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Sustainability of Shade-Grown Erva-Mate Production: A Management Framework for Forest Conservation

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Abstract: Despite the socioeconomic importance of erva-mate (*Ilex paraguariensis*) traditional agroforestry production for family agriculture in Southern Brazil, there has been no systematization of forest management best practices aiming at long-term sustainability. Here, I present an analysis of relevant forest characteristics that are combined with restoration and management best practices to maintain not only sustainable traditional erva-mate production but also a healthy forest environment. Additionally, I developed a framework that offers an easy tool to apply a focused analysis of general forest attributes to help determine best practices for forest restoration, species diversification, and overall sustainability and health of agroforestry systems. This study also demonstrates that the integration of knowledge and practices that small-scale farmers and traditional communities have been developing for generations should be leveraged for more inclusive research and extension, especially considering the threats family farming is facing due to the dominant paradigm of conventional, one-size-fits-all agriculture.

Keywords: traditional ecological knowledge; forest management; natural regeneration; forest restoration; agroforestry

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1. Introduction

The production of erva-mate (*Ilex paraguariensis* A.St.-Hil.) in the Araucaria Forest region is a traditional agroforestry system typical of Southern Brazil. The practices used in the system have their roots in Guarani Indigenous culture that has continued and developed for generations in Indigenous and traditional communities and on small-scale family farms [1]. Because erva-mate is produced in a forest environment, farmers have protected forests, creating a multi-use landscape where forest fragments are an important feature that help to maintain ecosystem services and biodiversity corridors, but are also essential to the maintenance of cultural and traditional agroecological practices [2,3]. Although there is a general understanding of the need to maintain sustainable production in a healthy forest, to date, there has been no systematization of forest management best practices for shade-grown erva-mate agroforestry in Southern Brazil that considers different forest attributes and aims at long-term sustainability.

Traditional erva-mate production is inherently a biodiverse system [4–6]. Silvicultural practices used in these systems are not limited merely to erva-mate but include a deep understanding of forest structure, tree species demography and diversity, and ecological succession that farmers employ to sustainably manage the forest itself in the context of erva-mate production [7]. Many of these technologies are based on traditional and Indigenous knowledge and social and environmental innovation [8] that contribute to climate change adaptation and mitigation [9].

In general, management practices ensure sustainable forest populations, especially in younger forests that are typically comprised of tree species in their initial-to-midlife stages. In some cases, when management activities repeatedly constrain adult population renewal, remove an excessive number of trees, or focus on some species or sizes, forest degradation can take place. In fact, gradual forest degradation has been a strategy that some farmers have used in order to increase erva-mate productivity. This shift is the result of the development of 'modernization' strategies that are driven by agricultural research and outreach institutions that see traditional systems as outdated and should be replaced by yield-focused monoculture systems [3,10].

Moreover, strategies to maximize erva-mate productivity are based on full-sun conditions that are at odds with environmental legislation that severely restricts most silvicultural practices in forests on private land due to the well-known link between agricultural modernization and deforestation [11,12]. Farmers that use an agroforestry system developed and adapted over generations now face pressure to abandon their cultural and ecological knowledge for an input-intensive (pesticides, fertilizers, herbicides) productive system that can only succeed through illicit practices. The move towards monoculture makes agricultural ecosystems more vulnerable to climate change, which, in turn, threatens food sovereignty, and is linked to biodiversity loss, soil degradation, and water and soil contamination [13–16], all of which tend to disproportionately affect smallholder livelihoods, such as traditional erva-mate farmers [15].

To counter such a conundrum, farmer-led initiatives to address a range of issues, including sustainability, profitability, productivity, and legal restrictions on forest use are necessary. Here, this study uses a comprehensive set of relevant ecological parameters to establish a framework for sustainable forest management in traditional erva-mate production, offering a decision-making tool with practices and restoration strategies. Considering the need to develop tools for a more complete assessment of the sustainability of traditionally managed forests, this study aims to systematize a framework to (1) assess the ecological state of the forest to be used and (2) indicate practices to maintain long-term forest structure, diversity, and economical sustainability.

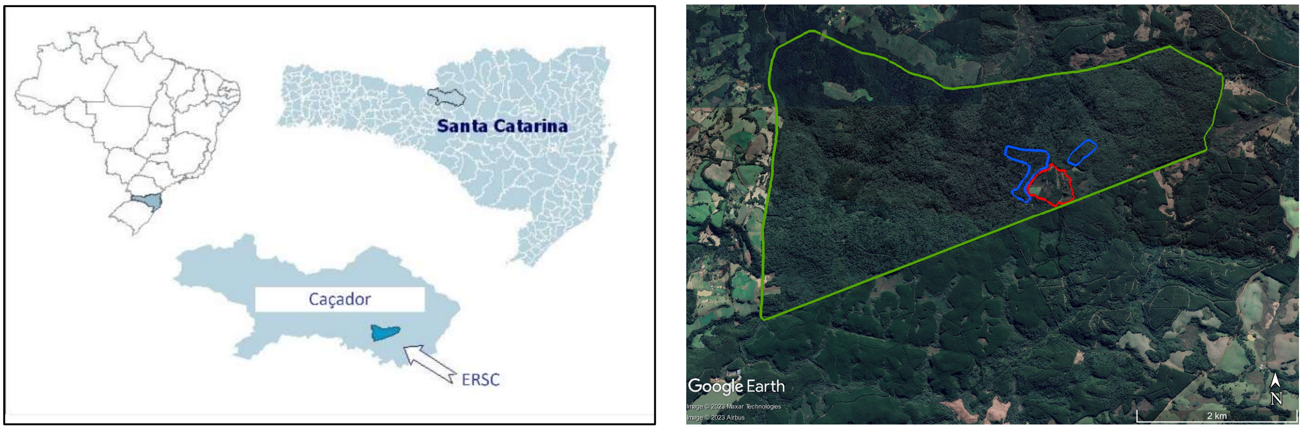
2. Materials and Methods

This study was carried out using a two-stage process. Initially, I proposed and tested different restoration systems that include detailed silvicultural practices aiming at restoring forest structure, diversity, and production. Secondly, I developed a decision-making framework designed to provide farmers, forest managers, and environmental agencies with a tool to choose ideal silvicultural practices based on the assessment of forest attributes that are easy to understand and encompass key aspects of forest structure and diversity.

2.1. Testing Restoration Systems

The establishment of one or more restoration systems that include the necessary silvicultural practices to ensure forest sustainability in the context of erva-mate agroforestry requires the definition of a rationale of intervention that identifies and addresses underperforming indicators. As such, instead of providing isolated silvicultural prescriptions to improve specific indicators, I aimed at establishing a (small) number of general restoration strategies that could be chosen by using the forest restoration framework previously mentioned.

