants et un suivi de la plantation et de l'entretien. Les premiers résultats sont prometteurs et d'autres municipalités rejoignent les projets.

Mots-clés : sol dégradé, plantation d'enrichissement, essence autochtone, plantation, bois, *Ilex paraguariensis*, Misiones, Argentine.

ABSTRACT

REHABILITATION OF DEGRADED LANDS IN MISIONES, ARGENTINA

Misiones Province, in Argentina, covers less than 1% of the total area of the country but harbors almost 40% of its biodiversity and produces over 70% of its timber. Forest clearing has caused substantial changes, and alternative land uses have become necessary due to soil degradation and land abandonment. This article presents the results of land rehabilitation projects using indigenous tree species. In 1990-1991, trials began to test mixed plantations and agroforestry with *Ilex paraguariensis*. *Enterolobium contortisiliquum* and *Astronium balansae* showed the best growth on poor soils. *Balfourodendron riedelianum*, a valued tree in this region, had excellent performance on fertile soils and with adequate management. The association of trees with *I. paraguariensis* appeared appropriate, since *I. paraguariensis* harvests bring short-term returns on investments. Enrichment trials were established in 1988-1990 in overexploited forests. Seven years after planting, the best species were *Bastardiopsis densiflora, E. contortisiliquum, Nectandra lanceolata, Ocotea puberula,* and *Peltophorum dubium*. In the Guaraní Reserve, the best species at thirteen years were *O. puberula, B. densiflora,* and *Cordia trichotoma*. These species also have beneficial effects on soils, and can thus improve the condition of degraded forests. Incorporating species with a shorter harvest age (*Euterpe edulis* palm) can accelerate investment returns. These results are being used to promote tree planting in community forestry projects. Researchers provide tree seedlings, help planting and advise on establishment and caring. Initial results are promising, and other municipalities are joining the projects.

Keywords: degraded land, enrichment planting, native species, plantation, timber, *Ilex paraguariensis*, Misiones, Argentina.

RESUMEN

RESTAURACIÓN DE SUELOS DEGRADADOS EN MISIONES, ARGENTINA

La provincia de Misiones representa menos del 1% de la superficie de Argentina, pero alberga casi el 40% de la biodiversidad y produce más del 70% de la madera. Misiones ha tenido cambios de uso de la tierra substanciales debido al corte de bosques, y son necesarios usos alternativos debido a la degradación de suelos y al abandono de tierras. Se presentan resultados de proyectos de restauración de tierras utilizando especies arbóreas nativas. En 1990-1991 se ensayó una serie de plantaciones mixtas y sistemas agroforestales con *Ilex paraguariensis*. *Enterolobium contortisiliquum* y *Astronium balansae* tuvieron el mejor crecimiento en suelos pobres. *Balfourodendron riedelianum*, una especie valiosa en la región, tuvo un comportamiento excelente en suelos fértiles y con manejo adecuado. La asociación de árboles con *I. paraguariensis* fue aparentemente apropiada, ya que las cosechas de *I. paraguariensis* representan un retorno de la inversión a corto plazo. En 1988-1990 se establecieron experimentos de enriquecimiento de bosques sobreexplotados. A los siete años, las mejores especies fueron *Bastardiopsis densiflora, E. contortisiliquum, Nectandra lanceolata, Ocotea puberula* y *Peltophorum dubium*. En la Reserva Guaraní, a los trece años las mejores especies fueron *O. puberula, B. densiflora,* y *Cordia trichotoma*. Estas especies también tienen efectos beneficiosos sobre los suelos, mejorando las condiciones de los bosques degradados. La incorporación de especies con cosecha más temprana (palma *Euterpe edulis*) puede acelerar el retorno de la inversión. Estos resultados se están utilizando para estimular la plantación de árboles en proyectos comunitarios. Los investigadores proveen los arbolitos, ayudan a mantener los árboles y asesoran sobre el establecimiento y cuidado. Los resultados iniciales son promisorios, y otras municipalidades se están incorporando a estos proyectos.

Palabras clave: tierra degradada, enriquecimiento, especie nativa, plantación, madera, *Ilex paraguariensis*, Misiones, Argentina.

Introduction

The Province of Misiones in north-eastern Argentina (25-28°S, 53-56°W, elevation 100-800 m) (Figure 1) covers an area of approximately 30 000 km², less than 1% of the total area of the country. However, the Province of Misiones harbors almost 40% of Argentina's biodiversity and produces over 70% of its timber (Gobierno de la Provincia De Misiones, 2003). In recent years, the province of Misiones, which has traditionally supplied timber products to the rest of the country and for export, has been applying the "multiple use" approach to its forest resources, to include the use of non-timber forest products and to develop environmental and recreational forest services.

However, alternatives for land use are clearly necessary to support current economic and ecological needs: inappropriate land uses and management, such as the proliferation of shifting agriculture or inadequate soil techniques in plantation management, have often led to soil degradation and subsequent abandonment of lands in the region (Montagnini, Jordan, 2005).

In 1989, the Yale School of Forestry and Environmental Studies (FES) signed an agreement with the School of Forestry at the National University of Misiones (UNaM) to carry out collaborative studies in reforestation and agroforestry. Experimental single-species and mixed plantations, agroforestry systems on degraded land and enrichment trials in degraded forests were established using native trees of economic value (Fernández *et al.*, 1997; Montagnini *et al.*, 1998; Eibl *et al.*, 2000). This article reports on the status of plantation forestry in Misiones and advances results of recent experiences on land restoration projects using indigenous tree species in the region.

