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Could native *Araucaria* forests be managed for timber production on small farms in southern Brazil?

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ABSTRACT

Most native *Araucaria* forests exist on small farms in the southern region of Brazil, with only a small area (< 1%) of coverage still present in the protected areas of mature forests. Current law restricts forest management for timber production in native *Araucaria* forests by prohibiting harvesting the main tree species—*Araucaria angustifolia* and other important commercial timber species. As a consequence, the forested areas of some small farms have been illegally converted to other land uses, resulting in the area of native *Araucaria* forest coverage in southern Brazil having been significantly reduced in recent decades. To gain a better understanding of the consequences of managing native *Araucaria* forests on small farms for timber production, we used a growth model to simulate nine different harvesting scenarios using different harvest intensities and cutting cycles to simulate *A. angustifolia's* long-term recovery after harvesting. The harvesting scenarios considered sustainable for supplying *A. angustifolia* timber were further tested in simulations of overall timber forest management that included harvesting angiosperm tree species in addition to *A. angustifolia*. The simulations were performed with data collected from 48 plots established on 19 small farms located in southern Brazil. Of the nine harvesting scenarios tested, four were considered sustainable for producing *A. angustifolia* timber: (1) removing 10% of the *A. angustifolia* basal area (G_{arauc} in $m^2\,ha^{-1}$) in 5-yr cutting cycles; (2) removing 20% of the G_{arauc} in 10-yr cutting cycles; (3) removing 35% of the G_{arauc} in 20-yr cutting cycles; and (4) removing 40% of the G_{arauc} in 25-yr cutting cycles. These four sustainable *A. angustifolia* harvesting scenarios remained sustainable when managing the forest as a whole by including some angiosperm tree species harvesting as well. This indicates that managing forests for timber production may be a promising pursuit to develop on the small farms of southern Brazil.

1. Introduction

Native *Araucaria* forests occur mainly in southern Brazil and are a part of the Atlantic Forest biome. Besides Brazil, this forest type also occurs in the northeastern region of Argentina and is scattered in eastern Paraguay (Souza, 2007). Native *Araucaria* forests comprise hundreds of tree species, but the main one is *Araucaria angustifolia*, belonging to the Araucariacea family. It is considered the most important conifer in Brazil due to its commercial importance for good quality timber and the production of edible seeds that are prized for human consumption, especially in southern Brazil.

In the early eighteenth century, native *Araucaria* forests dominated the landscape in southern Brazil (Souza et al., 2008). The colder climate relative to other regions of the country and the presence of fertile soils attracted many immigrant families (mainly from Europe) to southern Brazil, where they settled on small farms between the eighteenth and nineteenth centuries and developed agricultural communities (Waibel, 1950). While agricultural productivity abruptly increased with the arrival of new farming techniques, the southern region's native forest coverage lost area due to forest conversion. There was also intense exploitation of the native forests at that time because there were no restrictions on forest use. Until the mid-1980s, Brazilian law placed few restrictions on the timber production management of native *Araucaria* forests, with the harvest of virtually any tree with a diameter larger than 40-cm at breast height being permitted (Basso, 2010). As a consequence, the native *Araucaria* forests in southern Brazil have been drastically reduced from their natural coverage.

Today, most native *Araucaria* forests are fragmented, representing just 3% of the original total coverage, and occur mainly on small farms (Bittencourt and Sebbenn, 2009; Silva and Schmitt, 2015). Few areas