Silvicultural prescriptions were based on the literature with a focus on studies conducted in the region, especially those on traditional erva-mate agroforestry systems [3–5,17–24] and the experience gathered through a long-term silvicultural field study implemented in the Embrapa Research Station in Caçador (ERSC), Santa Catarina state, Brazil (26°50′32.69″ and 26°52′36.73″ S, 50°54′51.69″ and 51°58′40.36″ W; Figure 1a,b) [2,22,25–31]. Established in 2007, the silvicultural studies in ERSC include approximately 20 ha that aim at establishing strategies to control invasive bamboo species, restore forest canopy, manage forest regeneration, and increase species diversity in the context of sustainable forest management. Covering an area of 1157 ha, the ERSC has forests at different successional stages ranging from near-pristine conditions to young forests due to the historical selective logging and clearcutting that occurred in the area until the 1990s [29]. The old-growth forests in the ERSC are widely recognized as the region's late successional stage, while younger forests in previously clear-cut areas are characterized by the presence of pioneer tree species (mainly *Mimosa scabrella* Benth. And *Piptocarpha angustifolia* Dusén ex Malme) with bamboos (predominantly *Merostachys skvortzovii*) dominating the understory [26].



(**a**) (**b**)

Figure 1. (**a**) Location of the Embrapa Research Station in Caçador (ERSC) within Brazil, Santa Catarina state, the municipality of Caçador; (**b**) restoration experiments within the ERSC (green polygon—ERSC boundary; red—restoration of non-forested areas; blue—restoration of degraded forests).

The existence of forest cover—a basic land use assessment—was considered as the initial step in the process of defining forest management strategies. Continuing an area evaluation, the relevant indicators discussed below (Section 2.2) were arranged in a sequential order where two alternatives are offered regarding the general state of each individual indicator; the assessment continues until a management and/or restoration strategy is reached.

The restoration experiments in the ERSC were initially focused on restoring the region's two main contrasting land cover states: forested and non-forested areas. Forested areas are degraded forests that were subjected to historical logging and fire, which, in many parts, led to the dominance of invasive bamboo species, causing stagnation in forest development; in this forest type, forest management activities were carried out in 15 ha [27,30,31]. In contrast, non-forested areas were those that had been used for conventional agriculture for at least 40 years. In the second year after the fields were abandoned, productive restoration took place in 3.3 ha, while an area of 1.5 ha was left unmanaged as a control [28].

2.1.1. Restoration in Non-Forested Areas

The strategy for non-forested areas was based on the rationale that successful restoration requires the initial establishment of a forest cover to create the necessary environmental conditions for other species to thrive, thus facilitating forest succession. As such, *M. scabrella*—the most common fast-growing pioneer tree typical of the region—was used to rapidly form a forest canopy creating suitable conditions for erva-mate and other focus species. This would gradually lead to the recruitment of other tree species, and thus increasing diversity and structural complexity.

The first activity in non-forested areas was to remove the shrub vegetation using a rotary mower followed by soil decompaction using a winged subsoiler. After area preparation, *M. scabrella* seedlings were planted with a 6 m space between rows and 1.5 m within each row (approximately 1111 trees·ha^{-1}). In the first three years all *M. scabrella* trees had 50% of their branches pruned, i.e., lower branches were removed until the crown was reduced to half of the tree's total height. A systematic thinning at 50% was carried out between years three and four, a procedure repeated at years five–six. Erva-mate seedlings were planted at the end of year two as shade conditions were quickly improving; seedlings were arranged in two rows placed between *M. scabrella* rows with a spacing of 1.5 m.

A complete census of all *M. scabrella* trees was carried out at months 12, 24, 48, and 132 after planting, where all heights were measured with an 11 m collapsing ruler and diameter at breast height (DBH) was measured with tree calipers. Additionally, all recruits from natural regeneration were identified and measured for height (h > 30 cm) at month 60 (2017) and month 144 (2023). Recruits were found only under the *M. scabrella* canopy as a consequence of seed dispersal by birds that used their branches for perching.

Finally, adjacent to the restoration area, we maintained a 1.5 ha unmanaged area to serve as control. Because of the consistent lack of tree species recruitment, we decided to carry out only visual counting of the species recruitment.

2.1.2. Restoration of Degraded Forests

Large-scale forest restoration in the ERSC started with the control of invasive bamboos that dominate the forest structure. The first step was to mechanically remove bamboo cover using a bulldozer with a raised blade or a brush cutter in terrain that impeded the use of the mechanical removal; bamboo control continued until its population was reduced to patches or completely removed, a process that usually takes at least two–three years. The expectation was that bamboo removal would allow for the successful recruitment of forest species (especially *M. scabrella*) that would guarantee the establishment of a uniform forest canopy; diversification would be achieved by a gradual recruitment of shade-tolerant species.

Initially, *M. scabrella* recruitment occurred at a very high density (>100,000 seedlings$\cdot$ha^{-1}) and management was necessary. Thus, all seedlings were removed in 2–2.5 m wide rows, with 1 m wide rows left for seedling development. The remaining individuals were then reduced to about one plant each linear meter after reaching heights of about 1.5 m. Rows were thinned again to one plant each two linear meters. Trees should be pruned at around two and four meters by reducing 50% of their branches. Finally, as tree crowns started to overlap, a new thinning was applied to reduce the density to one plant every four–five linear meters, followed again by a pruning of 50% of the branches. Species of economic interest, such as erva-mate and Paraná-pine (*Araucaria angustifolia*), were planted interspaced with *M. scabrella* to guarantee the economic sustainability of the restoration and as a strategy that could improve overall household income. Tree growth monitoring began 12 months after implementation and was repeated at months 36, 84, and 108 (in 2015, 2017, 2021, and 2023, respectively), when all individuals of *M. scabrella* were measured in eleven plots of 100 m^2 (25 m $\times$ 4 m) placed randomly throughout the area. Again, height was measured with an 11 m collapsing ruler, and DBH with tree calipers (DBH $\geq$ 1 cm).

Forest gaps in the ERSC, resulting from natural processes, invasive species, or human interference, were restored by incentivizing natural regeneration. Regeneration areas (RA) were established, which are spaces in which seedlings are protected against any activity that may damage recruits. Natural regeneration recruitment was monitored using 23 regeneration areas (RAs) of 1 m^2; each RA had its corners marked with 1 m PVC pipes with their ends painted in red. In each monitoring event (months 1, 5, 12, 32, 41, and 59), every recruit was identified and measured for height; no management was carried out inside each RA.