Misiones forests, past and present

The Köppen system (Köppen, 1918) classifies the climate of Misiones as Cfa, where C stands for a mesothermic climate, f for lack of a well-defined dry season, and a for subtropical. Annual precipitation ranges from 1700 to 2400 mm. Means temperatures over a 17-year period (1985-2002) are 25°C with a maximum of 39°C for the hottest month (January), and 14°C with a minimum of -6°C for the coldest month (July) .

The Paranaense forest, a typical forest formation in Misiones, is one of the most diverse ecosystems in both Argentina and Paraguay. In its mature form, the Misiones forest contains an average of about 100 tree species per hectare. Species composition varies with geographical location: for example, the presence of *Araucaria angustifolia* (Bert.) O. Ktze. ("pino Paraná") in association with tree ferns is restricted to higher elevations in the north-eastern part of the province, while *Aspidosperma polyneuron* Müll. Arg. ("palo rosa") in association with the "palmito" palm (*Euterpe edulis* Mart.) only occurs in the North. The complex forest structure includes trees reaching heights of up to 40 m, with no single species reaching "importance values" greater than 8%. Importance values are generally calculated as the average of the relative abundance and relative frequency of each species in forest

Figure 1.
Map of South America showing the location of the Province of Misiones (in red) in north-eastern Argentina, on the border with Paraguay and Brazil.

Mixed plantation of native tree species: *Enterolobium contortisiliquum* (Fabaceae, "timbó colorado"), *Lonchocarpus muehlbergianum* (Fabaceae, "rabo molle"), *Astronium balansae* (Anacardiaceae, "urunday"), and *Peltophorum dubium* (Fabaceae, "caña fístula"), 8 to 13 year-old depending on the species. Site 1, the most degraded of the experimental sites, is located on land around the Escuela Agrotécnica, owned by the National University of Misiones. Photo F. Montagnini.

inventories, where individuals of each species are counted in sample plots. Importance values below 10-15% are typical of very diverse forests where no single species is dominant, leaving room for other species (Odum, 1983). In the Misiones forests there is also a dense understorey of lianas, tree ferns, palms and bamboos, small shrubs and herbaceous plants.

In Misiones, about 200 local producers own forest lands subject to Forest Management Plans, bringing the total area of managed forest to almost 500 000 hectares (Gobierno de la Provincia De Misiones, 2003). Timber extraction is subject to minimum diameter regulations (Montagnini *et al.*, 1998 and 2001). Under the Minimum Diameter cutting method that prevails in Argentina, commercial species may only be extracted if they have a minimum stipulated diameter at breast height (dbh) of 40 to 55 cm, depending on the species.

Natural protected areas cover a total of 481 000 hectares (almost 16% of the provincial territory). The 53 Protected Areas of different categories include national parks and reserves, 17 provincial parks, 16 private parks and wildlife refuges, one biosphere reserve, and one conservation and sustainable development area known as the Green Biological Corridor ("Corredor Verde"). Protected areas are found throughout the province of Misiones, although the largest tracts are in the North-East where the Iguazú National Park and the Corredor Verde are located. In general, all ecosystems in the Paranaense forest are being preserved in these protected areas (Gobierno de la Provincia De Misiones, 2003).

The establishment of industrial plantations

A forest inventory revealed that the total area of natural forests in Misiones amounted to 2 600 million hectares in 1850, but as a result of logging and clearing to establish plantations and agriculture, only 1 222 million hectares remained by 1977 (Gobierno de la Provincia De Misiones, 2003). This was largely the consequence of government incentives for commercial plantations of pulpwood (principally *Pinus elliotii* E. and *Pinus taeda* L.), and cash crops such as soybeans, "yerba mate" (South American holly, *Ilex paraguariensis* Saint Hilaire, Aquifoliaceae) and tea.

The first tree plantations were established in the 1920s with the native species *Araucaria angustifolia*. Pines, which were first planted in 1948, and now dominate the landscape in Misiones, especially in the West of the Province along the Paraná river. The first cellulose and paper plant was installed in the 1950s near the town of Eldorado on the Paraná river. The cellulose and paper industry soon consumed all natural and planted supplies from araucarias, and had to rely on plantations of pines and eucalypts to meet their needs for fiber. By the mid-1980s, there were already over 150 000 hectares of forest plantations, and as a result, forest cover in the province, including plantations, had increased to 67% by 1985.

Due to the relatively low prices paid by the cellulose industries for plantation pulpwood, sawmills harvesting timber for boards began to proliferate, especially in the northern part of the province, later spreading to the rest of the province. The advantages for the development of the pulp and timber industry in Misiones were: i) the high yields and relatively short rotation times of plantation species; ii) availability of high quality labor; and iii) highly diversified natural forest resources.

Today, Misiones has about 330 000 hectares of planted forest. In 2003, total production of roundwood from plantations in Misiones was about 5 million m³, or 70% of total production, with the remainder supplied from natural forests.

Most plantations consist of exotic species such as *Pinus* spp. (*P. elliotii*, *P. taeda*, and others), *Melia azedarach* L. var gigantea ("paraíso"), *Eucalyptus* spp., *Paulownia* spp., *Toona ciliata* M. Roem., *Grevillea robusta* A. Cunn., and the native *Araucaria angustifolia*. In Misiones, the area planted with native tree species (*Araucaria angustifolia* and a few others) covers less than 10% of the total area of forest plantations. This situation is partly due to insufficient information regarding suitable silvicultural methods for establishing and managing plantations of native species.

