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Agroforestry diffusion and secondary forest regeneration in the Brazilian Amazon: further findings from the Rondônia Agroforestry Pilot Project (1992–2002)

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Abstract

In July 1992 the Rondônia Agroforestry Pilot Project (RAPP) was launched in two agricultural municipalities (Nova União and Alto Paraiso) in the western Brazilian Amazon State of Rondônia. The purpose of the RAPP was to assess the conditions under which colonist farmers in the western Amazon would integrate agroforestry plantings into their small-scale farming systems and to assess the performance of those plantings over time. An experimental group consisting of 50 small-scale farmers was selected to participate. Plots were designed to accommodate between 3 and 25 different species, each producing one or more commodities with local market potential (hardwood, fruits, nuts, latexes, oils). Farmers planted seedlings typically on a 1-ha plot, located and designed by each farmer with the advice of a professional Brazilian extensionist. During the first phase of the project (1992–1998), the growth performance of the seedlings and changes in household characteristics were monitored on an annual basis. By 2002, 32 (64.0%) of the original 50 agroforest plots were found in place. This paper updates the research findings based on a 2002 follow-up visit to these 32 farms. In addition to growth performance, the authors' found that 17.95% of the farms in the neighboring control group had planted trees and other agroforest crops between 1992 and 2002, compared to only 5.38% of farms outside the project area, suggesting spontaneous diffusion. The authors also found a potentially synergistic relationship between agroforestry and secondary forest regeneration with the use of satellite image analysis. The experience of the RAPP indicates that colonist farmers in Amazonia can be successful managers of agroforest plots with minimal external inputs over the long-term (10 years).

Introduction

This paper updates the findings of the first 10-year period of the Rondônia Agroforestry Pilot Project (RAPP), an on-farm experimental agroforestry project initially involving 50 small-scale farmers in two tropical forest localities in the southwestern Brazilian Amazon state of Rondônia (Browder and Pedlowski 2000). One of the long-term goals of the RAPP is to identify and evaluate the conditions that influence the successful adoption of agroforestry systems by small-scale farmers in western Amazonia. In addition to biological growth performance of key timber species, this paper presents evidence of spontaneous diffusion of agroforestry practices from experimental group farmers to neighboring farmers, suggesting that agroforestry has the potential to spread on its own once introduced into a rural community. In addition, we hypothesize a possible synergy between tree-based agroforestry plantings and secondary forest succession. Based on a spectral analysis of natural vegetation recovery on the experimental plots we test the hypothesis that timber-based agroforest plots promotes spontaneous reforestation in the surrounding area. Agroforestry, in addition to conferring utilitarian benefits to farmers, may also facilitate the process of forest restoration through secondary growth succession. This may have implications for organizations interested in the relationship between agroforestry and atmospheric carbon sequestration.

In their socioeconomic content review of this journal spanning 1982 to 1996, Mercer and Miller (1998) found that 11% of the listings pertained to the agroforestry adoption behavior of farmers, the third most frequently cited listing along with 'gender issues'. Much of this research literature focuses on the financial performance of various agroforestry systems in comparison to other agricultural land uses (Mehta and Leuschner 1997; Ramírez et al. 2001). While this research shows that farmers are not likely to earn a positive cash flow from agroforestry during the short terms (1–3 years after planting), in the longer term the net present value of production from agroforestry systems often exceeds that of alternative land uses (Vosti et al. 1998), suggesting that farmers would rationally adopt agroforestry practices if impediments to doing so could be eliminated. A related line of agroforestry research, therefore, has focused on the identification and measurement of these impediments to adoption, ranging from insufficient agroforestry extension, inappropriate project design and management, policy distortions of market prices, deficient knowledge of innovations, uncertainty and risk, high interest rates, low levels of social participation, insufficient land or labor, weak markets, perishability of many agroforestry products once harvested; insufficient processing industries, and lack of high-quality planting material (Smith et al. 1996; Nibbering 1999; Pannell 1999; Salam et al. 2000; Mahapatra and Mitchell 2001; Fischer and Vasseur 2002). Much of this research focuses on the role of extension institutions, government research agencies and credit programs, connoting that agroforestry practices disseminate mainly through planned technology transfer projects sponsored by formal governmental or non-governmental organizations. Yet, in a region-wide survey of 136 polycultural fields in the Brazilian Amazon, Smith et al. (1996) found 108 agroforestry configurations involving 72 crops, most planted by 'small-scale entrepreneurs clearly experimenting with a wide array of perennial crops, mostly on their own initiative' (p. 15). The processes and dynamics of informal or 'spontaneous' diffusion of agroforestry practices in rural smallholder communities has not, as yet, attracted much attention from researchers. Yet, such diffusion may play a very influential role in the effective promotion of agroforestry alternatives to more destructive land uses in settlement areas of the Amazon Basin. In this paper we examine the hypothesis that spontaneous tree-planting adoption rates will be higher in rural 'neighborhoods' where a farmer has successfully introduced an agroforestry experiment. We test this 'neighborhood diffusion' hypothesis by comparing agroforestry adoption rates by farmers in RAPP experimental areas with those of farmers in control areas.