2.2. Developing a Forest Restoration Framework for Agroforestry

The definition of the most relevant attributes to be considered for assessing forest sustainability in the context of traditional erva-mate production involved a review of the literature followed by discussions with farmers and technical personnel from environmental, research, and extension agencies in order to gain a deeper understanding of their applicability. Considering the abundant forest literature, studies focused on the sustainability of forests managed in the context of small-scale farming were given preference as their real-world understanding is essential to achieve realistic and applicable solutions. There are a wide range of different methods, such as MESMIS [32,33], SAFA [34], Camino and Müller [35], Sangalli et al. [17], Araújo et al. [36], among others, that assess the various aspects of sustainability of agroforestry or agricultural systems through environmental, social, cultural, economic, political, ethical, and well-being indicators. As the focus of this study is forest sustainability and the associated silvicultural practices, only the applicable indicators were considered. Indicators were then consolidated where terms that reflect similar attributes were combined, e.g., "species diversity", "number of species of shrubs and herbs", and "diversity of species in the system" were all merged into "species diversity". The consolidated list of forest attributes are as follows:

(a) Invasive species—a common source of degradation in the Araucaria Forest, the dominance of invasive native bamboos (especially *Merostachys* ssp., and *Chusquea* ssp.) restrict forest development by limiting natural regeneration. Bamboos are able to maintain dominant populations in the long-term [25] that ultimately leads to the impoverishment of diversity and structural fragmentation [26,27]; they also create an unsuitable environment for erva-mate production.

(b) Canopy cover—considered by farmers as a sustainability goal [17] but also a requirement to maintain quality production, as shade-grown erva-mate is considered a prime product and is frequently rewarded with higher selling prices [37]. Thus, canopy cover has environmental and financial implications that demand continuous monitoring and planned interventions.

(c) Species diversity—high levels of species diversity is a universal attribute observed in both local [17,36] and general assessments [32]. Although diversity can be evaluated at different taxonomic levels for the fauna, flora, soil macro- and microflora, frequent evaluations are restricted to tree diversity. The framework followed this practice as it is considered an adequate surrogate for assessing overall diversity.

(d) Demography—demographic parameters, such as growth, survival, and reproductive success, are influenced by age, size, and life stage of individuals within a population [38]. In order to avoid local extinction, a species depends on the recruitment of young plants that reach maturity in a process that includes seed production and dispersion, germination, and establishment [39]. Thus, ideally, a population should have individuals in all life stages in sufficient numbers to guarantee its stability; as age is impractical to determine, size is frequently used as a surrogate in assessing a plant population.

(e) Tree spatial distribution—complementary to demography, population dynamics is dependent on successful pollination requiring individuals to have a spatial distribution within a pollinator's range and to be sufficiently large to maintain genetic diversity, which, in turn, is a key factor in evolution, fitness, and ultimately, the survival of tree species populations [40,41].

(f) Management practices—frequently the most important cause of forest degradation is forest resource management, which includes the control of plant populations (favoring or reducing) both in terms of their density (number of individuals) and spatial distribution. Management practices might be linked to the direct use of resources (e.g., firewood) or indirectly related (e.g., understory and canopy thinning to favor erva-mate production or forage species growth) [3].

(g) Tree species longevity—although there are several species' life-history traits that could be used to assess an agroforestry system, life cycle is likely the most important. While pioneer species are usually linked to a shorter lifespan, late successional species tend to live longer. The proportion between short- and long-living trees (and their spatial position) is a determinant factor for defining where and when management practices should be applied to maintain a stable forest cover.

After the selection of indicators, they were hierarchically organized as a decision tree that ultimately provides a general assessment of the forest attributes and leads to recommended restoration systems to be implemented for long-term forest sustainability.

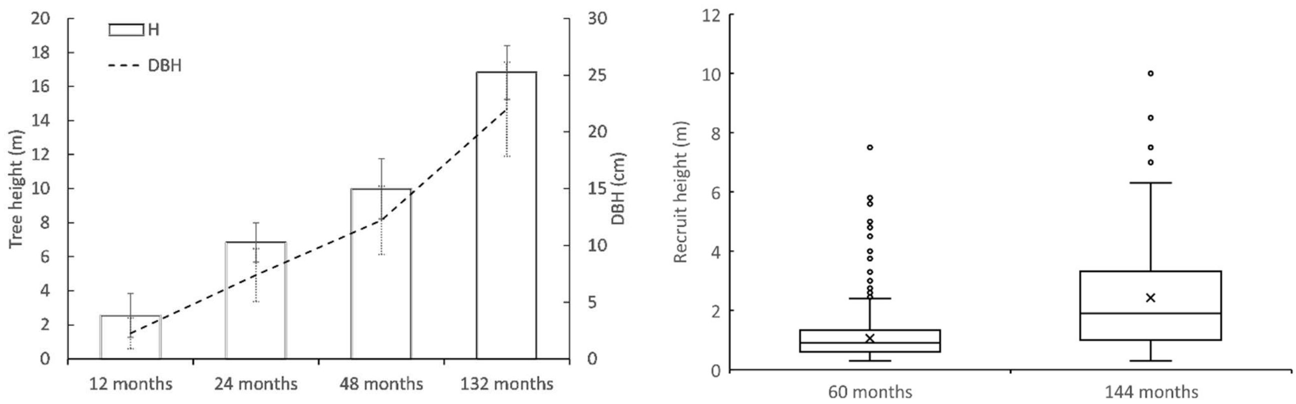
3. Results and Discussion

3.1. Restoration Systems

In subtropical Southern Brazil, land use/land cover (LULC) has been mostly consolidated where forests and agriculture have been in place for several decades. Therefore, restoration options for agricultural lands are limited due to the absence of soil seed banks and litter cover, soil compaction, and nutrient depletion. In contrast, forests in their various conservation status and successional stages tend to have environmental conditions that facilitate any restoration effort. As such, different approaches were developed to consider those opposing LULC characteristics and to differentiate the main forest degradation and development statuses: (1) Productive Agroforestry Restoration (PAR) for non-forested lands; (2) Accelerated Canopy Recovery (ACRE) for widespread degraded forests, and Active Regeneration Management (ARM) for restricted forest degradation.

3.1.1. Productive Agroforestry Restoration (PAR)

Our experience in restoring degraded agricultural lands after abandonment showed that natural soil recovery is a long-term process where the development of a forest cover tends to take a decade or longer if pioneer species are not widely available. In our 3.3 ha restoration plot where a common legume pioneer tree species (*Mimosa scabrella*) was planted, a forest cover was created in around four years as trees reached heights of about 10 m (Figure 2a) and crowns shaded the spaces between rows.



(**a**) (**b**)

Figure 2. (**a**) *Mimosa scabrella* average height (m) and DBH (cm) in Productive Agroforestry Restoration—PAR after 12, 24, 48, and 132 months (2013, 2014, 2016, and 2023, respectively) after implementation in the Embrapa Research Station in Caçador (ERSC). Whiskers represent standard deviation; (**b**) recruitment development (height—m) from natural regeneration in PAR after 60 and 144 months (2017 and 2023, respectively). X—refers to average; a circle refers to outliers.

