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Mechanized Direct-Seeding of Native Forests in Xingu, Central Brazil

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The Y Ikatu Xingu Campaign brought together indigenous people, farmers, researchers, governmental, and non-governmental organizations seeking riparian forest restoration in the Xingu watershed, in west-central Brazil. Forest restoration is challenging in the region because of scarce nurseries, long distances, and high costs associated with the usual technique of planting nursery-raised seedlings. This article describes mechanized direct seeding and compares it with the planting of seedlings, in terms of cost and tree densities at ages of 0.5 until 5.5 yr after planting. Direct-seeding was mechanized using common agricultural machines designed for sowing cereals or grasses, which were loaded with 200,000 seeds of native trees and 150,000 seeds of annual and sub-perennial legumes, plus 50–150 kg sand ha^{-1}. The Campaign restored more than 900 ha by direct-seeding and 300 ha by planting seedlings. The great demand for native seeds was met by the Xingu Seed Network, formed by Indians, small landholders, and peasants, which commercialized 98 tons of native seeds and earned US$500,000 since 2006. Direct-seeding costs less per hectare than planting seedlings (US$1,845 ha^{-1} against US$5,106 ha^{-1}), results in higher tree densities (2,500–32,250 trees ha^{-1} against 1,500–1,650 trees ha^{-1}), is more practical, and

The authors acknowledge the active contribution of seed-gatherers, farmers, and field technicians to this research. They also recognize the discussions with Rodrigo Junqueira (Farm São Luiz), Natalia Guerin, Giselda Durigan, Ernst Gostch, Antônio Melo, and others who visited the authors since 2006.
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creates layers of dense vegetation that better resembles natural forest succession.

KEYWORDS forest restoration, tree mechanized direct-seeding, watershed, biodiversity management

INTRODUCTION/BACKGROUND

The Xingu River Watershed and the "Y Ikatu Xingu" Campaign

The Amazon forest is the largest continuous tropical forest ecosystem in the world. While most of it is still intact, it has been progressively deforested in the south and east of the Amazonian Basin. The Xingu River—one of the Amazon's main tributaries—is located in this southeastern portion of the Amazon Basin, where the Cerrado and Amazon biomes meet. The Cerrado is a mainly evergreen vegetation occurring typically on oligotrophic soils with, at least, four dry months yearly, in which it differs from Amazonia, where dry seasons usually last less than four months. With contorted tree trunks and thick leaves, Cerrado is one of the world's biodiversity hotspots and has the richest flora among the world's savannas (over 7,000 species), with high levels of endemism. The Xingu Basin covers 51 million ha with extensive water resources, biodiversity and socio-diversity and is a site of intense agricultural expansion, especially in the headwaters region of Mato Grosso, where many of the remaining forests are situated on lands that are suitable for soy production and cattle ranching (Lima et al., 2006). While 24 indigenous groups and dozens of traditional riverine communities have conserved most of the native vegetation of Xingu in their territories, settlers that arrived in the last 40 yr have deforested large areas of the surrounding landscape (Sanches & Villas-Bôas, 2005), including riparian zones, which is specifically forbidden by the Brazilian Forest Code (Velasquez, Queiroz, & Bernasconi, 2010). The deforestation of 5.7 million ha of native vegetation, including 315,000 ha in riparian zones (Figure 1), is jeopardizing water quality and water flow regulation (Coe, Costa, & Howard, 2007), as well as the health, economy, and culture of people who, for over a thousand years, have used water from these rivers for drinking, cleaning, cooking, and fishing (Velasquez et al., 2010).

Concerned with the situation in the watershed, the Socio-Environmental Institute (ISA, in Portuguese) integrated socioeconomic and environmental data into maps of the region. ISA worked with several other organizations to bring farmers, peasants, Indians, NGOs, and governmental actors together to discuss these issues in 2004 in the city of Canarana (Sanches & Villas-Bôas, 2005). These partner organizations included the Association of the Xingu Indigenous Territory (ATIX), the Forum of Mato Grosso for Environment and Development (FORMAD), and the State University of

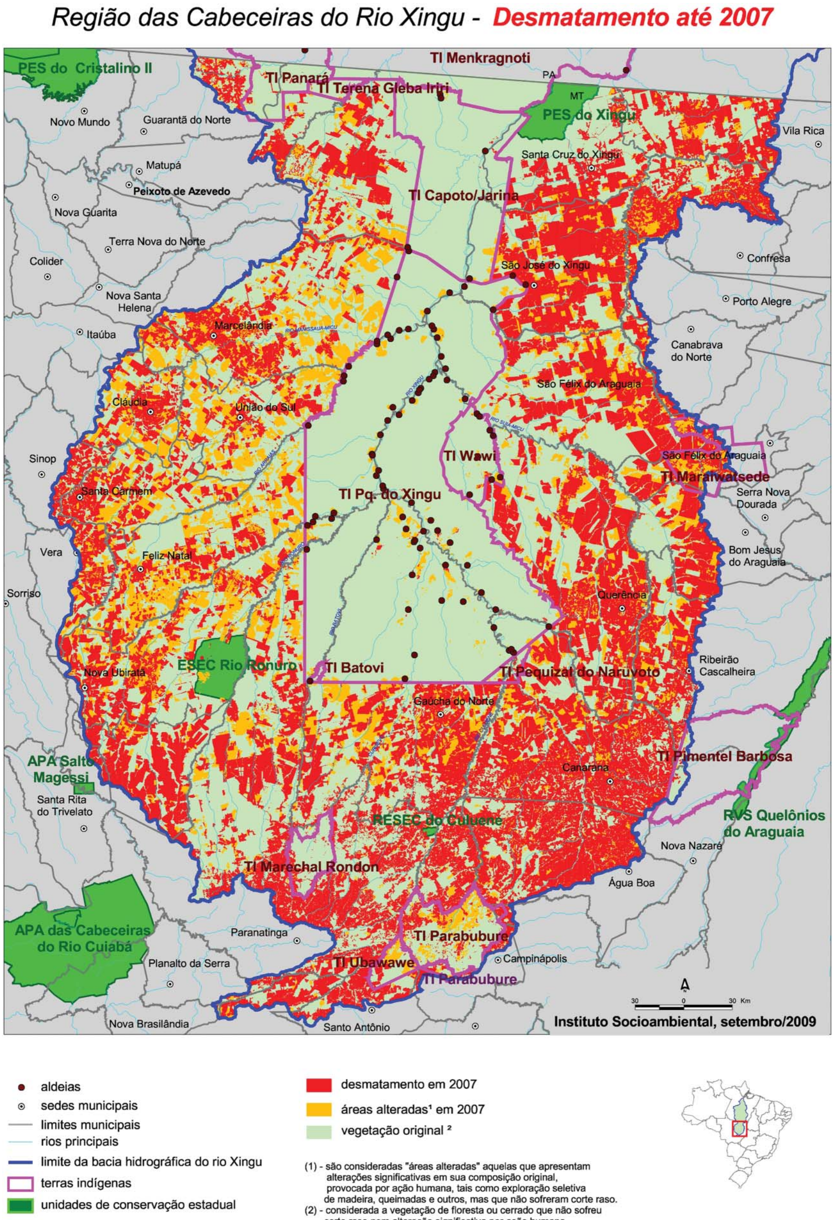

FIGURE 1 Map of the Xingu headwaters–deforestation up to 2007. The central non-deforested area is the Xingu Indigenous Park and the surrounding darker patches are deforested areas. More specifically, the map indicates indigenous villages (dark dots); cities (dotted circles); municipal limits (thin lines); limits of the river basin (dark, thick outer lines); indigenous territories (lighter thick lines); conservation areas (bordered shaded areas labeled, e.g., “PES do Cristalino II”); deforestation up to 2007 (dark gray areas); altered forests up to 2007, which contain vegetation presenting noticeable alteration in its original composition through exploration of timber or fire, but which was not cleared (lighter gray patches); and original vegetation up to 2007, which are areas that haven’t suffered noticeable anthropic alteration (gray background) (color figure available online).