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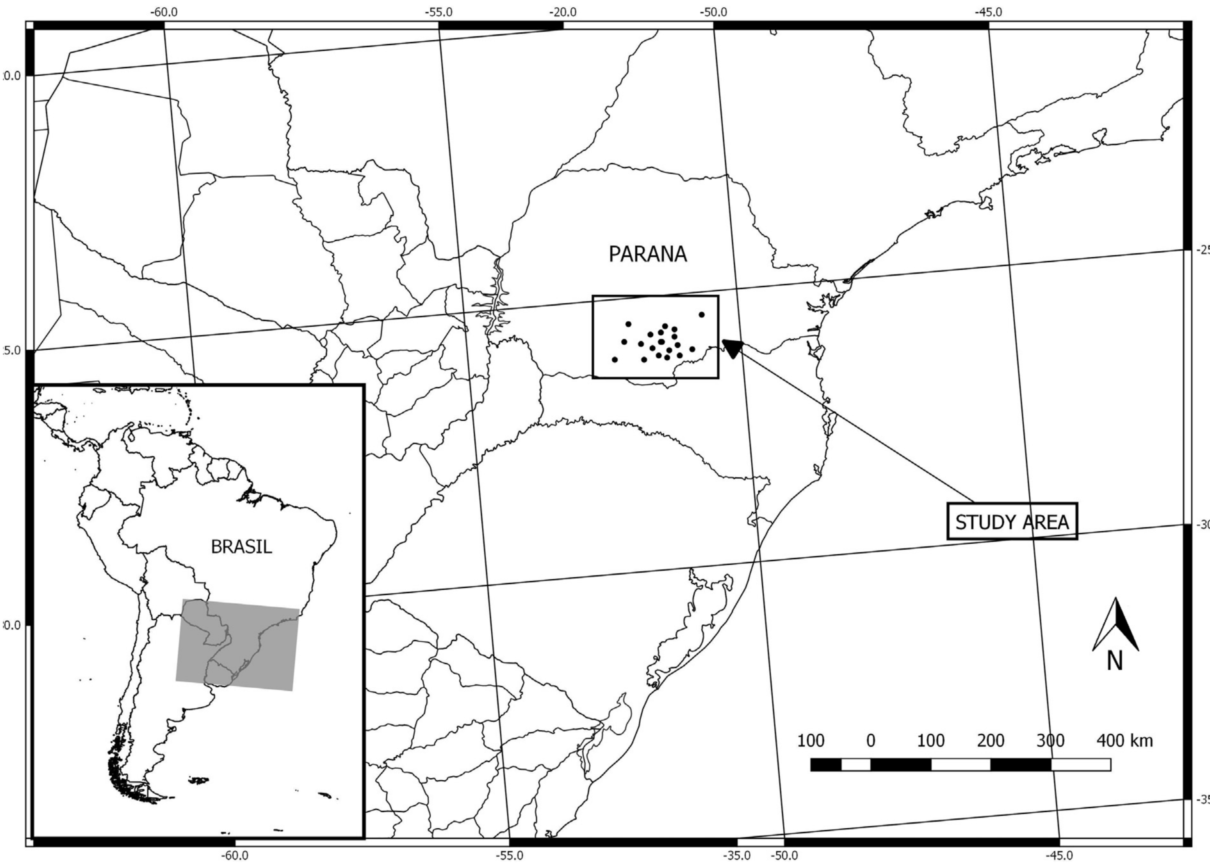

Fig. 1. Map of the study area illustrating the 19 small farms where the data were collected.

within the protected regions are still covered by mature forests. Despite current law prohibiting the harvesting of naturally occurring *A. angustifolia* and other important tree species in native *Araucaria* forests such as *Ocotea porosa*, *Cedrela fissilis*, and *Ocotea odorifera*, harvesting these species is still permitted for timber and non-timber production on established tree plantations. The prohibition on harvesting *A. angustifolia* is because the species is classified as critically endangered (Bittencourt, 2007; Silveira et al., 2006; Souza, 2007). However, the inclusion of *A. angustifolia* as an endangered species is highly questionable. Several studies conducted in different parts of southern Brazil have ranked *A. angustifolia* as one of the top 3 most important tree species among dozens of others, reporting a value index (IVI) of highest importance (Galvão et al., 1989; Negrelle and Leuchtenberger, 2001; Rondon Neto et al., 2002; Sanquetta et al., 2007; Silva and Marconi, 1990; Valério et al., 2008), which is computed based on the relative frequency, dominance, and abundance of all tree species in a specific study area. This contradicts the notion that *A. angustifolia* is critically endangered.

Small farms retain only the minimum area of native vegetation required by law, which in southern Brazil must account for 20% of the total area of a rural property. Because they do not receive any financial return from the forested areas on their farms, the landowners often think of them as unproductive (Sanquetta and Mattei, 2006). The lack of political incentives for active forest management of the native *Araucaria* forests has led to some small landowners not retaining the 20% of forested area required by law and illegally opting for other land uses, primarily agricultural, but also pastureland and plantations of commercial exotic timber species (Orellana et al., 2016). Not only has the area of forest coverage been reduced, but so too has biodiversity been lost, with many endogenous species (including fauna) having been reported as endangered (Morellato and Haddad, 2000). The edible seeds of *A. angustifolia* provide a good food supply source for the fauna, especially birds such as the azure jay (*Cyanocorax caeruleus*), an endemic species from southern Brazil that is classified as endangered. Other endangered fauna include the maned wolf (*Chrysocyon brachyurus*) and the vinaceous Amazon parrot (*Amazona vinacea*). Flora species have also been reported as endangered and include *Cabralea cangerana* (a neotropical tree), *Ocotea catarinenses* (a monoecious evergreen), and *Dicksonia sellowiana* (an arborescent fern).