M. scabrella growth was quite satisfactory as it reached an average height of 3 m after planting, 6 m after 24 months, 10 m at 48 months, and around 17 m at 132 months when trees were fully developed (Figure 2a). Complementarily, DBH also increased consistently during the period, reaching an average of 22 cm after 11 years. The quick forest canopy development created a suitable environment for the introduction of other species that can provide a return on the investment needed to implement the restoration strategy. For that purpose, we used erva-mate as it is the most important tree species in agroforestry in the region with a consolidated market.

The quick establishment of a forest cover in the PAR area brought about changes that not only attracted the avifauna responsible for tree seed dispersal but also created the environmental conditions for a diverse recruitment of tree species. We observed 38 tree species regenerating under the *M. scabrella* canopy just three years after planting [31]. Natural regeneration recruitment developed consistently, reaching an average height of

1 m after five years and 2.4 m after 11 years (Figure 2b). This trend was also detected by a general height distribution in which the first quartile and outliers also increased in the period. Observed growth seems to be compatible with the expectation that recruits will replace *M. scabrella* in the canopy in the next few years.

More importantly, as a shade-tolerant species, erva-mate takes advantage of an environment similar to a natural forest, which confers the characteristics of superior taste and enables farmers to achieve the market value of erva-mate grown in natural stands. Although a full financial analysis for this system has not been carried out, we confirmed that PAR can quickly restore basic forest attributes (forest and soil cover, natural regeneration) that can be combined with the production of erva-mate. Until erva-mate reaches maturity for harvesting (five to seven years) maintenance is basically restricted to weed cutting around seedlings. In comparison, the implementation of erva-mate systems in full-sun or monoculture conditions requires significant inputs of fertilizers and pesticides to combat the simplified environmental conditions. Thus, the investment required for small-scale farmers is minimal, with the added benefits of potential product diversification and the wide range of ecosystem services that a forested system provides.

In contrast to the PAR area, the number of tree species regenerating in the control remained at low levels in all evaluations with the occurrence of only three pioneer species (*M. scabrella*, *Schinus terebinthifolia*, and *Solanum granulosoleprosum*). During the 2012–2023 period, a 2–3 m tall dense shrubby vegetation dominated by *Baccharis dracunculifolia* and *B. uncinella* (Asteraceae) developed initially, after which it deteriorated into a more open shrub-herbaceous cover that has not evolved into a forest (Figures 3 and A1).

(**a**) (**b**)

(**c**) (**d**)

Figure 3. Development dynamics of Productive Agroforestry Restoration (PAR) and control over time. Overview of PAR and control in 2015 (**a**) and 2017 (**b**) and interior of PAR in 2019 (**c**) and general vegetation view of control in 2019 (**d**).

3.1.2. Accelerated Canopy Recovery (ACRE)

The Accelerated Canopy Recovery (ACRE) restoration strategy was designed to quickly restore degraded forest environmental conditions (temperature and humidity levels) and to protect crop plants and natural regeneration from severe climate events (frosts, droughts) by inducing the quick establishment of a forest cover that will gradually be replaced by a more diverse canopy.

Similar to PAR, fast-growing pioneers should be given preference. In addition to being common in the region, well-known, and with an established market, they are easily adopted by farmers as they are consistent with their local ecological knowledge in terms of management and there is a foreseeable economic return. Again, *M. scabrella* is a preferential species because of its regional distribution, very fast growth rate, wide familiarity among farmers, and most importantly, for the decades-long viability of seedbanks coupled with a very prolific regeneration [28,42].

Initially in ACRE, *M. scabrella* regeneration was facilitated by cutting the herbaceous vegetation that allows for direct sunlight to reach the soil, creating the temperature increase necessary to break seed dormancy (Figure 4a). In our experience, most degraded forests in the region have seed banks abundantly comprised of pioneer tree species, especially *M. scabrella*. In the unlikelihood of the absence or insufficient natural pioneer tree regeneration, sowing of *M. scabrella* seeds is advised (or even seedling planting). In the field, the presence of adult trees is generally sufficient to indicate the occurrence of its seeds in the seed bank. However, if no adult trees are present, a practical way to test its presence in the seed bank is to create small patches (~1 m^2) in which the vegetation is removed and the soil surface is revolved—if seeds are present in the soil bank, regeneration should be visible after a couple of weeks (Figure 4b).

During regeneration development, thinning is necessary to reduce recruitment density to levels compatible with the growth of other species such as erva-mate. Through a series of thinning carried out in the first five years, *M. scabrella* initial regeneration of up to 400 seedlings$\cdot m^{-2}$ (equivalent to 4 million per hectare) should be reduced to about 300–400 trees$\cdot ha^{-1}$, which is similar to its natural adult population density. After thinning, the remaining *M. scabrella* trees showed fast growth reaching an average height of 1.3 m ($\pm$0.5 SD—standard deviation; Figures 4c and 5) at month 12, a sharp increase reaching 6.3 m ($\pm$1.6 SD) at month 36, 11 m ($\pm$1.7 SD) at month 84 (Figures 4d and 5), and finally 13.1 m ($\pm$2.8 SD) at month 108.

Interestingly, in the ACRE system, trees showed a slower growth rate, reaching an average height of 1.3 m after 12 months, whereas in PAR, the height reached an average of 2.6 m. This trend continued: at month 24 in PAR tree height had reached 6.8 m, while in ACRE tree height was lower, with an average of 6.3 m at 36 months. The slower growth in height is likely a response to light conditions by the light-demanding pioneer *M. scabrella* with ACRE occurring in a partially shaded degraded forest environment in contrast with the growth-promoting full-sun conditions in PAR. Despite this difference in development, trees in ACRE reached heights in three years that opened up the understory for erva-mate production and diversification, and at year seven a stable new canopy was established.

Because *M. scabrella* is a short-lived species (<20-year life cycle) it is essential to take steps to guarantee the development of a second generation of (longer-living) trees early in the restoration process to ensure the continuation of a forest canopy in the future. This can be achieved by facilitating natural regeneration, seedling planting, or a combination of both. The use of both methods has the advantage of allowing for the introduction (planting) of tree species with commercial value, such as medicinal (i.e., *Monteverdia ilicifolia*), edible fruits (i.e., *Eugenia uniflora*, *Campomanesia xanthocarpa*, and other Myrtaceae), and nuts (*Araucaria angustifolia*), combined with natural regeneration management for forest species diversification using the ARM system (see next section) or any other method that facilitates species recruitment.