Interestingly, the Mercer and Miller content review of *Agroforestry Systems* found no socioeconomic research articles on the role of agroforestry in promoting secondary forest succession, although at least one paper on this subject has been published since 1996 (Simmons et al. 2002). A considerable amount of research by biologists, forest ecologists, and soil scientists has pointed to the positive role of agroforestry in restoring nutrient cycles (Sirois et al. 1998), in protecting biodiversity (Harvey and Haber 1999); and in providing buffers that seek to promote conservation of protected areas (Mehta and Leuschner 1997; Huang et al. 2002). The long-standing supposition in the agroforestry research literature has been that 'agroforestry practices provide stability to rural inhabitants, leading to better land use and its conservation, and therefore relieve the pressure on natural forests...[and] should be promoted' (Budowski 1980, p. 1). Whether true or not, some recent research has found minimal differences in soil characteristics (e.g. microbial biomass, faunal diversity, respiratory activity, etc.) between agroforestry systems and other agricultural land uses, e.g. pastures or peach palm plantations that might question the sustainability of commercial agroforestry systems (Tornquist et al. 1999; Vohland and Schroth 1999; Neupane and Thapa 2001). Other researchers have cautioned that agroforestry is not intrinsically sustainable (Coomes and Burt 1997; Fujisaka and White 1998), and 'may actually contribute to more forest clearing on small farms because of lack of farmer confidence in the future of the system' (McGrath et al. 2001, p. 271). The question of the sustainability of agroforestry systems, especially in non-indigenous smallholder contexts, will undoubtedly continue to be debated for some time to come. A question that has not been widely raised, however, is the role of agroforestry in promoting tropical forest regeneration in managed abandoned clearings. Based on a Landsat image chronosequence analysis of 16 of the agroforest plots over at 10 year period (1992–2002) we hypothesize that farmers who adopt timber-based agroforest systems are more likely to allow secondary reforestation to occur around valued timber juveniles than farmers who plant fruit-based agroforest systems.

Materials and methods

Site description

Two project sites were selected in recently settled agricultural communities in the municipios of Alto Paraiso and Nova União in the southwestern Brazilian Amazon State of Rondônia (Figure 1). Draining into a principal Amazon tributary, the Madeira River, Rondônia covers an area of 239,000 km^2 along the Bolivian border, roughly between latitude 7°35′30″ and 13°41′30″ S and longitude 59°50′04″ and 66°15′00″ W. The predominant vegetation class is 'transition forest' or 'tropical – seasonal moist transitional forest' extending over approximately 75% of the state's area. 'Dense' or 'closed' tropical forest occurs in large patches in the northern portions of the state bordering on the State of Amazonas. A band of savannah grassland *(cerrado)* is found in the higher elevations of the south-central hill ranges (Pacaas Novos, Uopione, and Parecis). Seasonally inundated floodplains follow the major boundary rivers (Guaporé, Mamoré) and their estuaries. The humid tropical climate falls within the 'Awi' classification on the Koppen scale, with a distinct rainy season (usually October to April). Annual rainfall ranges from 1800 to 2200 mm and average monthly temperatures vary from 21 to 27 °C. Approximately 90% of the land in Rondônia is covered by relatively infertile dystrophic latosols. Only 10% contains eutrophic podsols, considered suitable for annual or permanent cultivation (World Bank 1981).

The two project sites display many similar biophysical characteristics, but are distinguished in terms of predominant soil types (Table 1). Nova União with its predominantly eutrophic podsols, is somewhat preferable for conventional low-input farming than Alto Paraiso.

Project participant characteristics and land uses

The project participants are mainly small-scale, low-input, mixed-crop (perennial and annual) farmers, many of whom migrated to Rondônia in the early 1980s. However, several significant changes occurred during the 10-year period of the project which, at first glance, appear portentious for the viability of family farms. First, a pattern of property fragmentation is clearly evident. The average size of farms in the two study sites dropped from the 73–89 ha range to 63–64 ha (Table 1). Family farm subdivisions occur for many reasons (e.g. inheritance to multiple heirs, liquidation of assets to pay off debts, decline in soil fertility and reduced farm productivity, empty-nests, etc.). Second, the increased subdivision of properties has been accompanied by a growing proportion of farmers without legal title to their land, suggesting increased reliance on informal (non-contractual) land tenure conveyance or sharing arrangements. Third, these signs of increasing marginalization of the rural population are associated with a decline in financial liquidity, as suggested by the reduced proportion of the sample having bank savings accounts. Surprisingly, there has been a dramatic increase in the proportion of the households in the sample that received bank loans and government-backed rural credits suggesting an increasing commercialization of rural production in tandem with financial marginalization. Not surprisingly as remnant primary forest areas have declined on the