Mato Grosso (UNEMAT), the Xingu Headwater's Meeting. The discussions led to the creation of "Y Ikatu Xingu" (YIX—"Save the Fine Water of Xingu," in the Kamaiura language): a "shared socio-environmental responsibility" campaign aiming to contain and reverse degradation processes in the Xingu Basin. Each stakeholder recognized its own agenda for promoting sustainable agriculture, sanitation, education, interaction with public policy, and communication (ISA, 2013). Since water conservation and forest restoration was a common element across all of the stakeholders' respective agendas, it became a main focus of the YIX Campaign. The YIX Campaign has been a learning network for forest restoration, wherein findings are disseminated through lectures, workshops, field demonstrations, practical courses, videos, television, magazines, newspapers, interchange expeditions, and school activities.

Participative Planning and Innovation

The Y Ikatu Xingu Campaign has helped people to plant native trees on their lands, whether they be private farms, indigenous territories, or agrarian reform settlements. At the same time, YIX has received help from these people, since they are also acknowledged as researchers in the Participatory Action Research approach (Castellanet & Jordan, 2002) as well as entrepreneurs. Innovative models are welcome as they can benefit from local knowledge and YIX support in order to develop new strategies. YIX technicians facilitate diagnosis and planning by addressing important planning details—such as intended goals, site degradation factors and risks, soil type, vegetation cover, available tools, and available workforce—resulting in projects that suit people's different understandings, resources, and goals. This approach attempts to rely minimally on external technical assistance and inputs. YIX seeks to empower local entrepreneurship through restoration aimed at goals such as water quality, fruit production, timber production, carbon sequestration and forest restoration.

Techniques for Landscape-Scale Approach

Autogenic restoration is the preferred restoration process wherever natural regeneration potential is still available (Rodrigues et al., 2011). However, many degraded areas lack this potential, or present physical or biological barriers that delay it significantly or prevent it from developing into successional forests (Lugo, 1988; Nepstad, Uhl, & Serrao, 1991)—such as soil compaction, distance to forest remnants, long dry seasons, competition with invasive grasses and herbivory. In this scenario, the most usual technique for forest restoration in the tropics has been the plantation of nursery-raised tree seedlings (Lamb, Erskine, & Parrotta, 2005; Chazdon, 2008), a method that evolved through decades of research and eventually established a very popular model in Brazil. Presently, it is recommended and conducted by government agencies, legal agreements, and NGOs in Brazil as a dominant formula regarding various aspects of forest restoration. These prescriptions include seedling spacing (3 m × 2 m), density (1,666 seedlings ha^{-1}), and proportion (50%) between pioneer or "filling" group (fast-growing and wide canopy) and non-pioneer or "diversity" group (slow-growing and/or narrow canopy) tree species (Rodrigues et al., 2011). Planting seedlings may be a successful choice for forest restoration (Montagnini, 2001; Holl, Zahawi, Cole, Ostertag, & Cordell, 2010); however, it was found in other regions of Brazil that planting can be extremely costly (circa US$5,000 ha^{-1}, according to Aronson et al., 2011) and usually results in low-diversity stands (average of 35 species) dominated by pioneer trees (2/3 of planted individuals) with short life-cycles (10–20 yr), which raises concerns about the long-term diversity of these planted forests (Barbosa et al., 2003).

The main impediments to planting seedlings in Xingu were the scarce seedling production, poor dirt roads for transportation, high costs associated with intensive manual labor and long-standing control of invasive grasses, high mortality associated with long dry seasons, and unmotivated farmers (Durigan, Guerin, & Costa, 2013). Additionally, the technology for raising seedlings of regionally native species in forest nurseries is scarce, especially for Cerrado species, probably due to its early root depth, which might be an adaptation for long dry seasons (Oliveira et al., 2005). Thus, for a region such as Xingu, where distances between locales are long, and farms and degraded areas are extensive, natural regeneration and seedling transplantation techniques were ill-suited to a landscape-scale forest restoration initiative.

Indians and traditional riverine communities of Xingu have, for centuries, planted trees through the ancient technique of direct-seeding (Posey, 1985). YIX combined the direct-seeding technique with the use of common farm machines such as soybean planter machines, as seen at the São Luis Farm in southeastern Brazil. After the soy planter got stuck in the mud during the first trial in Xingu, the alternative found by the farmers was to throw seeds manually and then plow over them. Soon afterwards, broadcasting machines proved also to be a viable option for direct seeding.

Tree direct seeding is an ancient technique, with numerous references worldwide (Evelyn, 1670; Harmer & Kerr, 1995; Willoughby, Jinks, Gosling, & Kerr, 2004; Doust, Erskine, & Lamb, 2006, 2008; Cole, Holl, Keene, & Zahawi, 2010) and in Brazil (Franco, Nardoto, & Souza, 1996; Engel & Parrotta, 2001; Camargo, Ferraz, & Imakawa, 2002; Araki, 2005; Isernhagen, 2010; Santos, Ferreira, Aragão, Amaral, & Oliveira, 2012). These studies have found that some species are incompatible with this type of planting, some seeds must be buried, germination success and plant survival are directly related to seed size, and that it is cost-effective relative to planting seedlings and, thus, a promising alternative for forest restoration in the tropics.

This article aims to present a technique for mechanized direct seeding and compare it to the forest restoration technique most used in Brazil, which is planting seedlings that are pre-grown in forest nurseries. The hypothesis is that direct-seeding represents a cheaper, more practical, effective, and socio-beneficial technique for large-scale forest restoration.

The following presents the primary ecological aspects of the study area and describes the techniques used for establishing seedlings and direct-seeding plantations in Xingu, as well as the management and monitoring methodologies. Structural data of sapling density, diameter, and height sampled at 26 areas are compared and discussed with reference to the literature and lead to some concluding remarks.

METHODOLOGY

Study Area

This study analyzed 26 restoration areas randomly selected from 198 farms across the Xingu River Basin headwaters in the state of Mato Grosso. The Xingu River begins in the Cerrado of Mato Grosso State and flows north 2,700 km through tall, dense, moist forests before emptying into the main channel of the Amazon River (Figure 2). The Xingu River drains a landscape of ancient crystalline Precambrian shield, from 600 to 300 m above sea level, covered predominantly by oxisols. The climate type, according to Köppen (1948), is tropical AW with two defined seasons: "wet summer" (October to March) and "dry winter" (April to September). Annual rainfall in the south of the basin is around 1,400 mm and highly concentrated, with a 6-month period of severe drought; whereas to the north of the basin in Mato Grosso, it rains up to 1,900 mm annually, with only a 4-month drought (Ivanauskas, Monteiro, & Rodrigues, 2008).

PLANTING SEEDLINGS

Seeds of 47 species were obtained from the Xingu Seed Network, pretreated for breaking dormancy as necessary, and sown in germination beds made of washed sand in a local forest nursery. After germination, seedlings were transplanted into plastic bags of 25 cm × 18 cm filled with 40% sand, 40% clay, and 20% organic matter, plus 50 g of limestone and 25 g of fertilizer NPK (10-10-10) and raised 4 to 6 months. Restoration site preparation included spraying a broad spectrum contact herbicide, such as glyphosate, followed by plowing two times to break soil compaction. Seedlings were planted in holes of 30 cm × 30 cm × 40 cm, spaced 3 m × 2 m from each other, resulting in a density of 1,666 seedlings ha^{-1}, with a 50% proportion between