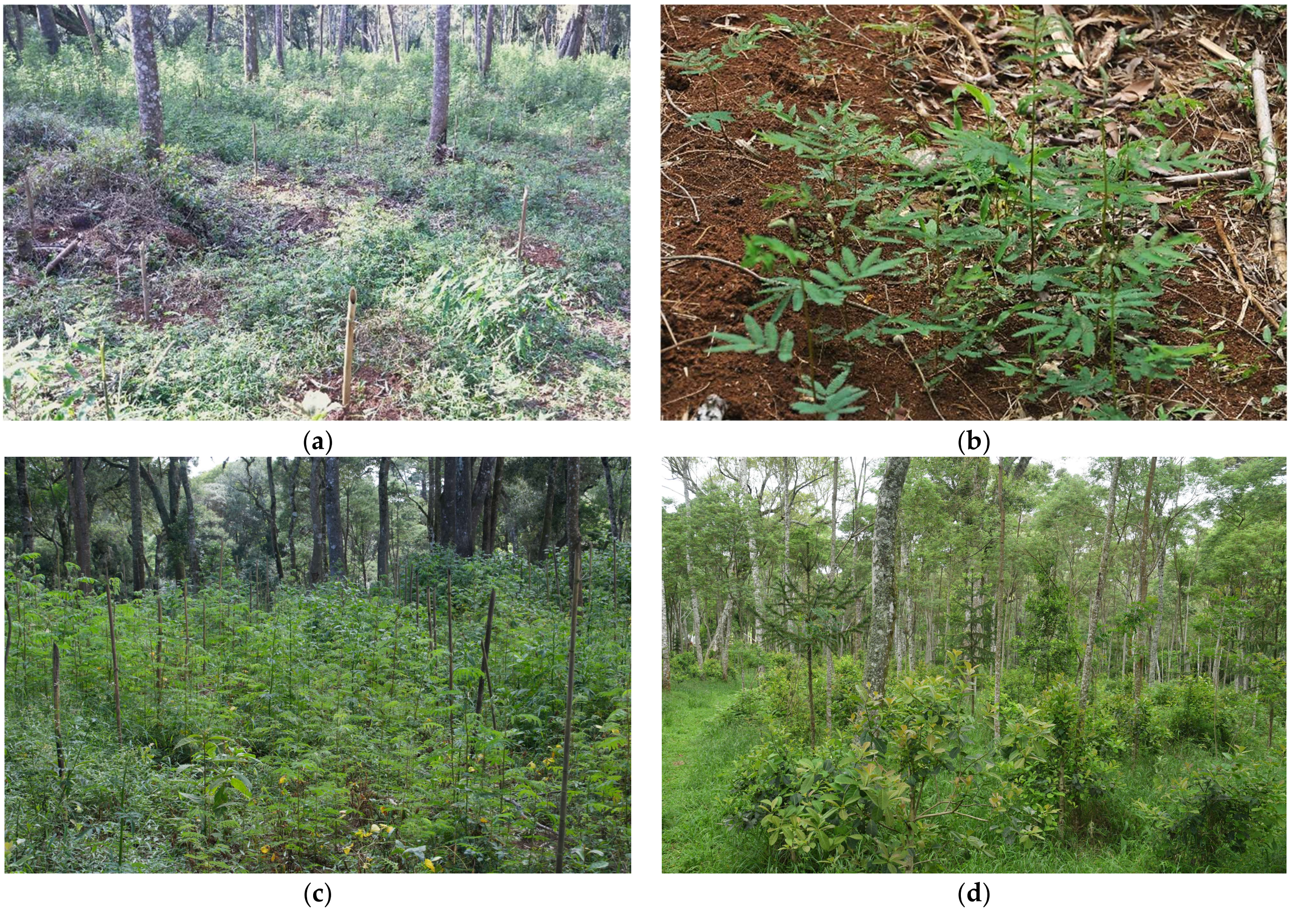


Figure 4 panels: (**a**) (**b**) (**c**) (**d**)

Figure 4. Degraded forest under restoration using the ACRE system: overview of regeneration of *M. scabrella* after six months since understory clearing (**a**); testing for *M. scabrella* regeneration using a small soil clearing (seedlings reached 30 cm in three weeks, confirming the potential for restoration using pioneer species regeneration) (**b**); *M. scabrella* regeneration reaching average height of 1.3 m 12 months after restoration implementation (**c**); and after six years forest canopy was restored with erva-mate at full production accompanied by other trees species (e.g., *Araucaria angustifolia*) that were planted to increase diversity (**d**). *M. scabrella* can be identified by their smooth trunks.

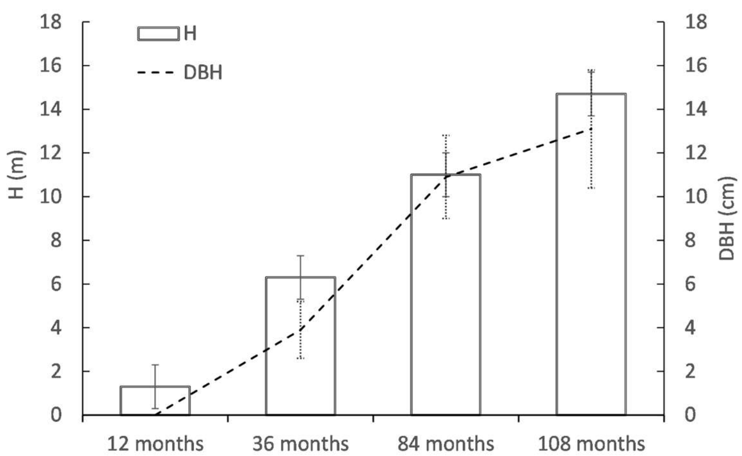


Figure 5. *Mimosa scabrella* growth dynamics (height and DBH) after 12, 36, 84, and 108 months (2015, 2017, 2021, and 2023, respectively) as part of the strategy to create a quick forest canopy applied in the Accelerated Canopy Recovery (ACRE) restoration system. Whiskers represent standard deviation.

Finally, the ACRE system can be easily combined with the cultivation of erva-mate, a native species that thrives in the forest understory. If planted, erva-mate is expected to start initial production at year three and reaches productive maturity at around year seven. The introduction of an economically attractive species such as erva-mate in restoration efforts is essential to gain buy-in from farmers as costs can be compensated and additional household income generated.

3.1.3. Active Regeneration Management (ARM)

Active Regeneration Management (ARM) is indicated to restore smaller forest gaps or degraded forests with a canopy that requires tree renewal due to an aging population and/or low species diversity. With a more focused strategy, ARM can also be used together with the larger-scale ACRE restoration system. In this case, ACRE focuses mainly on restoring the canopy in large gaps or degraded forests, while ARM complements the strategy by implementing localized management that focuses on species diversification through gradual natural regeneration recruitment.