Balfourodendron riedelianum (Rutaceae, "guatambú blanco"), 13 year-old, growing on moderately degraded soils in site 2, in a private property near the town of Eldorado. After surviving the critical establishment stage, this valuable timber species grew well on low-fertility soils. Notice yerba mate (*Ilex paraguariensis*, Aquifoliaceae) bushes growing in the understorey. Photo F. Montagnini.

Alternative land use systems for ecosystem restoration in Misiones

A number of initiatives were started in 1980-1990 as part of the Yale School of Forestry and Environmental Studies (FES) collaborative agreement with the School of Forestry at the National University of Misiones (UNaM). The trials focused on finding alternatives to restore degraded forests and lands that had been abandoned by agriculture or other land uses. The trials included mixed and single-species plantations, agroforestry systems and forest enrichment planting. All trials used indigenous species of economic value, building on local knowledge and previous research on ecological characteristics of the species.

Plantations and agroforestry systems using indigenous tree species

In view of the difficult economic and social situation currently prevailing in the province, practical solutions are urgently needed to increase productivity and lessen the negative impacts of land use on existing resources. Local farmers are willing to try new alternatives for ecosystem restoration, including agroforestry combinations with the most common cash crops. In order to suggest productive alternatives for restoring degraded soils, experiments to test the adaptability of native tree species to three sites with different degrees of soil degradation were started in 1990-1991. These trials included mixed plantations and agroforestry systems with yerba mate (*Ilex paraguariensis*), the most common cash crop in the province.

At all three sites used in this research, the terrain is gently undulating, with slopes of less than 6%. The soil, of the Great Group Kandiu-

dults type according to the US Soil Taxonomy classification (Fernández *et al.,* 1997), is reddish, deep, well to moderately well drained, with clay throughout the profile. These soils have low fertility and are poor in organic matter, nitrogen, phosphorus, and other nutrients (Table I). Due to their degraded condition, the suitability of these soils for tree plantations is poor to moderate.

The most degraded site (site 1) had been used for agriculture for over 40 years. In contrast, site 2, with moderate degradation, was an abandoned field that had been used for agriculture for about 20 years and was subsequently invaded by grasses (*Andropogum* spp., *Pennisetum* spp.). Site 3 was the least degraded, and had sustained a plantation of tung (*Aleuritis fordii* Forst.) for about 20 years.

Although the soils at the three sites belonged to the same Great Group of classification, the different use histories mentioned above has produced very different soil degradation situations at each site. Site 1 had the highest degree of physical degradation, as shown by its structural characteristics and high bulk density, with the resulting aeration problems and restrictions on plant root growth. In contrast, site 3 had the fewest symptoms of physical degradation. The same patterns appear in the chemical quality of soils at each site. Nutrient content in site 3 was 2-3 times higher than in site 1, and site 2 had intermediate values for the parameters examined (Table I).

The native tree species tested were: *Enterolobium contortisiliquum* (Vellozo) Morong (Fabaceae, "timbó colorado", *Lonchocarpus muehlbergianum* Hassler (Fabaceae, "rabo molle"), *Astronium balansae* Engl. (Anacardiaceae, "urunday"), *Peltophorum dubium* (Sprengler) Taubert (Fabaceae, "caña fístola"), *Balfourodendron riedelianum* (Engler) Engler (Rutaceae, "guatambú blanco") and *Tabebuia heptaphylla* (Vellozo) Toledo (Bignoniaceae, "lapacho negro").

These species were selected for their ability to grow in full sunlight and for their potential positive effects on soils, as indicated in previous experiments, as well as for their timber value (Eibl *et al.,* 2003). In Misiones, several private companies have planted some of these species as part of their own research, and the UNaM researchers had visited these trials. UNaM researchers have also conducted several studies on the ecology of the most common tree species of the Misiones forest, with the objective of determining their potential for timber production and other alternative uses. It was expected that the leguminous species would contribute to higher nitrogen availability in soils, as suggested by results of studies by UNaM researchers. In addition, studies of the effects of some of the tree species on soils have been conducted by Yale FES and UNaM researchers, to compare soils under the tree canopy with grass-covered soils in adjacent areas (Fernandez *et al.,* 1997).

Growth results of the native tree species are shown in Tables II-IV. In the most degraded site (site 1), *Enterolobium contortisiliquum* had the best growth, suggesting its use to restore poor soils (Table II). In other experiments within the same region, *E. contortisiliquum* showed good performance when grown under 18 year-old pine plantations (*P. elliottii*) with a density of 300 trees per ha. When planted under pine, *E. contortisiliquum* trees grew about one meter in height per year and by one cm dbh per year at four years of age, while their growth in the open was affected by attacks of *Epicauta adspersa* ("bicho moro"), a beetle that consumes the foliage (Crechi *et al.,* 2002). *Epicauta adspersa* had also initially affected the survival and growth of this species at site 3, but the trees later recovered from the attacks. *Enterolobium contortisiliquum* also grew well in enrichment planting trials in the Guaraní Forest Reserve in Misiones (Montagnini *et al.,* 1997). In addition, concomitant research results suggest the ability of this species to improve soil nitrogen and base cation concentration (Fernandez *et al.,* 1997), an excellent advantage when growing this species in the nutrient-poor conditions of highly degraded sites.

Astronuim balansae was also observed to be well suited to the degraded soil conditions of site 1, contrary to *Lonchocarpus muehlbergianum, Balfourodendron riedelianum*

Table I.
Chemical characteristics of soils before planting for the three sites under study.