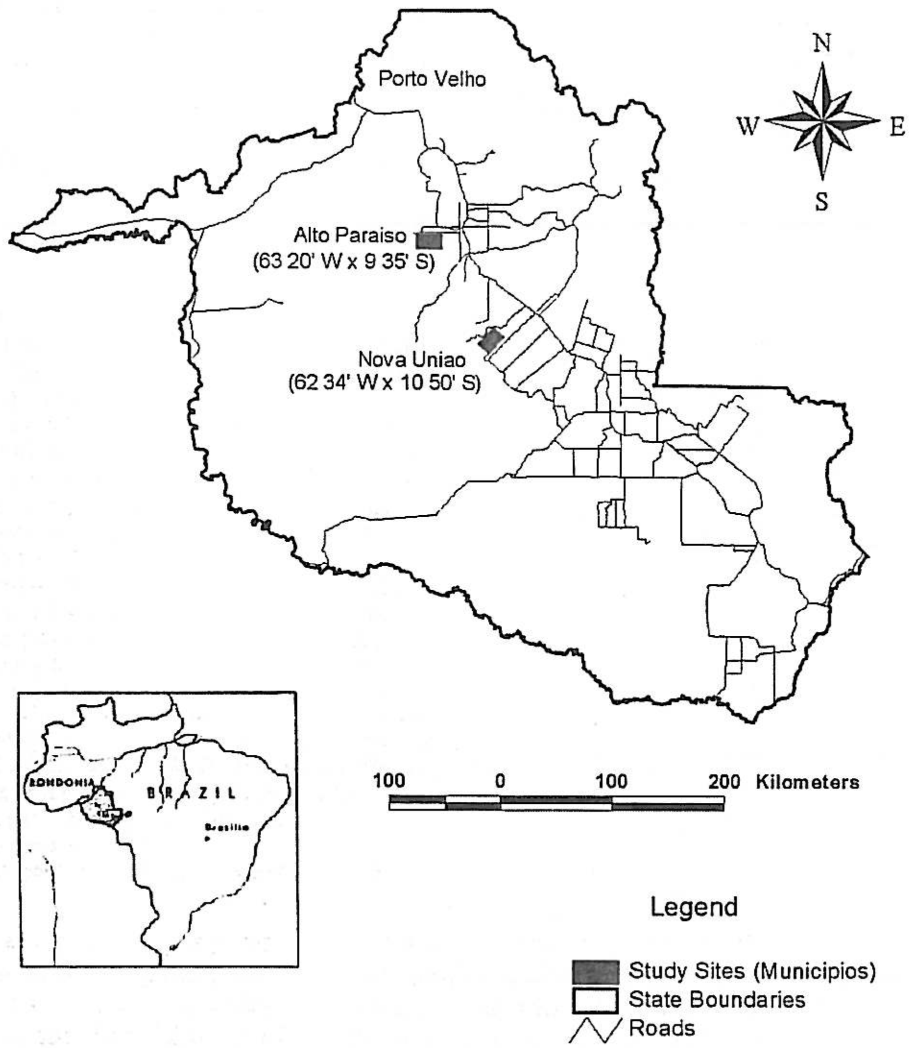

Figure 1. Location of study sites in the state of Rônia, Brazil.

surveyed farms, the proportion of farmers extracting natural forest products has also dropped by half. Finally, it seems that as conventional cropping choices prove less remunerative over time, farmers' interest in agroforestry rose during the 1990s, at least in Alto Paraiso. All of these observed patterns deduced from the two surveys (1992 baseline and 2002 follow-up surveys) are schematic and warrant further verification and analysis. They do, however, point to some interesting emergent tendencies over the 10-year timeframe of the project, that may affect the diffusion of agroforestry practices in the future, including a growing interest on the part of farmers in planting trees on their farms.

Research methods

The goals and objectives and experimental design of the RAPP are discussed in Browder and Pedlowski (2000), and will not be repeated here. In 1992 an experimental group of 50 farmers was initially selected on the basis of responses to a baseline survey administered by interview to the owners of 242 farms in three *municipios*. In 2002 the same 242 farms were revisited as part of a larger study on land use and land cover change in the Amazon, including all 32 remaining participants in the RAPP experimental group. The two surveys provide a 10-year longitudinal data set in which changes in land use at the farm level can be

Table 1. Selected Characteristics of Project Sites in 1992 and 2002, Rondônia Agroforestry Pilot Project, Southwestern Brazilian Amazon (standard deviation).

Variable	Nova União	Alto Paraiso
Location	62°34′ W × 10°50′ S	63°20′ W × 9°35′ S
Altitude (meters above sea level)[1]	100–225	110–369
Average annual rainfall (mm)	1600–1700	2000–2100
Main soil type[2]	PE 3/Re[3]	Pva 13/Rd 3[4]
Vegetation cover type[5]	TTSMF[6]	TTSMF
Settlement area (hectares)	7130	7273
Number of project farms – 1992	97	82
Number of project farms – 2002	116	109
Average farm size (hectares) – 1992	73.5 (42.3)	88.7 (23.9)
Average farm size (hectares) – 2002	62.7 (40.3)	63.6 (32.9)
Farmers with legal land title (%) – 1992	69.0	75.9
Farmers with legal land title (%) – 2002	62.0	63.0
Number of persons dwelling on farm – 1992	11.12 (6.4)	9.31 (5.2)
Number of persons dwelling on farm – 2002	5.59 (4.6)	5.37 (4.4)
Farms with bank savings accounts (%) – 1992	13.8	15.8
Farms with bank savings accounts (%) – 2002	10.1	10.7
Farms receiving loans/credits (%) – 1992	1.0	0
Farms receiving loans/credits (%) – 2002	29.7	16.8
Farms extracting forest products (%) – 1992	69.1	96.3
Farms extracting forest products (%) – 2002	33.0	48.2
Farmers interested in agroforestry (%) – 1992	48.9	50.0
Farmers interested in agroforestry (%) – 2002	47.0	60.0