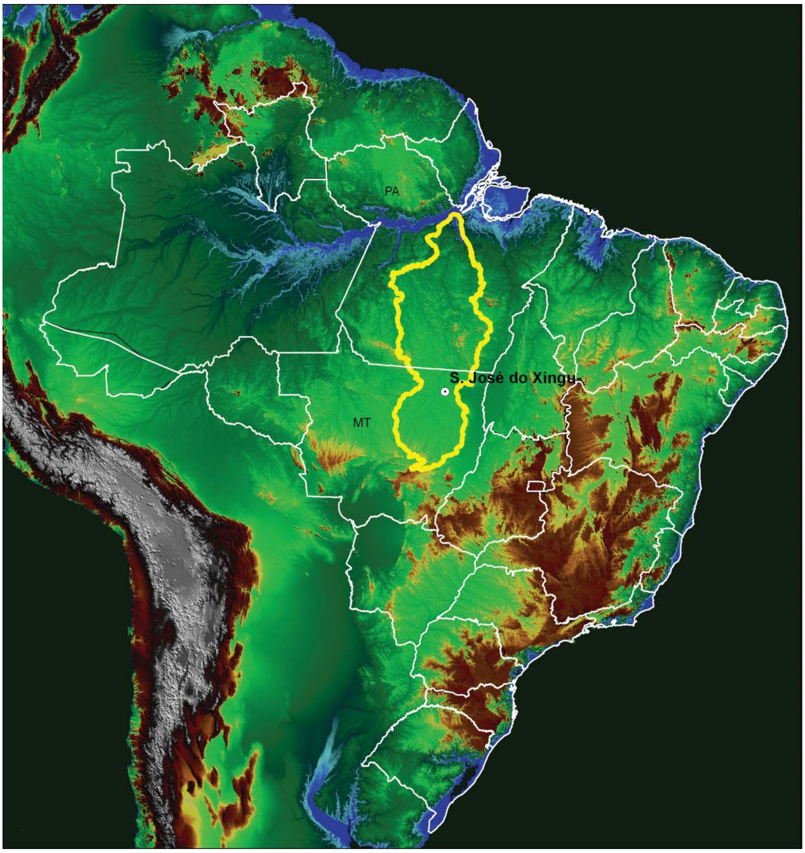

FIGURE 2 Location of the Xingu River Basin (thick line) in South America, Brazil and its headwaters in the Mato Grosso State (MT). Thin lines mark the limits of the Brazilian States (color figure available online).

pioneer (fast-growing with dense shading canopy) for "filling," and non-pioneer (slow-growing, shade tolerant) tree species for creating "diversity." At farm 2R, four jack beans and three pigeon peas were established around each seedling in a crown with a radius of 50 cm.

Species planted as seedlings for "filling" were *Anadenanthera colubrina* (Vell.) Brenan, *Cecropia pachystachya* Trécul., *Anacardium nanum* A. St.-Hil., *Enterolobium timbouva* Mart., *Guazuma ulmifolia* Lam., *Inga edulis* Mart., *Inga vera* Willd., *Mabea fistulifera* Mart., *Simarouba amara* Aubl., *Simarouba versicolor* A. St. Hil., and *Terminalia argentea* Mart. & Zucc. Seedling species for "diversity' were *Alibertia edulis* Rich., *Andira vermifuga* Mart. ex Benth., *Annona coriacea* Mart., *Apuleia leiocarpa* (Vogel) J.F. Macbr., *Astronium fraxinifolium* Schott ex Spreng., *Bauhinia* sp. L., *Buchenavia tomentosa* Eichler, *Byrsonima cydoniifolia* A. Juss., *Calophyllum brasiliense* Cambess, *Caryocar brasiliense* Cambess., *Copaifera langsdorffii* Desf., *Cybistax antisyphilitica* (Mart.) Mart., *Dipteryx alata* Vogel *Dypterix odorata* (Aubl.) Willd., *Eugenia dysenterica* DC., *Eugenia* sp. L., *Genipa americana* L., *Handroanthus heptaphyllus* (Vell.) Mattos, *Handroanthus ochraceus* (Cham.) Mattos, *Handroanthus serratifolius* (A.H.Gentry) S.Grose, *Hymenaea courbaryl* L., *Hymenaea stigonocarpa* Mart. ex Hayne, *Jacaranda cuspidifolia* Mart. ex A.DC., *Lafoensia pacari* A. St. Hil., *Machaerium acutifolium* Vogel, *Mauritia flexuosa* L.f., *Mouriri pusa* Gardner, *Myracrodruon urundeuva* Allemão, *Peltogyne confertiflora* (Mart. ex Hayne) Benth, *Physocalymma scaberrimum* Pohl, *Protium heptaphyllum* (Aubl.) Marchand., *Spondias mombin* L., *Sterculia striata* A. St. Hil. & Naud. *Syagrus oleracea* (Mart.) Becc., *Tabebuia aurea* (Silva Manso) Benth. & Hook.f. *ex* S.Moore, *Tabebuia roseoalba* (Ridl.) Sand.

"*MUVUCA*" DIRECT-SEEDING

The mix of sand or soil with seeds of crop, green manure (annual and sub-perennial legumes) and forest species is known as "*muvuca de sementes*" ("seed muvuca"). "Muvuca" is an expression made popular in Brazil by the agroforestry group *Mutirão Agroflorestal*. The *muvuca* direct-seeding technique was conducted either using planter machines, which mechanically dig and sow in rows, or broadcasting machines, that launch seeds randomly over the area, and require plowing in order to bury the seeds afterwards. All abandoned croplands were direct-seeded in rows with planter machines, while all abandoned pastures were direct-seeded with broadcasting machines and later plowed. Since the restoration areas were not previously designed as scientific experiments, it was not possible to establish adequate control plots for these two ways of direct seeding. Therefore, they were counted together as one methodology, which is compared with the conventional methodology of planting seedlings.

Soil Preparation

Adequate soil preparation may be accomplished by plowing, chemical weeding with herbicides, or a combination of both. Use of herbicides is only justifiable if aggressive grasses are dominant in the target area. Pastures are the most common scenario for restoration projects in Xingu and are usually formed by African grasses such as *Urochloa* P. Beauv. and *Panicum* L. Thus, site preparation on pastures usually begins with an application of a broad spectrum contact herbicide, such as glyphosate. After 2 weeks, the soil was plowed for breaking soil compaction. At least a month after first plowing, another plowing was conducted for killing the remaining grasses and leveling the terrain. Where slopes are steep, plowing may be done in leveled strips, leaving non-plowed strips between them in order to avoid erosion.

Where slopes are too steep, the *muvuca* may be sown in small seed beds made by hand. However, no steep areas were sampled for this research. The second most common scenario in Xingu are croplands, where direct-seeding machines are usually available, soil is flat, covered with "mulch" and need not be plowed, since soil compaction is low and weeds are nearly absent. In this scenario, no soil preparation is necessary.

Species Selection

Species for direct-seeding were selected for each site from a list of 214 species collected by the Xingu Seed Network. Species of seedlings were selected from a list of 47 species available in local nurseries. The first criteria guiding species selection is tolerance to water stress such as extended dry seasons, annual flooding, or permanently swampy areas. Species were grouped by occurrence in the following vegetation types: Amazon Forest, Cerrado Forest, Cerrado, Gallery (riparian) Forest, Temporary Flooded Forest, Permanently Swampy Forest, and Swampy Field. Second, the planting machine available was tested for seed size, because the size of a machine's apertures limits the maximum seed size, thus it may be necessary to exclude some species or to plant them separately. However, an average of 70 species were direct-seeded in each area, varying the group of species according to the factors described above.

Muvuca—Seed Quantity Calculation

Seed calculation aims at establishing a seed bank capable of out-competing invasive grasses and creating a canopy in which fast-growing plants get gradually replaced by slow-growing trees over time. Within the adequate group of species for the target site, species with economic value—such as edible fruits, medicines, and timber—were favored with higher seed densities. Nevertheless, each *muvuca* included species from the following groups: (a) leguminous herbs and shrubs (10 seeds m^{-2}) capable of recovering soil fertility and shading out invasive grasses, (b) fast-growing trees (10 seeds m^{-2}), and (c) slow-growing trees (10 seeds m^{-2}). Total seeding density averaged 300,000 seeds ha^{-1}; 200,000 seeds ha^{-1} of trees, plus 100,000 seeds ha^{-1} of annual and sub-perennial legumes; 3 seeds m^{-2} of jack-beans (*Canavalia ensiformis* [L.] DC.), 6 seeds m^{-2} of *Crotalaria spectabilis* Roth, and 1 seed m^{-2} of pigeon peas (*Cajanus cajan* [L.] Millsp.).