Site	Soil depth (cm)	Organic matter (%)	Total nitrogen (%)	Extractable P (ppm)	pH in H_2O	Ca^{2+}	Mg^{2+}	K^+	Sum of bases	CEC
							($cmol^+/kg$)		($cmol^+/kg$)	($cmol^+/kg$)
Site 1	0-10	2.1	0.09	1.5	5.2	4.3	1.1	0.20	5.6	7.7
	10-30	0.9	0.07	1.0	5.1	3.6	1.0	0.09	4.7	7.0
Site 2	0-10	2.6	0.24	3.2	5.2	5.8	1.5	0.29	7.6	10.7
	10-30	1.4	0.12	1.3	4.7	4.2	0.9	0.11	5.2	8.7
Site 3	0-10	3.9	0.31	5.4	5.4	8.6	2.3	0.41	11.3	19.6
	10-30	2.3	0.20	4.4	4.6	6.4	1.3	0.21	7.9	12.8

Analyses of organic matter, total nitrogen, pH, CEC, extractable Ca^{2+}, Mg^{2+}, K, and P were performed following standard procedures for tropical soils (Anderson, Ingram, 1989; Fernandez *et al.,* 1997).

Table II.
Growth in diameter at breast height, total height and survival of four native tree species in single-species and mixed plantations in site 1.

Species	Diameter (cm) (Standard deviation)	Height (m) (Standard deviation)	Survival (%)
Enterolobium contortisiliquum single-species Planted August 1990	25.4 (5.88) a max. 41 min. 13,2	11.82 (2.36) a max. 15.8 min. 6.3	46 c
Enterolobium contortisiliquum mixed Planted August 1990	25.3 (4.67) a max. 34.3 min. 14.9	10.57 (1.60) a max. 14 min. 9	70 a
Peltophorum dubium single-species Planted August 1995	8.45 (3.00) c max. 18 min. 3	6.57 (1.67) d max. 15 min. 2.3	78 a
Peltophorum dubium mixed Planted August 1995	10.24 (2.36) b max. 18.2 min. 5	9.18 (1.69) b max. 11.5 min. 5.4	56 b
Astronium balansae single-species Planted August 1993	10.18 (2.14) b max. 18.7 min. 4	6.78 (4.2) d max. 13.6 min. 4.7	59 b
Astronium balansae mixed Planted August 1993	10.91 (2.04) b max. 13.7 min. 7.4	8.23 (1.22) c max. 10.6 min. 4.8	78 a
Lonchocarpus muehlbergianum single-species Planted August 1990	7.4 (1.19) d max. 9 min. 4	4.4 (0.93) e max. 6 min. 2.4	48 c
Lonchocarpus muehlbergianum mixed Planted August 1990	2.8 (1.43) e max. 3.8 min. 2.5	2.75 (0.56) f max. 3.6 min. 1.5	28 d

Measurements done in December 2004.
The experimental design consisted of randomized blocks with four replicates. Statistical analyses were performed using Variance Analysis (ANOVA) and the Duncan test for means, with $p<0.05$.
Different letters indicate significant differences among groups.

Table III.
Growth in diameter at breast height, total height and survival of three native tree species in agroforestry systems in site 2.

Species	Diameter (cm) (Standard deviation)	Height (m) (Standard deviation)	Survival (%)
Enterolobium contortisiliquum Planted August 1991	19.3 (4.18) a max. 28.6 min. 10	7.92 (1.27) a max. 10 min. 4.15	46 b
Balfourodendron riedelianum Planted August 1991	9.85 (2,09) c max. 15.5 min. 7	8.16 (1.72) a max. 12.9 min. 5.8	92 a
Tabebuia heptaphylla Planted August 1993	14.87 (3.67) b max. 25 min. 6	7.97 (0.94) a max. 10 min. 4,9	90 a

Measurements done in December 2004.
The experimental design consisted of randomized blocks with four replicates. Statistical analyses were done using Variance Analysis (ANOVA) and the Duncan test for means, with $p<0.05$.
Different letters indicate significant differences among groups.

Commercial pulpwood plantations (principally *Pinus elliotii* and *P. taeda*) dominate the lowland landscape in Misiones. Note the natural forest cover on the top of the hill.
Photo F. Montagnini.

and *Bastardiopsis densiflora*, which did not grow well on highly degraded sites. Although it may be too early to draw conclusions on *P. dubium*'s adaptability to degraded sites, this species seemed to have low nutrient requirements and to be sensitive to soil compaction problems, therefore requiring good soil preparation including subsoiling down to 60 cm in depth.

On site 1, the mixed plantations grew well in comparison with single-species stands, with the exception of *Lonchocarpus muehlbergianum* (Table II). The advantage of mixed *E. contortisiliquum* and *A. balansae* plantations was a higher survival rate than in single-species stands, while *P. dubium* planted in a mixture with *Lonchocarpus muehlbergianum, E. contortisiliquum* and *A. balansae* grew higher and to a larger diameter than in single-species stands. On medium fertility soils at site 2, the best species were *E. contortisiliquum* and *T. heptaphylla* (Table III).

Balfourodendron riedelianum demonstrated better growth on sites 1 and 2, with higher fertility and less soil compaction than site 1 (Table IV). Overall, the best growth performance values were recorded for *B. riedelianum*, one of the most prized tree species locally. In contrast to *E. contortisiliquum* and *A. balansae*, which appeared to be well suited to the most degraded sites, *B. riedelianum* grows well in fertile soils and with adequate silvicultural management, as observed by tree heights of 11 meters and 15.7 cm dbh reached after 13 years at site 3, Santiago de Liniers (Table IV). The growth levels found at site 3 (Table IV) exceeded those found in other trials in the region where *B. riedelianum* had been tested in enrichment plantings, where soil conditions are generally good (Montagnini *et al.*, 1997). However, *B riedelianum* is apparently very sensitive to degraded soil conditions, as in the case of site 1 (Table II), where it could not be established due to high mortality or very slow growth. On site 2 (Table III) *B. riedelianum* grew poorly during the first couple of years, possibly due to the low soil fertility. However, once it survived the critical stage of establishment, this species grew well in low-fertility soils, to 8.16 meters in height and 9.85 cm dbh after 13 years (Table III).