ARM can be implemented through the installation of small 1 m^2 regeneration areas (RA) in which natural regeneration recruitment is protected against any interference, especially weed cutting and animal grazing. If an aging population is detected, RAs should be established throughout the forest to support forest renewal that provides for a homogenous forest canopy; in such cases, RAs could be installed in a grid varying from 3–6 m apart, with wider distances and distribution indicated if other activities are present (grazing, erva-mate). When forest gaps are present, RA can be established in a grid, spaced about 3 m apart. A denser distribution of RAs is advisable as forest canopy recovery and diversification can be combined enabling significant opportunities for the recruitment of pioneer species and those with other life traits.

The implementation of ARM at the Embrapa Research Station in Caçador (ERSC) by establishing 23 RAs produced a rapid response, with an average of three recruits after five months (in six RAs no seedlings were found) (Figure 6). In the subsequent assessments (at 12, 32, 41, and 59 months), 20 RAs (87%) showed recruitment with averages ranging between 3.1 and 3.5 plants. The results indicate an intense recruitment potential, with the results for the number of seedlings per hectare varying between 20.87 and 31.3.

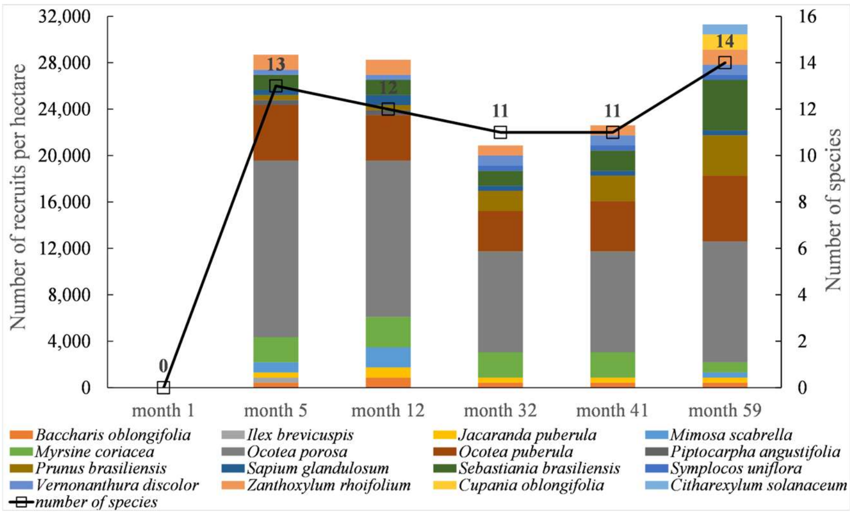


Figure 6. Recruitment dynamics (number of species, number of recruits, and recruit species) observed in designated regeneration areas (RAs) over a 59 month period as part of the Active Regeneration Management (ARM) system.

The species diversity found in RAs varied between 10 and 14 species, with the highest value recorded at month 59. Species with different life traits were found, including pioneers (e.g., *Myrsine coriacea*, *M. scabrella*, *Baccharis oblongifolia*, *Jacaranda puberula*, *Pipto-*

carpha angustifolia, *Vernonanthura discolor*, *Sapium glandulosum*), intermediate successional species (e.g., *Ocotea puberula*, *Prunus brasiliensis*, *Ilex brevicuspis*, *Zanthoxylum rhoifolium*, *Sebastiania brasiliensis*, *Symplocos uniflora*), and late successional species (*Ocotea porosa*). Interestingly, *O. porosa* was the most abundant during the whole evaluation. As expected, pioneer species showed a decrease in abundance over time while intermediate successional species increased. The presence of species with different ecological strategies indicates that environmental conditions—especially light—are not restrictive to any one species group.

In RAs, growth showed a constant increase in height over time where at month five seedlings were 0.25 m tall on average, increasing to 0.40, 0.65, 0.95, and 1.1 m at months 12, 32, 41, and 59, respectively (Figure 7). As expected, pioneer species showed the fastest growth, although other successional species showed a slower but constant growth.

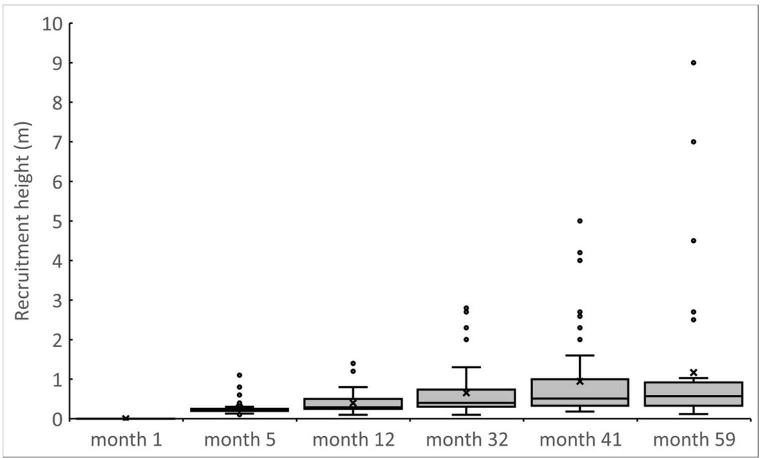


Figure 7. Boxplot showing recruitment observed height dynamics in designated regeneration areas (RAs) over a 59 month period as part of the Active Regeneration Management (ARM) system. X—refers to average; a circle refers to outliers.

With the implementation of simple solutions, such as RAs that offer the necessary conditions for germination and successful recruitment, the results clearly indicate that the use of the ARM system contributes to gradual restoration, increasing the diversity and structural complexity of forests with gaps and/or aging populations. Additional practices are advisable as recruits grow within the RAs, such as thinning and pruning that might be necessary depending on density and plant development. Although a diverse and plentiful regeneration is desired, thinning might be necessary when dense regeneration of one species is impeding the development of others, especially in the case of a large pioneer recruitment population. In most cases, however, we observed that no silvicultural practices are necessary apart from intermittent pruning to improve trunk form.

For convenience, we suggest marking the corners of RAs with 1 m poles with tips painted in a bright color so they can be easily seen, thus avoiding interference. This kind of marking is highly recommended as most forests in the region are actively managed, either to collect firewood, animal husbandry, and/or erva-mate production. Regardless of the marking system, protecting recruitment in RAs is necessary until seedlings reach heights above 1.5 to 2 m so they can be easily identified and avoided during activities such as weed cutting and erva-mate harvesting.

3.2. Forest Restoration Framework in the Context of Agroforestry

A framework for forest restoration in the context of agroforestry for Southern Brazil was developed by creating a logic sequence based on relevant forest attributes in which a user is given alternatives to assess each attribute; ultimately, the user is presented with a proposed forest management system that aims to maximize all forest attributes. The main forest attributes considered were canopy cover, species diversity, demography, tree spatial distribution, management practices, tree species longevity, invasive species, and diversification.