Seed quantity of each species should be calculated by dividing the desired quantity of adults by the rate of viable seeds per kilogram and their survival rates. Since there were no published studies about the rates of open field seed germination and tree survival in Xingu, calculation of seed quantities was based on local knowledge, resulting in a rough estimate of between 2 and 10% germination plus survival rate after 3 yr. Seeding density variations rely on the assumption that larger seeds present greater germination and survival rates. Between 10 and 50 seeds were sown for each desired adult tree, and around 3 seeds for each desired annual or sub-perennial adult legume.

Seed Collection

Seeds were ordered through the Xingu Seed Network (XSN), an organization of indigenous people and peasants for seed collection (Figure 3). XSN organizes seed quality, storage, delivery, and payments to 20 groups across a range of 750 km, providing seeds from 214 species. Annual meetings gather leaders from all groups to discuss organization agreements and prices, which vary from US$0.5 kg^{-1} for big and easy seeds to US$125 kg^{-1} for small and hard to get seeds, with an average of US$15 kg^{-1}. The XSN also provides information on species ecology and do research on seed collection, cleaning and storage (http://www.sementesdoxingu.org.br).

Muvuca—Seed Mixture Preparation

Before mixing the seeds with sand, all dormant seeds—due to seed coat impermeability—were treated with hot water (60°C) for 5 min

FIGURE 3 Women collecting Amazon forest seeds at Panará Indigenous Territory, Guarantã do Norte, MT, Brazil. Seeds are bought by neighbor farmers through the Xingu Seed Network and direct-seeded in degraded riparian areas of their farms in the Xingu Basin (Credit: Dannyel de Sá) (color figure available online).

and then immersed in cold water for 10 min. Pre-treatment was performed on all seeds from tree species of the leguminous family within the genera *Apuleia*, *Bauhinia*, *Dialium*, *Dimorphandra*, *Enterolobium*, *Hymenaea*, *Leptolobium*, *Ormosia*, *Parkia*, *Peltogyne*, *Samanea*, *Tachigali*, *Schizolobium*, *Senegalia*, *Senna*, and *Stryphnodendron*; but also of *Passiflora* (Passifloraceae), *Byrsonima* (Malpighiaceae) *Cecropia* (Cecropiaceae), and *Solanum* (Solanaceae). Following pre-treatment, sand was mixed with the seeds in order to favor a more homogeneous distribution of seeds with different sizes over the restoration site, resulting in the *muvuca*. More than one *muvuca* may be necessary, depending on the type of machine available. Machines for broadcasting limestone have the largest apertures and can launch seeds up to 15 cm in diameter. Smaller machines for broadcasting fertilizers and grass seeds have apertures that can sow seeds up to 5 cm. Planters designed for sowing soy and corn have the smallest apertures: 1 cm in the seed boxes and 2 cm in the fertilizer boxes (Figure 4).

Direct-Seeding

Seeds which were larger than the machine's apertures, as well as expensive and potentially economically valuable tree species, such as *Caryocar brasiliense* Cambess., were separated and sown manually in regularly spaced seedbeds. Large seeds, over 2 cm, were buried in the ground at a depth between 1 and 10 cm. Medium-size seeds, from 0.2 to 2 cm, were buried in the ground between 1 and 2 cm, but never deeper than 5 cm. They represent the majority of seeds available in Xingu and fit in several types of planting and broadcasting machines. Broadcasting machines designed for limestone, fertilizers, or grass seeds are used for direct seeding over plowed land (Figure 5). After broadcast sowing, the soil was superficially plowed (leveled) to cover the seeds with soil. Planter machines designed for grains were regulated to plant at a depth of 2–5 cm (Figure 6) and require no plowing afterward. Seeds that are very small, lightweight, photoblastic, and winged—such as *Maclura tinctoria* (L.) D.Don ex Steud., *Astronium fraxinifolium* Schott. ex Spreng., and *Aspidosperma* spp. Mart. & Zucc.—were separated in another *muvuca* and broadcast sown as the last operation in the area, so as to remain aboveground.

MONITORING

Planted areas were rapidly monitored by YIX technicians and landowners or employees walking together and estimating the percentage cover of invasive grasses, tree densities, and listing the species growing in the area. From those data, only the list of species will be presented here, due to a lack of

FIGURE 4 Preparing *muvuca*, a mixture of seeds of native trees, fast-growing legumes, and sand for direct-seeding (Credit: Luciana Akemi Deluci) (color figure available online).

systematic sampling for density and coverage estimations. Selection of sites for systematic sampling sought to include at least three sample areas of each age class (Table 1) and of each planting technique (direct-seeding in rows, broadcast direct-seeding, and planting seedlings) in each biome (Cerrado and Amazonia). However, the 5.5-yr-old areas were all in the Cerrado and there were no monitored areas planted with seedlings in Amazonia biome. Systematic sampling was accomplished in 26 areas, installing four permanent parcels of 20 m × 1 m in each, totaling 104 parcels and 2,080 m^2. All tree individuals in the parcels were counted and identified to the species

FIGURE 5 Mechanized direct-seeding using a machine originally designed for broadcasting fertilizers, in northeast Mato Grosso State, west-central Brazil. After launching seeds over the soil, the area is plowed to bury the seeds (Credit: Luciano Langmantel Eichholz) (color figure available online).

FIGURE 6 Planter machine used for direct-seeding in-rows, Mato Grosso State, west-central Brazil (Credit: Luciano Langmantel Eichholz) (color figure available online).

TABLE 1 Number of Sampled Areas in Each of Four Age Intervals and Respective Planting Technique in Xingu Region, State of Mato Grosso, West-Central Brazil

Age after planting (years)	Planting technique	Sampled areas	Parcels	Sampled area (m^2)
0–0.5	Broadcast direct-seeding	6	24	480
0.6–2	Broadcast direct-seeding	4	16	320
0.6–2	Direct-seeding in rows	3	12	240
2.1–2.5	Direct-seeding in rows	4	16	320
2.1–2.5	Broadcast direct-seeding	2	8	160
2.1–2.5	Planting seedlings	3	12	240
2.6–5.5	Direct-seeding in rows	2	8	160
2.6–5.5	Broadcast direct-seeding	2	8	160

level. Annual and sub-perennial legumes were not sampled because it would require other experimental designs and measurement methods. Height and diameter data were missing in some plots due to lack of adequate equipment at the time of monitoring and were thus excluded from this article.

MANAGEMENT

Only one area (Farm Simoni) did not receive any management measures (Figure 7). In all other sampled areas weed control after planting was necessary, because monitoring detected more than 30% of grass coverage (Melo, 2004). Weed control was done by spraying selective herbicides.

RESULTS AND DISCUSSION

Since 2006, the Y Ikatu Xingu Campaign has facilitated the restoration of 2,400 ha of riparian forest, on 198 farms in 23 municipalities of the Xingu watershed in the state of Mato Grosso. This included the planting of 98 tons of seeds from 214 native species, collected by over 300 people from 20 rural and indigenous communities that earned together over US$500,000. Approximately 1,100 ha underwent natural regeneration, 300 ha were planted with seedlings, and 1,000 ha were planted with *muvuca* by direct seeding (Figure 8).

Data from areas established by direct seeding presented very high variation of mean tree densities, regardless of the direct-seeding method or biome (Table 2). Beyond the fact that these areas were not initially established as scientific experiments, this large variation was not surprising, since areas feature different climates, soil types, degradation histories, received different assemblages of species from different lots of seeds, and seeds were randomly distributed in the areas. Rodwell and Patterson (1994) support the idea that

FIGURE 7 Area 5 months after being direct-seeded with *muvuca*. Note pigeon peas, jack beans, and maize—Farm Simoni, Canarana, MT, Brazil (Credit: Osvaldo Luis de Sousa) (color figure available online).

FIGURE 8 Same area shown in Figure 7, 3 yr after direct-seeding, with the trees forming a canopy as the last pigeon peas dies and jack beans and maize are already out of the system at Farm Simoni, Canarana, MT, Brazil (Credit: Elin Rømo Grande) (color figure available online).