Table IV.
Growth in diameter at breast height, total height and survival of two native tree species in agroforestry systems in site 3.

Species	Diameter (cm) (Standard deviation)	Height (m) (Standard deviation)	Survival (%)
Enterolobium contortisiliquum Planted August 1991	16.9 (5.3) a max. 25.7 min. 5	7.7 (1.6) b max. 11.3 min. 4.6	62 b
Balfourodendron riedelianum Planted August 1991	15.7 (3.7) b max. 26 min. 7.2	11.3 (2.3) a max. 16 min. 5.3	75 a

Measurements done in December 2004.
The experimental design consisted of randomized blocks with four replicates. Statistical analyses were done using Variance Analysis (ANOVA) and the Duncan test for means, with $p<0.05$.
Different letters indicate significant differences among groups.

A forest area showing recent selective cutting in accordance with the minimum diameter system, in the Guaraní Forest Reserve, administered by the National University of Misiones. The remaining basal area after harvest was about 10 m²/ha. Enrichment trials were established in these residual forests in 1990.
Photo F. Montagnini.

In these trials, the association of timber trees with yerba mate seemed appropriate, since yerba mate produced good harvests yielding a short-term return on investment. Several crops such as cassava, maize, peanuts, peppers, sweet potatoes, beans, sweet peas, onions, water melons, and cucumbers were intercropped with the trees at site 2. Production from the associated subsistence crops at site 2 covered the farmer's annual needs (Eibl *et al.*, 2000). This plus the long-term returns from timber make the systems proposed here an interesting alternative for small farmers in the region. Other agroforestry systems including native and exotic species are common in the region. In particular, agrosilvopastoral systems with improved cattle breeds are helping many farmers to accelerate returns on plantations, especially from araucarias and pines.

The results of this research are currently being used to stimulate tree planting in community forestry projects in municipalities near Eldorado, the town where the School of Forest Sciences of the National University of Misiones is located. The university researchers provide tree seedlings, help with tree planting and advise on species establishment and care. Local people with limited economic resources help to take care of these plantations, which are expected to provide forest products and improve the environmental conditions (soil, water quality) of the watershed. Initial growth results among native trees for timber, fuelwood and fruit in degraded areas are promising at one of the sites, the arroyo Pomar watershed, and other municipalities intend to join and initiate similar tree planting projects.

Enrichment planting in degraded and secondary forests

Line enrichment trials using native species of commercial value were established in 1988-1990 in overexploited forests in Misiones, on public and private lands. Two of the trials were conducted on the property of Celulosa Argentina S.A., located in the North-East of the province in Paraje Gramado, Department of San Pedro (26° 38' S, 54° 08' W, 530 m in elevation). The Celulosa Company owns about 7 500 ha of native forest where selective thinning is carried out using the conventional minimum diameter method. This forest was logged in 1986 and the remaining basal area (trees ›10 cm dbh) after harvest was less than 10 m²/ha (Montagnini *et al.*, 1997).

Table V.
Growth in diameter at breast height, total height and survival of four native tree species in forest enrichment experiments trials at the Guaraní Reserve.

Species	Diameter (cm) (Standard deviation)	Height (m) (Standard deviation)	Survival (%)
Ocotea puberula	19.08 (6.9)a max. 28.6 min. 3.5	9.9 (2.9)a max. 14.8 min. 3.5	75 a
Balfourodendron riedelianum	4.3 (2.4)c max. 10 min. 1.0	5.87 (2.4)c max. 9.9 min. 2.4	55 c
Bastardiopsis densiflora	13.3 (5.6)b max. 20.8 min. 5	10.4 (2.7) a max. 14 min. 5.5	65 b
Cordia trichotoma	10.9 (4.6)b max. 23 min. 4.7	8.6 (2.2) b max. 12.3 min. 4.3	75 a

Measurements made in November 2004. Tree species were planted in 1991.
The experimental design consisted of randomized blocks with four replicates. Statistical analyses were done using Variance Analysis (ANOVA) and the Duncan test for means, with $p<0.05$.
Different letters indicate significant differences among groups.

Enterolobium contortisiliquum (Fabaceae, "timbó Colorado"), 13 year-old, growing on moderately degraded soils in site 2, in a private property near the town of Eldorado. This native nitrogen-fixing tree performed best in the most degraded sites. Photo F. Montagnini.

Another trial was conducted in the Guaraní Forest Reserve, Department of Guaraní (26° 15' S, 26° 56' W, 267-574 m in elevation), also located in the North-East of the province, approximately 150 km from San Pedro. This 5 340 ha reserve was established in 1975 and is managed by the Department of Forest Science at the National University of Misiones. Guaraní is part of the Yabotí Forest Reserve covering 250 000 hectares, which was integrated into the UNESCO Biosphere Reserve Program in 1994.

The floristic composition and physical characteristics of the forest reserve are typical of most native forests in the province. Most of the reserve remains pristine; only 1 000 hectares, i.e. 20% of the total area, have been allocated for research use. Trials were conducted in an area where the undisturbed forest had been harvested in 1990, and the remaining basal area after harvest was about 10 m^2/ha.