1. Source: Instituto Brasileiro de Geografia e Estatistica (IBGE), Elevation maps, 1974.
2. Source: Projeto Radambrasil. *Mapa Exploratório de Solos*, 1:1,000,000. *Folha SC.20 Porto Velho*, 1979.
3. Eutrophic yellow–red podsols with patches of eutrophic litolic soils.
4. Alic yellow–red podsols with patches of distrophic litolic soils.
5. Source: IBGE, *Mapa de Vegetação de Brasil*, 1988.
6. Transitional tropical seasonal moist forest (*Floresta Ombrófila Aberta*).

assessed. In addition, a separate survey was administered by interview to RAPP participants. This survey produced data on the commercialization of agroforest products, social participation of farmers, and general condition of plots. Initially 50% of the timber seedlings planted were tagged and numbered for future identification and measurement, usually by alternating rows within the agroforest plot. During these household visits circumference measurements were made of this subset of individual trees planted. In addition, agroforestry diffusion from experimental group farms to neighboring farms was compared to such diffusion in control group areas during the 10-year project period. Finally, LandSat scenes for each year between 1992 and 2002 were acquired and registered to GPS points taken at the location of each agroforest plot in the experimental group. Since each agroforest plot ranged in size from 0.6 to 1.0 ha (100 m × 100 m), spectral data were collected from the single pixel corresponding to the GPS point plus groups of six to nine contiguous pixels surrounding or adjoining the GPS point. The precise choice of pixel configurations was corroborated with ground-truthed information (photographs, maps, annual monitoring reports) collected over the preceding 10 years of the project. With this ground-truthed data verifying the satellite image location of a sub-sample of agroforestry plots in the project's experimental group, the authors were able to conduct a spectral analysis of vegetation recovery on timber-based and non-timber-based plots. The results of these analyses follow:

Results and discussion

Biological performance

Initial biological growth measures for selected species during the first 42 months were reported in Browder and Pedlowski (2000). In general, survival and growth rates were unexpectedly high given the wide range of planting conditions and management mistakes encountered on the experimental group farms (Browder and Pedlowski 2000). After 120 months, a sample of timber species was measured and the general conditions of non-timber components were evaluated by a trained extensionist during the experimental farm surveys in 2002.

Timber species

A total of 10 different industrial wood species were offered to experimental group farmers during the planting phase of the project. Of the 32 surviving agroforest plots, 23 (71.8%) included one or more tropical industrial wood species, mostly hardwoods. The inclusion of long-growing hardwoods seems to encourage farmers to allow natural secondary reforestation to occur on the plots and may be an important catalyst to forest restoration, as is reported below. The most frequent planting density for the industrial hardwoods was 10 m × 10 m, with some variations for certain species. The average survival rate after 18 months for the seven most frequently planted species was 81.5%, and ranged from a low of 64.5% for cerejeira (*Torresea acreana*) to 88.5% for cedro (*Cedrela odorata*) (Table 2). The average diameter at breast height (DBH) was 3.85 cm 6 months after planting and 18.58 cm after 120 months. DBHs after 10 years ranged from 11.5 cm for cerejeira to 29.4 cm for teak (an exotic). The average DBH of mahogany (*Swietenia macrophylla*), the highest priced commercial hardwood native to Amazonia, grew to 17.5 cm after 10 years, however nearly 100% of the individuals inspected had suffered from shoot-borer (*Hypsipila grandella*) infestation of the apical stems in earlier stages of growth, occurring within 5 years of planting. The damage to the bole caused by this moth larvae will reduce the effective yields of mahogany sawnwood and raises questions about the financial viability of mahogany plantings in Amazonia on a commercial scale (Browder et al. 1996).

Key agroforest crops

Seven key agroforestry cash crops included in RAPP demonstrated reasonable survival rates during the first 18 months following planting (Table 3). The most widely planted crop was cupuaçu (*Theobroma grandiflorum*), a relative of cacao, planted on 87.8% of those experimental agroforest plots surviving until 2002. After 10 years, 72.4% of the plots planted with cupuaçu were still producing fruit of this species. Pupunha palm (*Bactris gasipaes*), planted in more than half of the surviving plots, also demonstrated considerable resilience with 73.7% of these palm plantings still producing seeds after 10 years. Other common agroforest species had more mixed results. A total of 16 different non-timber fruit, palm, oil, nut species were planted. After 10 years an estimated 66.4% of these plantings are still productive. It is interesting that 10 (30.3%) of the agroforest plots surviving until 2002 contain only non-timber cash crops, as will be discussed below.

Commercialization of agroforest products

While nearly two-thirds of the agroforest plots in RAPP continue to be productive, it is interesting that less than one-third (10 or 30.4%) of the participating farmers successfully sold any agroforest products during the first 10 years, excepting

Table 2. Survival Rates and Mean Diameter at Breast Height (DBH) in centimeters (standard deviations) by month after planting of selected industrial wood species in the Rondônia Agroforestry Pilot Project.