TABLE 2 List of Monitored Areas, Restoration Techniques Applied, Local Biome, Age After Planting (Years), and Mean Density (trees/hectare) in the Xingu Region of the State of Mato Grosso, West-Central Brazil

Local	Technique	Biome	Age	Mean density
Farm Destino Lado B	Broadcasting	Amazon	0.5	4,850
Farm Destino Lado A	Broadcasting	Amazon	0.5	6,650
Farm Destino Lado C	Broadcasting	Amazon	0.5	7,750
Farm São Carlos direito	Broadcasting	Cerrado	0.5	8,500
Farm São Carlos–esq.	Broadcasting	Cerrado	0.5	12,650
Farm Destino Lado D	Broadcasting	Cerrado	0.5	21,750
Farm Brasil	Seeding in rows	Cerrado	0.6	3,625
Farm Bang-pasto 10	Broadcasting	Amazon	1.0	4,000
Farm Bang-pasto 82	Broadcasting	Amazon	1.4	5,750
Farm Cajuru	Seeding in rows	Cerrado	1.5	4,500
Farm Cajuru 2010	Seeding in rows	Cerrado	1.5	21,875
Farm São Roque 2010	Broadcasting	Cerrado	1.5	32,250
Farm Bang-pasto 71	Broadcasting	Amazon	1.9	2,875
Farm Don José	Seedlings	Cerrado	2.5	1,500
Farm 22 de maio	Seedlings	Cerrado	2.5	1,500
Sítio 2 R	Seedlings and legumes	Cerrado	2.5	1,625
Farm Cajuru	Seeding in rows	Cerrado	2.5	2,500
Farm Candeia	Seeding in rows	Amazon	2.5	6,000
Farm Schneider–flores	Seeding in rows	Amazon	2.5	8,375
Farm Roncador	Broadcasting	Amazon	2.5	9,125
Farm Schneider–natura	Seeding in rows	Amazon	2.5	9,750
Farm São Roque 2009	Broadcasting	Cerrado	2.5	21,375
Casa da criança	Seeding in rows	Cerrado	2.6	20,000
Farm São Roque 2008	Broadcasting	Cerrado	3.5	14,500
Farm Simoni linhas	Seeding in rows	Cerrado	5.5	7,250
Farm Simoni lanço	Broadcasting	Cerrado	5.5	7,375

local variation in tree spacing and size, including small areas of randomly occurring open space, creates a more natural appearance in the developing new native forest, as the anthropogenic "fingerprint" of regular spacing and standardized tree size is reduced.

A mean young tree density of 9,535 trees ha^{-1} may be considered high in comparison to areas planted with seedlings. The lowest tree density in direct seeding areas, ranging from 2,500 to 32,250 trees ha^{-1}, were still higher than the highest tree density found in areas planted with seedlings (1,500 to 1,625 trees ha^{-1}) in Xingu and in most areas planted with seedlings in Brazil (1,666 trees ha^{-1} and 3 m $\times$ 2 m spacing) at the same age (Rodrigues, Lima, Gandolfi, & Nave, 2009). However, high densities of young trees (dbh $\leq$ 5 cm) seem to reflect better what was observed in mature forests elsewhere. Silva, Leite, Silveira, Nassif, and Rezende (2004) observed 21,482 young trees ha^{-1} in areas of Cerrado riparian forest in central Brazil; whereas in Amazonian forests in the state of Pará, northern Brazil, Carvalho (1982) observed 7,653 young trees ha^{-1}. Rayol, Alvino, and Silva (2008) observed 70,800 and 80,600 trees ha^{-1}, in 15- and 20-yr-old secondary forests, respectively.

Initially, high density areas direct-seeded in Xingu showed signs of natural thinning, as can be inferred by comparing areas of different ages at the same farm. For instance, at Farm São Roque 32,250 trees ha^{-1} were found 1.5 yr after planting, 21,375 trees ha^{-1} were found after 2.5 yr, and 14,500 trees ha^{-1} were found after 3.5 yr (Table 2). According to Willoughby et al. (2004), high tree densities means that occasional damage to trees is less serious than when establishing seedlings at substantially lower stocking levels. Indeed, natural thinning by extended droughts leave survivors more resilient, while natural thinning by herbivores indicates that animals are using the area and possibly contributing to nutrient cycling (Miyawaki, 2004). Regarding the initiation of a restoration process, Willoughby et al. (2004) have found that high sapling densities and absence of transplant shock can result in much earlier canopy closure (3–5 yr after sowing) for direct-seeded stands compared with traditional seedlings plantation at a wider spacing. Thus a forest environment is created far more quickly and early canopy closure reduces the length of time herbicides and other management measures may need to be applied (Willoughby et al., 2004).

Sub-perennial (*Cajanus cajan*) and annual legumes (*Cannavalia ensiformis* and *Crotalaria spectabilis*), regarded as green manure, were present in all direct seeding treatments and in one of the seedling treatments. *C. spectabilis* and *C. ensiformis* died with 6 to 8 months, while the sub-perennial legume (*Cajanus cajan*) survived until the 4th yr after planting. None of those legumes were observed resprouting or regenerating in these areas beyond the 5th yr, which was desirable since those are not native species. Those short-lived, fast-growing, and N-fixing legumes formed an early and heterogeneous canopy cover over the germinating trees from the 2nd month after planting (field observation), while in areas planted only with seedlings canopy cover were not formed after 30 months. In southeast Brazil, canopy cover of areas planted with seedlings begins to close between 2 and 3 yr (Brancalion *et al.,* 2010). During the initial 2.5 yr, the appearance of areas direct-seeded with *muvuca* (annual plants, sub-perennial legumes, and trees-forming layers of vegetation with spatial heterogeneity) is very different from the appearance of areas planted with seedlings (a layer of grasses with regularly spaced trees). *Muvuca* areas more closely resemble areas of natural regeneration and seem to provide a greater diversity of suitable niches for re-colonization by non-introduced species.

While fast-growing nitrogen-fixing legumes may compete for water and light with young trees, an adequate density seems to foster growth of trees by enhancing aeration, de-compaction, and water absorption in the soil (Dubois & Viana, 1994). Legumes also yield a nitrogen-rich litterfall, possibly accelerating nutrient cycling and restoration of soil fertility (Peneireiro, 1999). An excessively dense canopy of fast-growing legumes, such as pigeon pea and jack bean, slows tree growth during the wet season when its dense foliage prevents most of the sunlight from reaching the saplings, but it also seems to slow the growth of invasive grasses, which is desirable. Competition seems to turn into facilitation during the dry season, when fast-growing legume species protect young trees and the soil from sunlight and heat, creating humid and stable microclimates under its canopy.

The large variation in tree density obtained from similar direct-seeding operations, with high seeding density and diversity of species and guilds, derives from uneven germination and survival at different sites and complies with the idea that ecological restoration is a non-deterministic process open to stochastic events that may not lead to a single pre-defined climax (Pickett, Collins, & Armesto, 1987; Parker & Pickett, 1999; Pickett & Cadenasso, 2005). The density sampled in seedling plantations in Xingu and which is usually recommended in Brazil (1,666 trees ha^{-1}) is based on the average density of adult trees (dbh > 10 cm) in tropical forests, thus ignoring the large stock of young trees that leads to the inverse J-shaped curve of diameter distribution typically found in natural forest communities (Barbour et al., 1987). By planting seedlings at the approximate desired density of adult trees, it becomes necessary to fight against ecological processes that cause natural thinning of seedlings and lead to an old-growth forest structure. This is a problem of major concern when planting seedings, if re-establishing ecological process is the main goal of a restoration project.

A list of all the native species that were direct-seeded and germinated is presented in Table 3. Sampling was not extensive enough to determine species-specific survival rates resulting from direct seeding.

Although the Xingu Seed Network provided 214 species, we could only find 89 species growing in the direct-seeded areas (42% of the species sown). Those 214 species germinated in nurseries, although some at very low rates, some required complicated pretreatments for breaking dormancy that could not be conducted in the field, some died during storage and some were too few and could have been overlooked during sampling. Most of the sampled species have orthodox[1] behavior, which makes them easier to store and wait until the beginning of the rainy season to plant. Storing recalcitrant seeds is still a major challenge. Those species must be either collected just before seeding or planted as seedlings. The pre-treatment method for breaking seed dormancy of orthodox seeds is not effective for all species, but was useful to accelerate the germination of part of the introduced seed bank, while the rest germinated throughout the following years. However, the number of species established by direct seeding (89) in Xingu is higher than the richness established by planting seedlings in Xingu (47) and in most projects established in the Brazilian Atlantic Forest (30 species), where forest restoration has a much longer research history (Barbosa et al., 2003; Rodrigues et al., 2009).