The overall aim of enrichment was to improve forest composition in terms of both quantity and quality of commercially important species, so as to allow harvests from short and medium cutting cycles (15 to 40 years). In the Misiones forests, about 40 m^3/ha of commercial trees are usually extracted using the minimum diameter method, and the tree basal area of the residual forests ranges from 10 to 15 m^2/ha (Montagnini *et al*. 1998 and 2001). In the region, residual forests with ‹15 m^2/ha are considered to be overexploited, with relatively slow natural regeneration, and enrichment planting is recommended to accelerate their recovery.

Ten timber species were tested, as well as the palm *Euterpe edulis* Mart. ("palmito") which can be harvested after 10-12 years for its palm heart. The enrichment trials involved cutting lines running east to west in the forest to provide more light for planted seedlings. All lines were initially 2 m wide and were widened to 4 or 6 m in the second or third year after planting to increase light incidence for each species. This was done based on general information on the species' light requirements gathered from other trials in the region. Seedlings were one year-old, 40-50 cm tall nursery specimens raised in pots. Seedlings that died were replaced up to the third year. The enrichment lines were weeded 2-3 times per year dur-

Tabebuia heptaphylla (Bignoniaceae, "lapacho negro"), 11 year-old, growing on moderately degraded soils in site 2, in a private property near the town of Eldorado. Together with *Enterolobium contortisiliquum*, this species performed best under low and medium soil fertility conditions, in comparison with the other species in this trial which did not adapt to degraded soils.
Photo F. Montagnini.

The association of timber trees with yerba mate shrubs appears to be an appropriate agroforestry combination, with a short-term return on investment from the yerba mate leaf harvests, and production from corn and other subsistence crops.
Photo F. Montagnini.

ing the first three years and once or twice per year thereafter as needed.

At the San Pedro site, seven years after planting, the timber species with the greatest mean height and dbh were *Bastardiopsis densiflora* (Hook et Arn.) Hassl. (Malvaceae, "loro blanco", *Enterolobium contortisiliquum, Nectandra lanceolata* Nees et Mart ex Nees (Lauraceae, "laurel amarillo"), *Ocotea puberula* (Nees et Mart.) Nees (Laureaceae, "laurel guaicá", and *Peltophorum dubium* (Montagnini *et al.*, 1997). Two highly valued timber species, *Cordia trichotoma* (Vell.) Johnst. (Boraginaceae, "peteribí", "loro negro"), and *Balfourodendron riedelianum*, could also be recommended for enrichment despite their relatively slow growth.

At the Guaraní Forest Reserve, from measurements taken in December 2004, the timber species with greatest mean height and dbh 13 years after planting were *Ocotea puberula, Bastardiopsis densiflora,* and *Cordia trichotoma* (Table V). *Ocotea puberula*, a prized timber species, had suffered severe attacks from a stem borer beetle, *Oncideres gutturator* Fabr. (Cerambycidae), locally known as "quiritó", "cortapalos" or "taladro podador", an insect that cuts the lateral and terminal branches of several important timber species in the Misiones forest (Vizcarra, 1990). After severe *Oncideres gutturator* attacks, the *Ocotea puberula* trees in the enrichment trial re-sprouted vigorously, producing the largest stem growth of the four species tested.

Bastardiopsis densiflora and *Cordia trichotoma* were next in terms of height growth (Table V). *Bastardiopsis densiflora*, a prized timber species, grows well in secondary forests forming dense, single-species species stands. Previous experiments on the effects on soils of native tree plantations established that the greatest differences in C and N soil concentrations were found under *Bastardiopsis densiflora*, where they were twice as high as those in areas beyond the influence of the canopy (Fernández *et al.*, 1997). The pH was also observed to be better under *Bastardiopsis densiflora* and *Cordia trichotoma* compared to adjacent areas with no trees, while the sum of bases (Ca^{++}, Mg^{++} and K^{+}) was highest under *Cordia trichotoma, Bastardiopsis densiflora* and *Enterolobium contortisiliquum*. Thus, these species which perform well in enrichment planting may also be beneficial by improving soil characteristics of degraded forest areas.

Feasibility of enrichment planting

Because of the relative complexity of enrichment planting management, some authors consider it economically viable only for small or medium scales (Ramos, Del Amo, 1992). The high cost of establishing and maintaining plantings in the early years has been cited as one disadvantage of enrichment techniques. However, including species of medium and shorter harvest age could improve the economics of this technique, and enrichment planting could play an important role in the recovery of degraded forests (Weaver, 1987; Montagnini *et al.*, 1997).

Bamboos tend to dominate, competing with natural regeneration from woody species in gaps and openings with a large amount of light as a result of selective cutting. In this situation, enrichment planting can be an alternative to accelerate forest recovery.
Photo F. Montagnini.

Bastardiopsis densiflora Hassl. (Malvaceae, "loro blanco"), one of the fastest growing species in the San Pedro and Guaraní enrichment trials. This species forms dense stands in secondary forest areas of the region and is a prized timber tree.
Photo F. Montagnini.

An alternative to compensate for the high labor costs of enrichment is to plant species that grow quickly and/or yield highly valued products. In Indonesia, enrichment of depleted dipterocarp forests has become an economically attractive alternative due to increasing lumber prices (Korpelainen *et al.*, 1995). In another example, sensitivity analysis of enrichment plantings in Kalimantan, Indonesia, showed that enrichment of secondary forest with fruit trees, such as *Dialium* spp., *Garcinia* spp., and *Willughbeia* spp., was an economically and ecologically viable alternative (Schulze *et al.*, 1994). Another option is to combine timber trees with species that produce an earlier profitable harvest, such as the palm *E. edulis*, to accelerate returns on investment and to make this technique more economically attractive.