Species	Seedlings measured	Spacing (meters)	Survival rate at 18 months (%)	DBH at 6 months	DBH at 42 months	DBH at 120 months
Andiroba (*Carapa guianensis*)	15	10 × 10	75.0	1.17 (0.25)	3.07 (1.62)	14.66 (5.20)
Bandarra (*Parkia paraensis*)	30	10 × 10	80.0	10.8 (1.75)	14.1 (5.79)	21.80 (5.45)
Cedro (*Cedrela odorata*)	27	10 × 10	88.5	4.25 (1.31)	9.34 (1.67)	19.93 (4.50)
Cerejeira (*Torresea acreana*)	22	10 × 10	64.5	0.75 (0.35)	6.49 (1.77)	11.50 (6.94)
Freijó (*Cordia alliodora*)	69	9 × 9, 12 × 12, 15 × 15	87.1	2.21 (1.37)	7.95 (2.83)	15.33 (3.63)
Mahogany (*Swietenia macrophylla*)	53	10 × 10, 12 × 12	87.8	3.03 (1.70)	7.43 (2.65)	17.47 (3.93)
Teak (*Tectona grandis*)	56	10 × 10, 10 × 15	87.7	4.77 (1.45)	8.50 (8.65)	29.40 (9.92)

Table 3. Survival rates and productivity of key non-timber agroforest crops.

Species	Est. survival rates after 18 months (%)	Percent of surviving experimental farms planting	Percent producing fruit after 120 months (% of plots)
Cupuaçu (*Theobroma grandiflorum*)	86.3	87.8	72.4
Pupunha palm (*Bactris gasipaes*)	86.4	57.6	73.7
Açai palm (*Euterpe olercea*)	78.9	36.4	100.0
Araça boi (*Eugenia stipitata*)	93.2	36.4	50.0
Acerola (*Malphighia punicifolia*)	100.0	3.0	0
Lemon (*Citrus* spp.)	75.0	9.0	66.6
Orange (*Citrus sinensis*)	82.8	6.0	100.0

Source: Annual Project Monitoring Reports, 1993–2002.

annual ground crops (e.g. beans, corn, upland rice) cultivated on the agroforest plots in the first 2 years by several participating farmers. The principal reason given by the majority of farmers who did not sell any agroforest products was 'lack of market,' cited by 19 farmers (82.6% of those not selling). In fact, all of the agroforest crops offered to participating RAPP farmers have local markets, and several (e.g. cupuaçu, pupunha, açai, acerola) have national and even international markets. The main problem is inadequate market access and the shortage of local processing, storage and marketing facilities in the project areas.

The farmers who have successfully marketed some products from their agroforest plots have apparently done so on a very small scale, selling mainly to neighbors. The most frequently traded products are palm seeds (both pupunha and açai) reported by five of the 10 farmers marketing anything. The initial expectation was that participating farmers would manage the palms for palmito (palm heart), by harvesting, peeling, and jarring the one or two stems per plant after 18 months, allowing the apical buds to sprout. Farmers, however, have elected to allow the palms to grow to maturity (often as high as 15 m) in order to harvest the fruits, which occurs in thick bunches near the top of the tree. Açai fruits are locally processed into a fermentable juice, while the seeds are also fed to pigs.

Only four of the 10 farmers marketing agroforest products sold frozen cupuaçu pulp, which has a robust and growing national market in Brazil. Processing cupuaçu for market requires shucking the shell, removing and freezing the pulp. Obvious marketing constraints include the lack of electricity during much of the decade (the central power grid was only extended to parts of the project area in the late 1990s), the high cost of purchasing a freezer, and the considerable labor time necessary to manually shuck and extract the pulp. Without an intermediate demand for fresh cut fruit (unpulped) most farmers are unlikely to sell significant quantities of this product. Interestingly, a couple of cooperative membership organizations have emerged in recent years to buy and sell cupuaçu and it is likely that future prospects for marketing this crop will improve. At recent producer prices farmers could earn $3–4000 per year from the management of cupuaçu and pupunha palmheart (Browder and Pedlowski 2000).

Values of agroforestry

If participating farmers are not realizing a significant financial gain from their agroforest plots, then what values do they find in agroforestry? It is noteworthy that when asked whether or not their efforts to plant and maintain their agroforest plots were worthwhile, 30 (93.7%) said yes. Of those 24 responding to the follow-up question, 'why?', 15 (62.5%) spoke of the importance of restoring the forest vegetation cover; six (25.0%) referred to the commercial value of the growing timber on their plots; and, three (12.5%) mentioned general 'environmental' reasons. The significance of these perceptions is reflected by the fact that 12 (37.5%) of the 32 experimental group farmers expanded the size of their agroforest plots from the original 1 ha template to as high as 9.8 ha.

Project 'neighborhood effects' and the spontaneous diffusion of agroforestry in Rondônia

One of the original premises of the RAPP was that farmers who successfully adopt agroforestry would become passive agents of the diffusion of agroforestry practices in their communities. Neighbors would take notice of farmers planting trees and agroforest cash crops and would begin to experiment on their own. Such 'neighborhood effects' of the project might be evident after 10 years.