Comparing costs of different techniques is also essential to scaling up a forest restoration campaign. The overall cost per sapling established in

TABLE 3 List of Species and Respective Families That Were Sampled in YIX Restoration Projects Planted by Direct Seeding in the Xingu Region, State of Mato Grosso, West-Central Brazil

Botanic family	Scientific name
Anacardiaceae	*Myracrodruon urundeuva* Allemão
Anacardiaceae	*Anacardium humile* A. St. Hil.
Anacardiaceae	*Astronium fraxinifolium* Schott ex Spreng.
Anacardiaceae	*Anacardium nanum* A. St. Hil.
Anacardiaceae	*Spondias mombin* L.
Apocynaceae	*Himatanthus obovatus* (Müll. Arg.) Woodson
Apocynaceae	*Himatanthus sucuuba* (Spruce ex Müll. Arg.) Woodson
Apocynaceae	*Aspidosperma macrocarpon* Mart.
Apocynaceae	*Aspidosperma tomentosum* Mart.
Apocynaceae	*Aspidosperma subincanum* A.DC.
Arecaceae	*Attalea maripa* (Aubl.) Mart.
Arecaceae	*Attalea phalerata* Mart. ex Spreng.
Arecaceae	*Mauritia flexuosa* L.f.
Arecaceae	*Syagrus oleracea* (Mart.) Becc.
Bignoniaceae	*Cybistax antisyphilitica* (Mart.) Mart.
Bignoniaceae	*Jacaranda copaia* (Aubl.) D.Don.
Bignoniaceae	*Jacaranda cuspidifolia* Mart. ex A.DC.
Bignoniaceae	*Handroanthus heptaphyllus* (Vell.) Mattos
Bignoniaceae	*Handroanthus ochraceus* (Cham.) Mattos
Bignoniacee	*Handroanthus serratifolius* (A.H.Gentry) S.Grose
Bignoniacee	*Tabebuia aurea* (Silva Manso) Benth. & Hook.f. *ex* S.Moore
Bignoniacee	*Tabebuia roseoalba* (Ridl.) Sand.
Bixaceae	*Bixa orellana* L.
Calophyllaceae	*Calophyllum brasiliense* Cambess
Caryocaceae	*Caryocar brasiliense* Cambess
Combretaceae	*Terminalia argentea* Mart. & Zucc.
Combretaceae	*Buchenavia tomentosa* Eichler
Combretaceae	*Buchenavia capitata* (Vahl) Eichler
Dilleniaceae	*Curatella americana* L.
Euphorbiaceae	*Mabea fistulifera* Mart.
Euphorbiaceae	*Mabea angustifolia* Spruce ex Benth.
Fabaceae	*Anadenanthera colubrina* (Vell.) Brenan
Fabaceae	*Andira cujabensis* Benth.
Fabaceae	*Andira vermifuga* Mart. ex Benth.
Fabaceae	*Apuleia leiocarpa* (Vogel) J.F. Macbr.
Fabaceae	*Bauhinia* sp. L.
Fabaceae	*Copaifera langsdorffii* Desf.
Fabaceae	*Copaifera marginata* Benth.
Fabaceae	*Copaifera martii* Hayne
Fabaceae	*Dialium guianense* (Aubl.) Sandwith
Fabaceae	*Dimorphandra mollis* Benth.
Fabaceae	*Dipteryx alata* Vogel
Fabaceae	*Dipteryx odorata* (Aubl.) Willd.
Fabaceae	*Enterolobium timbouva* Mart.
Fabaceae	*Enterolobium schomburgkii* (Benth.) Benth.
Fabaceae	*Enterolobium maximum* Ducke
Fabaceae	*Hymenaea courbaril* L.
Fabaceae	*Hymenaea stigonocarpa* Mart. ex Hayne
Fabaceae	*Leptolobium nitens* (Vog.) Yakov.
Fabaceae	*Machaerium acutifolium* Vogel

(*Continued*)

TABLE 3 (Continued)

Botanic family	Scientific name
Fabaceae	*Mimosa setosa* Benth. var. *paludosa* (Benth.) Barneby
Fabaceae	*Ormosia excelsa* Spruce ex Benth.
Fabaceae	*Ormosia paraensis* Ducke
Fabaceae	*Parkia pendula* (Willd.) Benth. ex Walp.
Fabaceae	*Peltogyne confertiflora* (Mart. ex Hayne) Benth
Fabaceae	*Plathymenia reticulata* Benth.
Fabaceae	*Platypodium elegans* Vogel
Fabaceae	*Pterodon pubescens* (Benth.) Benth.
Fabaceae	*Pterogyne nitens* Tul.
Fabaceae	*Samanea tubulosa* (Benth.) Barneby & J. W. Grimes
Fabaceae	*Schizolobium amazonicum* Huber ex Ducke
Fabaceae	*Senegalia polyphylla* (DC.) Britton & Rose
Fabaceae	*Senna silvestris* (Vel.) H.S.Irwin & Barneby
Fabaceae	*Stryphnodendron pulcherrimum* (Willd.) Hochr.
Fabaceae	*Tachigali paniculata* Aubl.
Loganiaceae	*Strychnos pseudoquina* A. St. Hil.
Malpighiaceae	*Byrsonima crispa* A. Juss.
Malpighiaceae	*Byrsonima cydoniifolia* A. Juss.
Malpighiaceae	*Byrsonima pachyphylla* A. Juss.
Malpighiaceae	*Byrsonima verbascifolia* (L.) DC.
Malvaceae	*Apeiba tibourbou* Aubl.
Malvaceae	*Ceiba speciosa* (A. St. Hil.) Ravenna
Malvaceae	*Eriotheca gracilipes* (K. Schum.) A. Robyns
Malvaceae	*Guazuma ulmifolia* Lam.
Malvaceae	*Sterculia striata* A. St. Hil. & Naud.
Malvaceae	*Sterculia apetala* (Jacq.) H.Karst.
Meliaceae	*Swietenia macrophylla* King
Menispermaceae	*Abuta grandifolia* (Mart.) Sandwith
Moraceae	*Maclura tinctoria* (L.) D.Don ex Steud.
Passifloraceae	*Passiflora coccinea* Aubl.
Passifloraceae	*Passiflora nitida* Kunth
Rubiaceae	*Genipa americana* L.
Sapindaceae	*Magonia pubescens* A. St. Hil.
Simaroubaceae	*Simarouba versicolor* A. St. Hil.
Simaroubaceae	*Simarouba amara* Aubl.
Solanaceae	*Solanum lycocarpum* A. St. Hil.
Solanaceae	*Solanum crinitum* Lam.
Strelitziaceae	*Phenakospermum guyannense* (A.Rich.) Endl. ex Miq.
Urticaceae	*Cecropia pachystachya* Trécul.

direct-seeding in Xingu was US$0.19 per 2.5-yr-old sapling, US$0.25 per 5.5-yr-old sapling, and US$0.74 per 2.5-yr-old sapling in the area with the lowest resulting density (2,500 saplings ha^{-1}). While the latter density is comparable to that usually attained by planting seedlings in Brazil, costs per established sapling by direct-seeding are still 4.6 times cheaper than that of seedlings, at the same age. Costs per area of direct-seeding in the Xingu region (Table 4) were US$1,845 ha^{-1} (53% for seeds and 47% for planting and taking care of each hectare during 3 yr), slightly higher than the costs

TABLE 4 Costs in Dollars per Hectare of Forest Restoration Using Direct-Seeding, With 3-Yr Maintenance, in the Xingu Region, State of Mato Grosso, West-Central Brazil