Strategically, the framework starts with a general land use/land cover assessment (forest × no forest) that includes areas without forest cover as farmers that are interested in establishing agroforestry systems can take advantage of the framework for forest restoration. In this first stage, forest canopy, structure, and diversity are not yet relevant but only the existence of some kind of forest cover (Figure 8). As non-forested areas will require an extensive restoration strategy, the PAR system should be implemented (Section 3.1). On the other hand, areas with any type of forest cover should be further evaluated following the framework to determine best restoration practices.

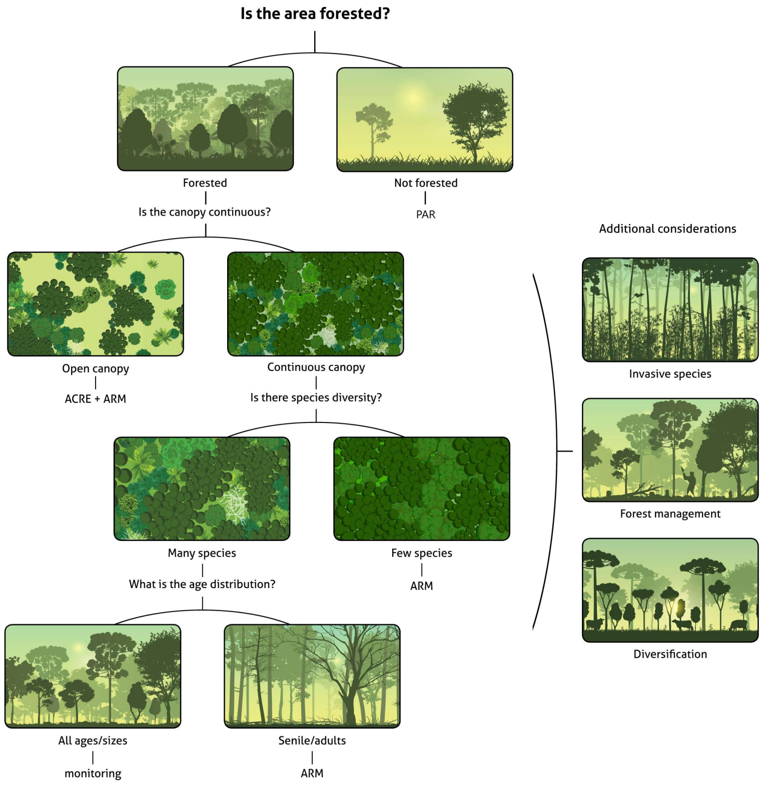


Figure 8. Framework for forest management decision-making process in traditional agroforestry production. Land use and land cover and forest characteristics are assessed to determine practices to be implemented.

At this stage, forests are assessed for basic forest attributes including canopy cover, diversity of species, and the age/size of trees. Forest cover is assessed in terms of having a continuous canopy or being open or fragmented. In general, a continuous canopy has no gaps, or gaps are infrequent and smaller than the size occupied by one or a few tree crowns. An open canopy is considered as areas with very open forests in which tree crowns are separated from each other or with gaps of varying sizes that are widely distributed. To facilitate the decision-making process, a continuous canopy is considered when the space between tree crowns is less than their own crown diameters, while an open canopy or large forest gaps are considered if the gaps have an area of more than 500 m^2, which is the space occupied by approximately four large trees or up to 14 smaller trees, such as *M. scabrella*. Thus, the presence of large gaps or an open canopy will require the implementation of the ACRE system. In the case of a continuous canopy, the user is prompted with two alternatives regarding diversity of species.

Considering that forests under agroforestry management in the region contain a relatively large number of species (>30) that together represent most of the region's biodiversity (>120), they are likely to maintain high levels of diversity at the landscape level [6]. As such, tree diversity lower than 30 is considered low and should be improved using ARM. This restoration system should help gradually increase overall forest diversity and contribute to landscape biodiversity conservation.

Finally, if a continuous forest canopy with a high diversity is present, then the final forest attribute to be evaluated is its demographic structure in terms of whether the tree population is comprised of trees of different ages and, more importantly, that trees are not concentrated in the adult/senile life stages. This attribute is especially important in cases of pioneer dominance as they tend to have shorter life cycles that, if not managed, could lead to forest degradation; *M. scabrella* for example, has a life expectancy of 15 to 20 years. As such, if a population has a structure comprised of trees of different ages (or sizes), it is considered to be in optimal conservation status and only requires monitoring. In contrast, if a population is mostly adult/senile (or large trees), the implementation of ARM is necessary for long-term sustainability, as recruitment will introduce trees of different ages allowing for the replacement of those that are senile.

It should be noted that the recommendation to use the ARM system for species diversity restoration in low-diversity continuous canopy forests is different from continuous canopy forests dominated by pioneer species, for which the ACRE system is initially recommended. These distinct recommendations for managing natural regeneration and canopy are because, in forests with low diversity and non-pioneer species, the canopy tends to remain consistent for a long time, allowing species diversification and the gradual replacement of individuals, which can occur using the ARM system. In this case, it does not apply to situations in which large individuals are in the senile phase of their life cycles. On the other hand, forests dominated by pioneer species tend to lose their canopy in the short term, requiring more broadly applied actions to support the formation of a new canopy.

The development of a framework for sustainably managing erva-mate production systems in a forest environment is a novel contribution to analyses of erva-mate as an economic species. To date, the vast majority of studies on erva-mate have focused on the species in monoculture systems and have ignored the important implications of erva-mate as an element of agroforestry or forested ecosystems (see, for example, [42,43]). This distinction is key as it is clear that to better understand how to develop, implement, and manage erva-mate, we must consider the species as part of a functioning human-mediated ecosystem that has important implications for forest sustainability in the long term, as well as human health and well-being in local communities.

4. Conclusions

Here, I present a comprehensive analysis of relevant forest characteristics that are combined with restoration and management best practices to maintain not only sustainable traditional erva-mate production but also a healthy forest environment. Based on our long-term community-based research, we provide evidence-based understanding on how to implement solutions to maintain forest diversity and structure that is ideal for erva-mate but can be applied more generally to other agroforestry systems. The framework presented herein offers an easy tool that applies a focused analysis of general forest attributes to help determine best practices for forest restoration, species diversification, and overall sustainability and health of agroforestry systems.

Although this study is focused on erva-mate productive systems, the practices recommended can be adapted and applied to other contexts, especially agroforestry systems under shade-grown conditions in tropical and subtropical forest ecosystems, such as cocoa, coffee, rubber, juçara heart of palm (*Euterpe edulis*), and açaí (*Euterpe oleracea*). Despite the differences among those systems, the proposed framework includes the most relevant forest attributes to be considered for assessing forest sustainability. Future analyses should include testing and adapting the forest attributes and restoration methods in different agroforestry systems to develop general forest management principles for sustainable agroforestry. It would also be interesting to test those principles in systems with a higher diversity of products to understand their integration and impacts on management practices and overall sustainability. In that regard, our team has begun testing the above-described restoration methods with a wider range of potential products that include fruits and medicinal plants with different life traits (e.g., shrubs and vines) aiming to improve their economic return and maximize the use of the forest environment.