Comparing the findings of the larger household survey conducted in 1992 with the follow-up survey in 2002 enables an evaluation of the project's diffusion hypothesis. In the original RAPP project design experimental group farms were clustered on specific roads (*linhas*). Control group farms were located on separate roads to minimize possible project contagion effects. Each group included five road segments. The diffusion hypothesis states that farmers not participating in RAPP but located on the same road as the experimental farms are more likely to adopt agroforestry through passive or spontaneous diffusion than farmers located on the control group roads. The results of the surveys reveal a significant difference in adoption rates consistent with this 'neighborhood diffusion hypothesis' (Table 4). Overall, 17.95% of non-project farms surveyed in the experimental group area planted trees and other agroforest crops between 1992 and 2002, whereas only 5.38% of control group farms did so.

Of course, this finding does not confirm that project diffusion actually occurred; it only strengthens the likelihood of such occurrence, and it raises the question about the mechanisms of diffusion: How do new land use practices transfer through a rural farming community in Amazonia? Certainly it is unlikely that experimental farmers could have concealed their agroforest plots from their neighbors for very long. Moreover, annual monitoring visits by project personnel would not have gone unnoticed by the local population (a possible instrumentation effect) – anybody in a vehicle on these back roads draws attention. But, it is also very likely that experimental farmers had numerous opportunities over the 10-year project period to discuss their agroforest plots with neighbors in multiple venues: mutual help association meetings, church meetings, or just informally. Social participation rates among the experimental group farmers are significantly higher than those of the sample overall. For example, 78.6% of farmers participating in RAPP reported that they also participate in the local rural workers union and 67.8% participate in a mutual aid association on their *linhas*. For the adopters not in the experimental group social participation rates were also higher than for the

Table 4. Number and percent of farms spontaneously adopting agroforestry practices, 1992–2002.

Experimental area	Number of farms surveyed	RAPP farms	All other farms	Number of other farms adopting agroforestry	Percent of all other farms adopting
A. Within Pilot Project experimental area					
Linha 40	32	6	26	3	11.54
Linha 44	42	9	33	5	15.15
Linha 80	45	7	38	9	23.70
Linha 85	33	5	28	5	17.85
Linha 95	38	7	31	6	19.35
Overall	190	34	156	28	17.95*

Control area	Number of farms surveyed	Number of farms adopting agroforestry practices	Percent of control farms adopting agroforestry
B. Within Pilot Project control area			
Linha 32	7	0	0.00
Linha 36	30	3	10.00
Linha 38	1	0	0.00
Linha 176	21	0	0.00
Linha 168	34	2	5.88
Overall	93	5	5.38*

Source: John Browder, 1992, 2002 survey data.
*Significant at $p = 0.005$.

sample overall, 71.4 and 57.1%, respectively. For the overall sample these corresponding participation rates were 64.4 and 50.4%, respectively. Farmers who participate in social organizations within their rural communities appear more likely to adopt agroforestry practices. Such organizations may be an important venue for lateral technology transfer.

Agroforestry and secondary forest succession – a spectral analysis

The RAPP provides an opportunity to examine the hypothesis that small farmers who successfully establish agroforest plots, especially with long-growing timber components, are more likely to encourage secondary forest succession in those plots than farmers whose agroforestry plots does not include timber, and so, promote reforestation with possible benefits of ecosystem restoration and atmospheric carbon sequestration. There are several logical reasons why farmers might behave this way. First, allowing the agroforest plot to revert into secondary forest may provide some protection for the juvenile timber located within, both from prying eyes of passing lumbermen and from biological pests. But, perhaps the best reason is economic: The timber component of the agroforest plot adds value into the land that otherwise would have value only if cleared and planted in other crops. While the timber is not immediately fundable, farmers can conserve their labor (reduce their costs) by allowing the forest to return, knowing that doing so does not impair the future value associated with the timber which continues to grow over time.

To examine this hypothesis Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper (ETM+) scenes during the dry season for each year between 1992 and 2002 were acquired from USGS, INPE, and TRFIC and co-registered (using ERDAS Imagine, version 8.5, Leica Geosystems, Inc.) to the 2002 ETM+ images. Fifty control points and 25 check points were utilized for each image, and the check point error for the first order polynomial (affine) transformations never exceeded one-third of a pixel, and almost all were within one-fifth of a pixel. This is important, as Dai and Khorram (1998) have shown that a registration accuracy of less than one-fifth of a pixel is necessary to keep change detection error to within 10%. Images were re-sampled (nearest neighbor) to the 28.5 m resolution of the 2002 scenes.

A total of 15 plots were accurately identified on the satellite images with these data sources. Global positioning system (GPS) points were taken within each of these plots with an expected 15 m horizontal accuracy. Since each agroforest plot ranged in size from 0.6 to 1.0 ha (100 m × 100 m), spectral data were collected from the single pixel corresponding to the GPS point plus groups of 6 to 9 contiguous pixels surrounding or adjoining the GPS point, yielding a total sample of 136 pixels. The precise choice of pixel configurations was corroborated with ground reference data (photographs, maps, and annual monitoring reports) collected over the preceding 10 years of the project.