Item	Unit	Cost per unit (US$)	Units/hectare	Total (US$/hectare)
Jack bean seeds	kg	2.00	30	60.00
Pigeon pea seeds	kg	2.50	6	15.00
Native seeds	Kg	15.00	60	900.00
Heavy plowing	machine/hour	60.00	2	120.00
Soft plowing	machine/hour	60.00	2	120.00
Sowing	machine/hour	60.00	0.5	30.00
Herbicide	application	50.00	2	100.00
Planting and Management	day-work	25.00	20	500.00
Total				1,845.00

TABLE 5 Costs in Dollars per Hectare of Forest Restoration Using Seedlings, With 3 Yr of Maintenance in the Xingu Region, State of Mato Grosso, West-Central Brazil

Item	Unit	Cost per unit (US$)	Units/hectare	Total (US$/hectare)
Seedlings	seedling	1.00	1,666	1,666.00
Seedlings transport	freight	75.00	3	225.00
Herbicide	application	40.00	4	160.00
Pit opening	machine/hour	60.00	8	480.00
Planting	day-work	25.00	8	200.00
Irrigation	machine-hour	60.00	12	720.00
Formicide	application	20.00	24	480.00
Replanting	day-work	25.00	2	50.00
Weeding	day-work	25.00	45	1,125.00
Total				5,106.00

calculated by Engel and Parrotta (2001) in southeastern Brazil, ranging from US$760 to US$1,450 ha^{-1}. Planting seedlings in Xingu (Table 5) cost about US$5,100 ha^{-1} (32% for raising seedlings in a nursery and 68% for planting and taking care of each seedling) or US$3.4 per established 3-yr-old sapling. This is comparable to costs calculated among several projects in the Brazilian Atlantic Forest of southeastern Brazil, which ranged between US$3,315–US$5,216 ha^{-1} or US$3.45 per sapling, whereas US$0.45 (13%) for raising one seedling in a nursery and US$3 (87%) for planting and taking care of each seedling during 3 yr (Rodrigues et al., 2011). The difference in cost per hectare is such that, with the same money, one can either restore 1 ha using seedlings or 2.77 ha by direct-seeding. Still, one can either establish one 3-yr-old sapling with seedlings or between 4 to 18 3-yr-old saplings by direct-seeding, with the same cost.

Establishing operations for direct seeding requires less time and fewer workers than seedling transplantation. As an example, six workers have planted 20 ha in 1 day by direct-seeding, while planting seedlings in the same area could take about 20 days for the same six workers. Seeds are easier and cheaper to transport—a pick-up truck can either carry seedlings for 1.2 ha or seeds for 15 ha—and do not suffer during long trips on poor roads, while seedlings suffer damages from excessive shaking and dry wind. In addition to the economic advantage, Willoughby et al. (2004) explain that direct seeding uses techniques that are more akin in many ways to the production of arable crops than to conventional forestry. All ground preparation and sowing can be carried out using modified agricultural machinery. This may be more attractive to a farmer, skilled in establishing agricultural crops but less skilled and perhaps unwilling to engage in the largely labor-intensive planting and establishment of trees using seedlings.

CONCLUSIONS

Both techniques of mechanized direct-seeding established more saplings of up to 5.5 yr old with much lower costs and greater expediency than by transplanting seedlings. High initial densities of introduced trees, herbs, and shrubs allowed reduction of maintenance costs for controlling herbivores and invasive grasses. Further research is needed to understand the interactions between densities of species of trees and fast-growing legumes concerning facilitation and competition processes during dry and wet seasons. Meanwhile, beans can be harvested for seed or to feed animals, while others are edible to humans and can render commercialization that may attenuate the restoration costs.

However, effective weed control during the first years is essential to ensure sapling survival and reduce the need for weeding in subsequent years. In most large-scale projects, overall spraying of herbicides is currently the cheapest and most practical option for controlling weeds. Improvements in machines for cutting grasses and mulching around the trees can be an alternative means of controlling and benefiting from grasses, which would be useful for both direct-seeding and seedling techniques. Mulching would provide more biomass, faster soil restoration, and probably enhance tree growth.

There is further research to be done on regional plants' life cycles, growth rates, shade tolerance, associations for nutrient fixation, phenology, dispersal syndromes, and pollination systems. Such considerations inform the process of providing adequate densities of individuals from each successional phase and forest stratum, composing a mix of species with all the vegetation ecological features, and thus avoiding waste of seeds and ecological gaps. Adequate seeding density of trees and fast-growing legumes may enhance seed germination and survival and help to avoid the use of herbicides for grass control.

The use of machines originally designed for broadcasting limestone, fertilizers, and grass seeds proved to be very practical and allowed mixing of larger seeds. In spite of the fact that in-row planters limit seed size and require more attention to the plant, they facilitated weed control and seeding of alternative rows with distinct assemblages of species. Overcrowding may prove detrimental to biomass accumulation and, if that is the objective, require future thinning of established trees.

Direct seeding may be particularly suited to large-scale areas where mechanization is technically and economically viable. However, it is important to note that direct-seeding and planting seedlings should be complementary techniques for high-diversity forest restoration, since recalcitrant seeds can hardly be introduced on a large scale by direct-seeding and nurseries remain the only reliable way for doing so. We believe that it is possible that the YIX model of broad community-based seed network associated with *muvuca* mechanized direct-seeding, small nurseries, and natural regeneration can be multiplied and adapted to accomplish the restoration of the other 312,600 degraded hectares of riparian areas in the Xingu Basin.

NOTE

1. Orthodox seeds can be stored dry (seed water content between 3–4%) and cold (less than −15°C) for long periods (over a year). Typical recalcitrant seeds die if stored with less than 14% of its water content and if stored at less than 10°C. Over these limits, recalcitrant seeds either germinate or rot.

REFERENCES

Araki, D. F. (2005). *Avaliação da semeadura a lanço de espécies florestais nativas para recuperação de áreas degradadas* (Master's dissertation). São Paulo University, Piracicaba, SP, Brazil.

Aronson, J., Brancalion, P. H. S., Durigan, G., Rodrigues, R. R., Engel, V. L., Tabarelli, M.. . . . Scarano, F. R. (2011). What role should government regulation play in ecological restoration? Ongoing debate in São Paulo State. *Brazilian Restoration Ecology*, *19*, 690–695.

Barbosa, L. M., Barbosa, J. M., Barbosa, K. C., Potomati, A., Martins, S. E., Asperti, L. M., . . . Plaza, A. P. (2003). Recuperação florestal com espécies nativas no Estado de São Paulo: Pesquisas apontam mudanças necessárias. *Florestar Estatístico*, *6*, 28–34.

Barbour, M. G., Burk, J. H., & Pitts, W. D. (1987). *Terrestrial plant ecology* (2nd Edition). Menlo Park, CA: Benjamin/Cummings Publishing.

Brancalion, P. H. S., Rodrigues, R. R., Gandolfi, S., Kageyama, P. Y., Nave, A. G., Gandara, F. B., . . . Tabarelli, M. (2010). Legal instruments can enhance high-diversity tropical forest restoration. *Revista Árvore*, *34*(3), 455–470.

Camargo, J. L. C., Ferraz, I. D. K., & Imakawa, A. M. (2002). Rehabilitation of degraded areas of central Amazonia using direct sowing of forest tree seeds. *Restoration Ecology*, *10*, 636–644.

Carvalho, J. O. P. (1982). *Análise estrutural da regeneração natural em floresta tropical densa na região de Tapajós no Estado do Pará* (Master's dissertation). Federal University of Paraná, Curitiba, PR, Brazil.

Castellanet, C., & Jordan, C. F. (2002). *Participatory action research in natural resource management: A critique of the method based on five years' experience in the Transamazônica region of Brazil*. New York, NY: Taylor & Francis.

Chazdon, R. L. (2008). Beyond deforestation: Restoring forests and ecosystem services on degraded lands. *Science*, *320*, 1458–1460.

Coe, M. T., Costa, M. H., & Howard, E. A. (2007). Simulating the surface waters of the Amazon River Basin: Impacts of new river geomorphic and dynamic flow parameterizations. *Hydrological Processes*, *22*, 2542–2553.