Even though the framework is an attempt to create a unified method to analyze forest status and propose best practices, it is essential that the sustainability of agroforestry systems include other aspects, such as human well-being, and economic and cultural considerations, among others. As such, new tools are necessary that offer innovative ways to integrate the different aspects of sustainability. Management practices carried out on each farm are determinant factors in the success of forest restoration. Forests with agroforestry systems like erva-mate production can have a negative impact on forest conservation if forest renewal through recruitment is constantly suppressed, a situation common in properties focused on maximizing production. However, in most traditional agroforestry systems, forest attributes can be maintained at optimal levels despite animal grazing, erva-mate harvesting, firewood collection, and fruit and nut gathering.

Conversely, the absence of management practices by humans does not necessarily guarantee better forest conservation status. In Southern Brazil, as in many other countries around the world, some forest fragments are stuck in a cycle of degradation because of the dominance of native invasive bamboos [25–27,44–46]. Nevertheless, active management has been shown to restore succession, increasing diversity levels and structural complexity [27]. In such situations, the presence of invasive species should be considered in terms of the area affected in order to implement a larger-scale restoration such as ACRE or localized action such as ARM.

These different points of view show that forest conservation and agroforestry are sometimes seen as opposing strategies, with divergent rationales, creating controversial practices and dialogue. In Brazil, forest management is often seen as incompatible with conservation, yet the region with the most forest cover in Southern Brazil coincides precisely with where traditional erva-mate agroforestry systems continue to be used. On the other hand, erva-mate production per se does not guarantee long-term forest sustainability, especially in the context of production maximization. One of the most important lessons from this study was to understand the need to combine the traditional ecological knowledge and interests of farmers with formal research to collaboratively create solutions that are relevant to landowners (socially, culturally, and economically) while, in turn, increasing the potential for implementation and success.

In many parts of the world, the knowledge and practices that small-scale farmers and traditional communities have been developing for generations are under threat due to the dominant paradigm of conventional, one-size-fits-all agriculture. Climate crises, food insecurity, and displacement are affecting many communities despite calls from scientists to transition towards more sustainable ways of living and to consider Indigenous Peoples' and Local Communities' lands, territories, and traditional practices [47]. Traditional agriculture can provide us with technological solutions that have been used for generations, but they need to be valued and integrated into formal scientific and extension programs. In times of global challenges, leveraging traditional knowledge for the conservation of forests and biodiversity that also delivers human well-being is essential.

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Conflicts of Interest: The author declares no conflict of interest.

Appendix A

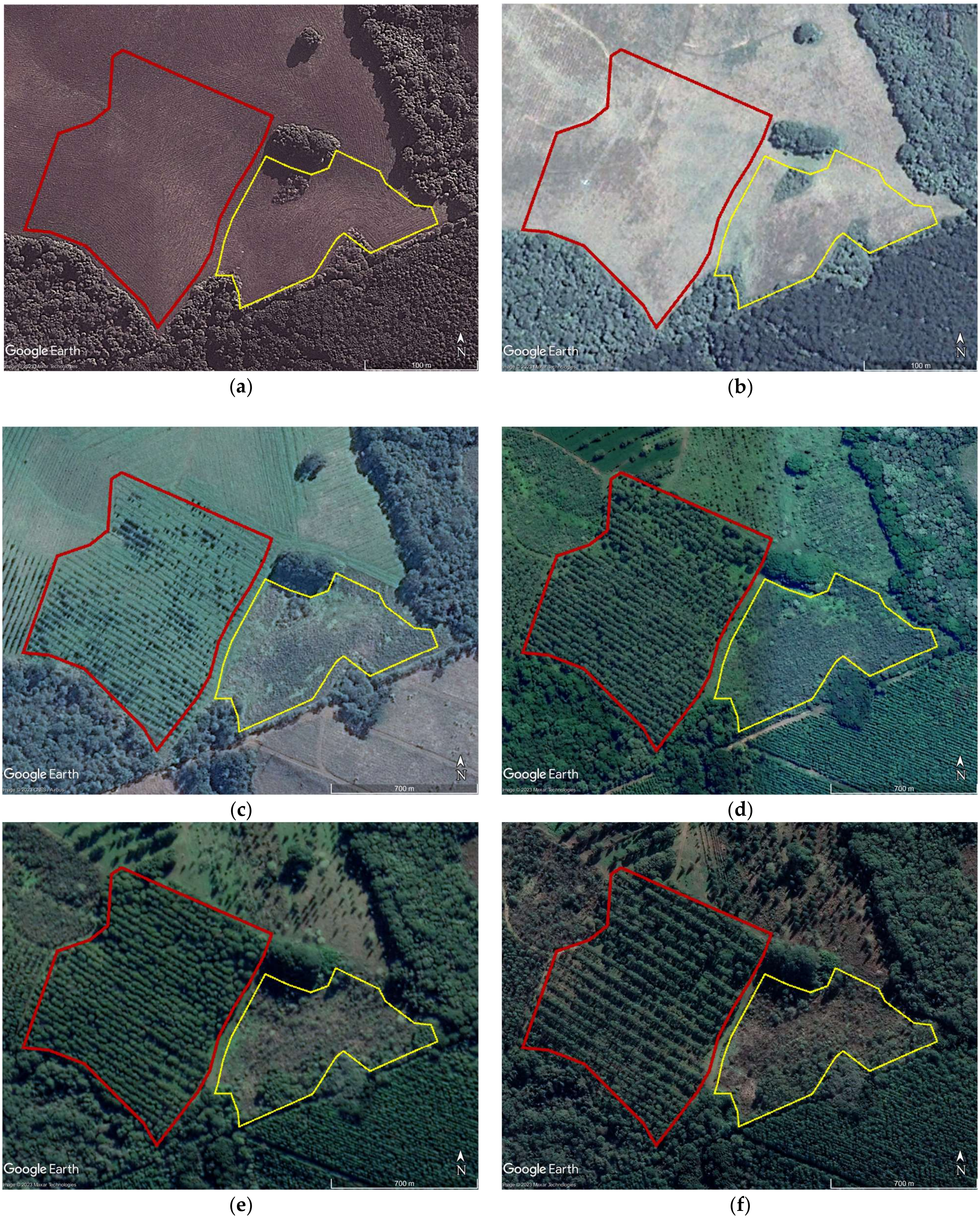

Figure A1. Satellite imagery showing development dynamics of Productive Agroforestry System and control plot in the ERSC prior to implementation: July 2011 (**a**); during implementation—November 2011 (**b**); August 2013 (**c**); February 2017 (**d**); June 2019 (**e**); and July 2021 (**f**). Source: Google Earth.

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