Management of enrichment plantings should be complemented by tending of natural regeneration within the lines. The weeding necessary for initial establishment and maintenance of the enrichment lines also tends to favor natural regeneration. Therefore, silvicultural treatments should be designed to encourage the establishment and growth of line plantings and at the same time favor natural regeneration, especially of commercially important species (Sips, 1993). Once the seedlings are established, the whole forest should be tended throughout, not just along the enrichment lines (Dawkins, 1961). If regeneration in the enrichment lines is considered together with planted trees, enrichment planting may become a more economically attractive alternative. However, the need for trained personnel and the costs associated with tending may limit the widespread applicability of this approach, especially at large scale.

In other trials in private properties in Misiones using some of the same species as in this article, the economic profitability of enrichment planting was calculated (Sánchez *et al.*, 1993). For a 25-year rotation, and using expected prices for timber from native species, these authors calculated a 11.2% rate of return on the investment. Although this was high, it was lower than the returns expected from other investment alternatives at the time. However, the growth rates estimated by these authors were low, being based on the density of about 180 to 200 trees per ha generally used for enrichment in the region. As discussed above, other trees from natural regeneration that are tended and favored while practicing enrichment planting should be added in the estimation of final yields. In addition, the authors pointed out that enrichment planting is a low-risk investment in comparison to other alternatives in the region, so that a relatively lower rate of return could be acceptable.

Partial view of the arroyo Pomar watershed, where university researchers are collaborating with resource-poor local people in tree planting projects. Early results for the growth of native trees for timber, fuelwood and fruit are promising, and other municipalities are intending to join and initiate similar projects. Photo F. Montagnini.

They also suggested that other indirect benefits, such as environmental protection and ecotourism, ought to be considered in evaluating the profitability of enrichment practices. However, these environmental benefits may not be directly perceived by the local farmers, and initial government subsidies would therefore be needed to bring this practice into more widespread use in the region.

In Argentina, the 1999 National Law (n° 25080) for the Promotion of Cultivated Forests subsidizes plantations with native species as well as with non-traditional exotic species, both in enrichment planting and in open plantation. For enrichment planting, there is a restriction on the number of trees that can be planted per hectare. In order to obtain the legal subsidies, there must be enough information on growth of the proposed species, and sometimes the native species are not approved for subsidies due to lack of information. This is where the results of the present research become important as background information that can be used to promote enrichment planting of native species of the Misiones forest.

In Misiones, UnaM researchers are working on proposals to obtain subsidies for enrichment plantings of several native species in secondary forest. This project would benefit small farmers who are interested in producing organic honey in community forestry projects. The project includes enrichment planting using some of the native timber species tested in this study. In the same areas, small trees and shrubs that grow naturally in open, degraded areas and are used by honey bees such as *Solanum granuloso leprosum* Dun. (Solanaceae, "fumo bravo"), *Trema micrantha* (L.) Blume (Ulmaceae, "palo pólvora", and *Brassica* spp., among others, are tended and encouraged. The combination of species that regenerate naturally and timber species that are planted for enrichment results in a mixed forest that lessens the risk of only planting species for which there is little background information on growth. In addition, the species are expected to protect the soil and offset the adverse environmental conditions that are often found in degraded secondary forests, locally called "capueras".

Enrichment adds value to previously logged, low-volume forests by increasing the expected harvestable volume. This added value may prevent their conversion to plantations or other prevailing uses. With increases in the area of secondary and overexploited forest across the globe (Achard *et al.*, 2002), forest recovery will require techniques such as enrichment. In the province of Misiones, local farmers are seeking guidelines on species choice and management for the enrichment of overexploited and secondary forests. Though long-term results are required to document potential growth and production quality for each species, results from the trials described in this article can provide insights into the use of these species for enrichment planting in overexploited and secondary forests in the Yabotí Biosphere Reserve and other areas in the region exposed to similar conditions.

Conclusions

Despite the fact that in Argentina, the National Forestry Law does not exclude native species for subsidizing open plantations or enrichment planting, few farmers are interested in planting native species. This is mainly due to the lack of guarantees regarding the returns that can be expected from native species. For open plantations, subsidies are given only for single species planted in blocks. The results of this study have increased the body of information on the growth and profitability of native species used for open plantations and enrichment planting in Misiones, and can thus help to encourage more farmers in the region to plant native species.

The findings from this study are already being used in small community forestry projects in Misiones that include open mixed and single-species plantations, and enrichment planting of degraded secondary forests or "capueras". It is expected that more farmers in the region will join these projects and that the positive results in terms of growth and environmental benefits will encourage more widespread planting of native tree species.

Forestry development in the province of Misiones has helped to increase productivity and to diversify the economy of the province, while respecting environmental constraints. Plantations for pulp and timber are expanding continually, but they are generally established on relatively flat land whereas the upper elevations of watersheds and riparian areas in the province are still largely covered by natural forests. The relatively large proportion of forest under protected status ensures conservation of the diverse ecosystems of the region. Their use in ecotourism is also helping to diversify the economy of the province. The challenge is to ensure that forest management complies with management plans, prevents illegal logging

and controls the encroachment of people in the forest, especially from the poorly protected borders with Brazil and Paraguay. In addition, implementation of forest restoration projects such as those described in the present article can help to increase ecosystem productivity and preserve native resources.