Cole, R. J., Holl, K. D., Keene, C. L. & Zahawi R. A. (2010). Direct seeding of late successional trees to restore tropical montane forest. *Forest Ecology and Management*, *261*, 1590–1597.

Doust, S. J., Erskine, P. D., & Lamb, D. (2006). Direct seeding to restore rainforest species: Microsite effects on the early establishment and growth of rainforest tree seedlings on degraded land in the wet tropics of Australia. *Forest Ecology and Management*, *234*, 333–343.

Doust, S. J., Erskine, P. D., & Lamb, D. (2008). Restoring rainforest species by direct seeding: Tree seedling establishment and growth performance on degraded land in the wet tropics of Australia. *Forest Ecology and Management*, *256*, 1178–1188.

Dubois, J. C. L., & Viana, V. M. (1994). Da capacidade produtiva da terra. *Informativo Agroflorestal*, *6*(3) editorial.

Durigan, G., Guerin, N., & Costa, J. N. M. N. (2013). Ecological restoration of Xingu Basin headwaters: Motivations, engagement, challenges and perspectives. *Philosophical Transactions of the Royal Society of London, Series B*, *368*, 20120165.

Engel, V. L., & Parrotta, J. A. (2001). An evaluation of direct seeding for reforestation of degraded lands in central São Paulo state, Brazil. *Forest Ecology and Management*, *152*, 169–181.

Evelyn, J. (1670). *Sylva or a discourse of forest trees* (Vol. 1). York, United Kingdom: Doubleday & Co.

Franco, A., Nardoto, G. B., & Souza, M. P. (1996). Patterns of soil water potential and seedling survival in the cerrados of Central Brazil. In R. C. Pereira & L. C. B. Nasser (Eds.), *Proceedings of the 1st International Symposium on Tropical Savannas* (pp. 277–280). Planaltina, Brazil: Embrapa-CPAC.

Harmer, R., & Kerr, G. (1995). Creating woodlands: To plant trees or not? In R. Ferris-Kaan (Ed.), *The ecology of woodland creation*. Chichester, United Kingdom: John Wiley.

Holl, K. D., Zahawi, R. A., Cole, R. J., Ostertag, R., & Cordell, S. (2010). Planting seedlings in tree islands versus plantations as a large-scale tropical forest restoration strategy. *Restoration Ecology*, *19*, 470–479.

ISA. (2013). *'Y Ikatu Xingu'—Salve a água boa do Xingu, na língua Kamaiurá*. Retrieved from http://www.yikatuxingu.org.br/linhas-de-acao/mapa-de-iniciativas/

Isernhagen, I. (2010). *Uso de semeadura direta de espécies arbóreas nativas para restauração florestal de áreas agrícolas, sudeste do Brasil* (Doctoral thesis). São Paulo University, Piracicaba, SP, Brazil.

Ivanauskas, N. M., Monteiro, R., & Rodrigues, R. R. (2008). Classificação fitogeográfica das florestas do Alto Rio Xingu. *Acta Amazonica*, *38*(3), 387–402.

Köppen, W. (1948). *Climatologia*. Mexico, DF, Mexico: Fondo de Cultura Económica.

Lamb, D., Erskine, P. D., & Parrotta, J. A. (2005). Restoration of degraded tropical forest landscapes. *Science 310*, 1628–1632.

Lima, E., Merry, F., Nepstad, D. C., Amacher, G., Azevedo-Ramos, C., Lefebvre, P. A., & Resque, F. (2006). Searching for sustainability: Forest policies, smallholders, and the Trans-Amazon Highway. *Environment*, *48*(2), 26–38.

Lugo, A. E. (1988). The future of the forest. Ecosystem rehabilitation in the tropics. *Environment*, *30*, 17–20, 41–45.

Melo, A. C. G. (2004). *Reflorestamentos de restauração de matas ciliares: Análise estrutural e método de monitoramento no Médio Vale do Paranapanema (SP)* (Master's dissertation). São Paulo University, São Carlos, SP, Brazil.

Miyawaki, A. (2004) Restoration of living environment based on vegetation ecology: Theory and practice. *Ecological Research*, *19*, 83–90.

Montagnini, F. (2001). Strategies for the recovery of degraded ecosystems: Experiences from Latin America. *Interciencia*, *26*, 498–503.

Nepstad, D., Uhl, C., & Serrao, E. A. S. (1991). Recuperation of a degraded Amazonian landscape: Forest recovery and agricultural restoration. *Ambio*, *20*, 248–255.

Oliveira, R. S., Bezerra, L., Davidson, E. A., Pinto, F., Klink, C. A., Nepstad, D. C., & Moreira, A. (2005). Deep root function in soil water dynamics in cerrado savannas of Central Brazil. *Functional Ecology*, *19*(4), 574–581.

Parker, V. T., & Pickett, S. T. A. (1999). Restoration as an ecosystem process: Implications of the modern ecological paradigm. In K. M. Urbanska, N. R. Webb, & P. J. Edwards (Eds.), *Restoration ecology and sustainable development* (pp. 17–32). Cambridge, United Kingdom: Cambridge University Press.

Peneireiro, F. M. (1999). *Sistemas agroflorestais dirigidos pela sucessão natural: Um Estudo de Caso* (Master's thesis). São Paulo University, Piracicaba, SP, Brazil.

Pickett, S. T. A., & Cadenasso, M. L. (2005). Vegetation dynamics. In E. van der Maarel (Ed.), *Vegetation ecology* (pp.172–198). Oxford, United Kingdom: Blackwell.

Pickett, S. T .A., Collins, L. S., & Armesto, J. J. (1987). Models, mechanisms and pathways of succession. *Botanical Review*, *53*, 335–371.

Posey, D. A. (1985) Indigenous management of tropical forest ecosystems: The case of the Kayapó Indians of the Brazilian Amazon. *Agroforestry Systems*, *3*(2), 139–158.

Rayol, B. P., Alvino, F. O., & Silva, M. F. F. (2008). Structure and floristic composition of the natural regeneration of two secondary forests in Capitão Poço, Pará, Brazil. *Amazônia: Ci. & Desenv.*, *4*(7), 103–116.

Rodrigues, R. R., Gandolfi, S., Nave, A. G., Aronson, J., Barreto, T. E., Vidal, C. Y., & Brancalion, P. H. (2011). Large-scale ecological restoration of high-diversity tropical forests in SE Brazil. *Forest Ecology and Management*, *261*(10), 1605–1613.

Rodrigues, R. R., Lima, R. A. F., Gandolfi, S., & Nave A. G. (2009). On the restoration of high diversity forests: 30 years of experience in the Brazilian Atlantic Forest. *Biological Conservation*, *142*, 1242–1251.

Rodwell, J., & Patterson, G. (1994). *Creating new native woodlands* (Forestry Commission Bulletin, 112). London, United Kingdom: HMSO.

Sanches, R. A., & Villas-Bôas, A. (2005). Planejando a gestão em um cenário socioambiental de mudanças: O caso da bacia do rio Xingu. *Revista Brasileira de Administração Pública*, *39*, 365–379.

Santos, P. L., Ferreira, R. A., Aragão, A. G., Amaral, L. A., & Oliveira, A. S. (2012). Estabelecimento de espécies florestais nativas por meio de semeadura direta para recuperação de áreas degradadas. *Revista Árvore*, *36*(2), 237–245.

Silva, J. A., Leite, E. J., Silveira, M., Nassif, A. A., & Rezende, S. J. M. (2004). Phytosociological and floristic characterization and natural regeneration of the undergrowth at Tamandua Forest Genetic Reserve, Brazil. *Ciência Florestal*, *14*(1), 121–132.

Velasquez, C., Queiroz, H., & Bernasconi, P. (2010). *Fique por dentro: A bacia do Rio Xingu em Mato Grosso* (Series Cartô Brasil Socioambiental). São Paulo, Brazil: Instituto Socioambiental, Instituto Centro de Vida.

Willoughby, I., Jinks, R. Gosling, P., & Kerr, G. (2004). *Creating new broadleaved woodland by direct seeding—Practice guide*. Edinburgh, United Kingdom: Forestry Commission.