Given the diverse sources of data consulted it was not possible to obtain metadata that were precise enough to afford a conversion to at-satellite reflectance using standard methods. As a result, reflectance values could not be compared from image to image. As such, using both ground reference data and the image chronosequences, we first identified areas of primary forest that were stable from the beginning to the end of the project period. For each image (year) the spectral (Euclidean) distances were calculated in Matlab (version 6.5.0.180913a Release 13, MathWorks, Inc.) between the means of the brightness value vectors in each agroforest plot and the brightness value mean of the primary forest in that image, using the following equation:

$$d = \sqrt{(f - mk)(f - mk)'},$$

where d is the spectral distance, f the mean brightness value vector for primary forest, m the mean brightness value vector for each agroforest plot, k

The sample of 15 plots was classified as follows: Group 1, timber-based agroforest plots (where the majority of species planted are timber); Group 2, non-timber-based plots (where no timber species were planted); and, Group 3, mixed plots (roughly comparable numbers of timber and non-timber species). The means for each of the groups are shown in Figure 2 and the correlations among the time series for the group means are shown in Table 5. The onset of active management (1993) resulted in a notable increase in the distance from

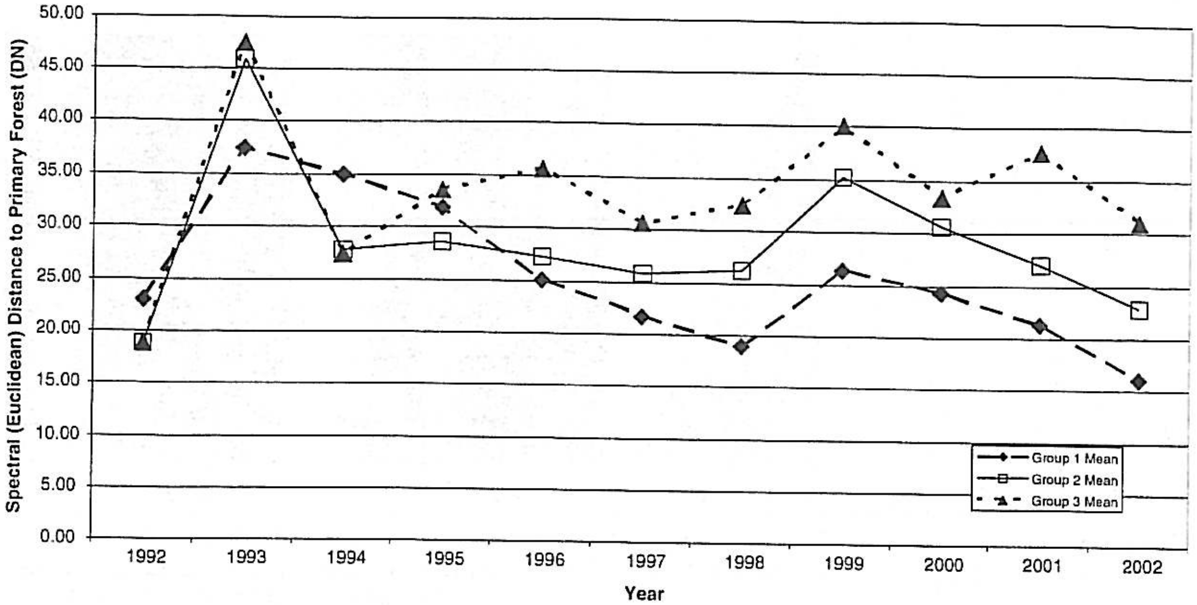

Figure 2. Mean Spectral Distance from Primary forest by Agroforestry Group Type.

Table 5. Spectral analysis of experimental Groups 1 (Timber-Based), 2 (non-timber-based), and 3 (mixed) agroforestry plots.

Year	Group 1 Mean	Group 2 Mean	Group 3 Mean
A. Distribution of mean spectral values by group and year (Standard Deviations)			
1992	23.02 (10.57)	18.75 (17.64)	18.92 (9.74)
1993	37.50 (16.42)	45.98 (24.32)	47.45 (15.78)
1994	34.94 (13.51)	27.76 (12.96)	27.41 (15.79)
1995	31.84(5.73)	28.53 (13.37)	33.53 (17.19)
1996	25.01 (7.49)	27.29 (13.52)	35.58 (14.72)
1997	21.76 (7.09)	25.85 (8.76)	30.64 (7.87)
1998	18.88 (10.46)	26.20 (10.29)	32.49 (10.27)
1999	26.42 (12.16)	35.19 (17.71)	40.00 (10.81)
2000	24.25 (16.39)	30.69 (23.29)	33.42 (21.10)
2001	21.23 (17.55)	26.98 (15.96)	37.68 (19.49)
2002	16.04 (9.53)	22.89 (5.54)	31.08 (9.54)
B. Correlation coefficients of means			
Group 1 mean	1		
Group 2 mean	0.668832271	1	
Group 3 mean	0.358851287	0.878936273	1

forest in all groups due, we suspect, to the clearing of vegetation in the plot establishment phase. The growth in the year following plot establishment resulted in a decrease in distance to forest as vegetation cover returned to the plot, but the degree to which the groups were temporally coherent after the establishment phase varied. Groups two and three exhibited the highest degree of coherence, 87.9%, while groups one and three were least coherent (35.9%). In addition, group three is 10–15 digital numbers more distant from primary forest than group one beginning in 1996, 3 years after establishment (Figure 2). While the degree of variability within each group precludes any ability to demonstrate statistical significance given the small sample number, the plot composition (and resulting management) differences in the three groups do appear to be associated with different