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Euterpe edulis Mart. ("palmito") in an enrichment trial at the Guaraní Reserve. Planting this species can accelerate returns on investment, since palm hearts can be harvested after 10-12 years. This palm does not grow well in open plantations, and is considered an endangered species in both Argentina and Brazil. Photo F. Montagnini.

References

ACHARD F., EVA H. D., STIBIG H. J., MAYAUX P., GALLEGO J., RICHARDS T., MALINGREAU J. P., 2002. Determination of deforestation rates of the world's humid tropical forests. Science, 297: 999-1002.

ANDERSON J. M., INGRAM S. I. (ed.), 1989. Tropical soil biology and fertility: a handbook of methods. CAB International, Wallingford, United Kingdom, 171 p.

CRECHI E., FERNÁNDEZ R., DOMEQ C., HENNIG A., EIBL B., 2002. Silvicultura inicial de 3 especies latifoliadas nativas de interés económico en Misiones: peteribí, guatambú y timbó. IX Jornadas Técnicas Forestales. INTA-FCF-MEYRNRYT. Eldorado, Misiones, Argentina, Mayo 2002, Actas en Disco Compacto.

DAWKINS H. C., 1961. New methods of improving stand composition in tropical forests. Caribbean Forester, 22: 12-20.

EIBL B., FERNÁNDEZ R., KOZARIK J.C., LUPI A., MONTAGNINI F., NOZZI D., 2000. Agroforestry systems with *Ilex paraguariensis* (American Holly or yerba mate) and native timber trees on small farms in Misiones, Argentina. Agroforestry Systems, 48: 1-8.

EIBL B., VERA N., MENDEZ R., 2003. Silvicultura de diez especies arbóreas nativas con potencialidades para la producción de madera y otros usos alternativos. Facultad de Ciencias Forestales. UnaM. Proyecto Forestal de Desarrollo-SAGPyA. Misiones, Argentina, 18 p.

FERNÁNDEZ R., MONTAGNINI F., HAMILTON H., 1997. The influence of native tree species on soil chemistry in a subtropical humid forest region of Argentina. Journal of Tropical Forest Science, 10 (2): 188-196.

GOBIERNO DE LA PROVINCIA DE MISIONES, ARGENTINA, 2003. Actitud forestal. Un mundo de oportunidades para una Misiones estratégica. Subsecretaría de Bosques y Forestaciones. Ministerio de Ecología, Recursos Naturales y Turismo. Posadas, Misiones, Argentina.

KÖPPEN W., 1918. Klassifikation der Klimate nach Temperatur, Niederschlag und Jahreslauf. Peterm. Geogr. Mitt., 64: 193-203, 243-248.

KORPELAINEN H., ÅDJERS G., KUUSIPALO J., NURYANT K., OTSAMO A., 1995. Profitability of rehabilitation of overlogged dipterocarp forest: a case study from South Kalimantan, Indonesia. Forest Ecology and Management, 79: 207-215.

MONTAGNINI F., EIBL B., GRANCE L., MAIOCCO D., NOZZI D., 1997. Enrichment planting in overexploited subtropical forests of the Paranaense region of Misiones, Argentina. Forest Ecology and Management, 99: 237-246.

MONTAGNINI F., EIBL B., WOODWARD C., SZCZIPANSKI L., RÍOS R., 1998. Tree regeneration and species diversity following conventional and uniform spacing methods of selective cutting in a subtropical humid forest reserve. Biotropica, 30 (3): 349-361.

MONTAGNINI F., FINEGAN B., DELGADO D., EIBL B., SZCZIPANSKI L., ZAMORA N., 2001. Can timber production be compatible with conservation of forest biodiversity?—Two case studies of plant biodiversity in managed neotropical forests. Journal of Sustainable Forestry, 12 (1/2): 37-60.

MONTAGNINI F., JORDAN C. F., 2005. Tropical Forest Ecology. The Basis for Conservation and Management. Springer-Verlag, Berlin-New York, 295 p.

ODUM E. P., 1983. Basic Ecology. Saunders College Publishing, Philadelphia, USA, 408-415.

RAMOS J. M., DEL AMO S., 1992. Enrichment planting in a tropical secondary forest in Veracruz, Mexico. Forest Ecology and Management, 54: 289-304.

SÁNCHEZ J. R., GOTZ I., SEGOVIA W., 1993. Enriquecimiento de bosques nativos. Implantación bajo cubierta. Tercera comunicación. *In*: VII Jornadas Técnicas: Ecosistemas Forestales Nativos. Uso, Manejo y Conservación. Inst. Subtrop. Invest. For., Fac. Cs. For., UNaM. Eldorado, Misiones, Argentina, 300-308.

SCHULZE P. C., LEIGHTON M., PEART D. R., 1994. Enrichment planting in selectively logged rain forest: a combined ecological and economic analysis. Ecological Applications, 4: 581-592.

SIPS P., 1993. Management of tropical secondary rain forests in Latin America. Today's challenge, tomorrow's accomplished fact? National Reference Center for Nature, Forests and Landscape, Ministry of Agriculture, Nature Management and Fisheries. Wageningen, The Netherlands, 72 p.

VIZCARRA J., 1990. Ficha técnica: insectos de interés forestal. *Oncideres gutturator* (Fabr.). Yvyraretá, Argentina, 1: 91.

WEAVER P. L., 1987. Enrichment planting in tropical America. *In*: Management of the Forests of Tropical America: Prospects and Technologies. Figueroa Colón J. C, Wadsworth F. H., Branham S. (ed.), Inst. Trop. For., USDA Forest Service and Univ. Puerto Rico. Río Piedras, Puerto Rico, 258-278.