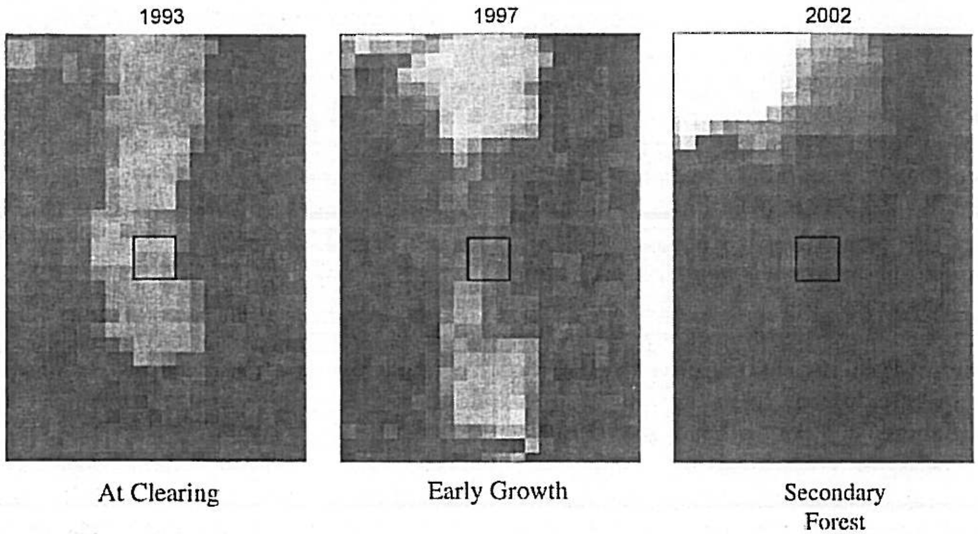

Figure 3. Thematic Mapper images of timber-based agroforest plot at clearing (1992), in the early growth phase (1997), and after succession to young secondary forest (2002). Each pixel is 900 m^2.

land use strategies, with group one being most proximate to the spectral characteristics of primary forest toward the end of the project period.

As noted earlier, group one is most proximate to the spectral characteristics of primary forest toward the end of the project period. However, it is necessary to reiterate that the differences between the means of groups one and two are not statistically significant, due to the small sample size, the low density of tree planting per pixel (two to three seedlings) and high intra-group variability. Indeed, contrary to the hypothesis, ground-level data indicate that most (53.3%) of the farmers managed their timber-based agroforestry plots by periodically clearing away secondary regrowth, largely for aesthetic reasons. Another 40% managed their plots (removed invasive secondary vegetation) during the first 5 years, and then left their plots to grow back. To the extent that farmers do allow secondary growth to subsume their agroforest plots after several years, they may well be increasing the flow of both the private (timber value) and public goods (array of ecosystem services associated with reforestation) from their property.

To visually illustrate this agroforestry-enriched secondary reforestation process, 1993, 1997, and 2002 Landsat Thematic Mapper images of one timber-based agroforest plot are presented in Figure 3.

In these images pixels with lighter tones correspond with high spectral reflectivity and less vegetation. Conversely, darker tones represent low reflectivity and, hence, denser vegetation. In this particular agroforestry plot, the farmer planted five different timber species (bandarra, cedro, freijó, mahogany, and teak) and two non-timber species (cupuaçu and pupunha palm) in 1993. By 2002, the farmer had abandoned any prospect of managing the plot for non-timber products (fruit and palm hearts/seeds) and allowed the secondary forest succession to subsume the plot. Yet, a sample of timber specimens of all five species planted in 1993 were readily identified and measured. The farmer probably would have recycled the abandoned agroforestry plot into pasture, the fate of most secondary growth, were it not for the valuable timber ensconced in this successional vegetation.

Conclusions

The RAPP, launched in 1992 with a seed grant from the John and Teresa Heinz Charitable Trust to Virginia Polytechnic Institute and State University continues to produce useful lessons for tropical agroforestry development. In terms of biological productivity, the project reveals that:

- Valuable timber species (e.g. mahogany, cerejeira, teak) enjoy high seedling survival rates and grow well in virtually unmanaged agroforestry plots, although shoot-borer afflicts virtually 100% of mahogany juveniles.
- Key agroforestry cash-crops, like cupuaçu, and pupunha palm, appear to be durable in mixed agroforest settings. After 10 years, 72.4% of the plots planted with cupuaçu were still producing fruit of this species.
- Farmers value these agroforestry plots for the long-term (at least 10 years), even when they do not earn a cash income from the sale of agroforest products, suggesting that farmers appreciate agroforestry for reasons other than immediate income interests in this land use.
- Agroforestry practices tend to spontaneously diffuse more rapidly within a rural neighborhood with a demonstration farm, than within a rural neighborhood without one. Passive neighborhood demonstration may be an effective strategy for disseminating agroforestry practices within rural communities.
- Timber-based agroforestry designs (i.e. where the majority of species are long-growing valuable hardwoods) may be an effective strategy for promoting secondary forest succession, and therefore restoring ecosystem functions.

Although inconclusive, the findings presented would warrant further research of the hypothesis that farmers planting timber-based agroforestry plots are more likely to permit secondary succession to subsume their plots over the long-term (after 5 years) than farmers who plant non-timber agroforestry plots.

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