Integrating different revenue sources such as timber and non-timber forest products (NTFP) as well as environmental services may be key to the future of species-rich forests, allowing standing forests to become economically competitive with other land uses (Klimas et al., 2012). Protecting and managing the current large areas of secondary and regrowth forests is one way of increasing forest coverage (Lamb et al., 2005). Many researchers defend the idea that native *Araucaria* forests should be sustainably managed for timber production, as this would financially benefit landowners with small farms whose main objective is usually to maximize their land revenue. This action would also promote expanding the area of native vegetation coverage because small landowners would place more importance on the native forests on their properties.

However, because the law restricts timber harvesting, even for scientific purposes, there are no studies available demonstrating the consequences of harvesting *A. angustifolia* and other tree species for timber production. Studies on managing these forests for timber production are needed to provide a better understanding of how native *Araucaria* forests would recover after being harvested for timber (Orellana et al., 2017).

The objective of this study was to evaluate the effects of harvesting timber on small farms with native *Araucaria* forest coverage in southern Brazil. Due to the restrictions imposed by law, we used an individual tree-growth model to simulate nine *A. angustifolia* harvesting scenarios. In addition, we simulated managing timber production for the forest as a whole by evaluating those scenarios that could sustainably supply *A.*

angustifolia timber in conjunction with additional harvesting of angiosperm tree species.

2. Methods

2.1. Research plots on the small farms

In 2011, 48 plots were randomly established on 19 small farms in southern Brazil (Fig. 1). The farm sizes ranged from 6.4 to 65.1 ha, and the plot sizes ranged from 800 to 2000 m^2. The number of plots per farm was determined by the forested area on the property, but at least 40% of the total forested area was sampled on any given farm. The larger the forested area on the farm, the more plots were established. On some properties with a relatively large forested area, we established up to six plots, whereas small farms with little forested area had fewer plots, in some cases only one (Appendix A).

The forest fragments on the small farms varied in structure and ecological group composition. For example, five plots had no *A. angustifolia* trees but instead had angiosperm tree species, while in five other plots, the *A. angustifolia* basal area was greater than that of the angiosperms (Appendix A). The different types of forest structure found among the plots reflect the different degrees of anthropic activity to which these forest fragments have been subjected to in the past.

2.2. Refining the growth model to simulate the harvesting scenarios on small farms

The individual tree-growth model used to simulate the harvesting scenarios in this study was constructed based on twenty-five 1-ha plots established in a native *Araucaria* forest fragment located in the Irati National Forest (Orellana et al., 2017, 2016). The original model was constructed to run with 1-ha plot sizes, with diameter growth, survival, and recruitment sub-models parameterized for six ecological groups. It was also constructed using a local site-productivity index termed a site form (Vanclay and Henry, 1988).

Adjustments were made to run the model using the data collected from the plots established on the small farms as follows: (1) all 48 plots established on the small farms were run simultaneously; (2) the six ecological groups were reduced to two major groups, *A. angustifolia* and angiosperms; (3) the volume equations were updated for *A. angustifolia* and angiosperms; and (4) the local site-productivity index was removed and replaced with two merchantable height equations to produce separate estimates for the *A. angustifolia* and angiosperms.

2.3. Evaluating the model's performance at estimating stand-volume growth in plots smaller than 1-ha

The plots established on the small farms varied in size between 800 and 2000 m^2. Because the original growth model was parameterized based on a 1-ha plot size, our first analysis was to assess whether the model accurately estimated the stand-volume growth when using plots smaller than the original 1-ha.

The permanent plots established in the Irati National Forest comprise 25 contiguous 1-ha plots, each divided into 4 quadrats, with each quadrat further subdivided into 5 strips (Fig. 2). The division of the 1-ha plots into quadrats and strips allowed us to perform this analysis.

We evaluated the model's performance when simulating stand-volume growth for three different plot sizes: 5000 m^2, 2500 m^2, and 500 m^2. The stand-volume growth ($m^3\,ha^{-1}$) was simulated for all plots, quadrats, and strips of the previously established 25-ha sample area in the Irati National Forest using a simulation period of 50 years. Therefore, the simulations generated 25 outputs for the 1-ha plots, 50 outputs for the half-plots (5000 m^2), 100 outputs for the quadrats (2500 m^2), and 500 outputs for the strips (500 m^2).

The simulated stand volumes for the twenty-five 1-ha plots were compared to the stand volume outputs for the smaller-sized test plots after 50 years. A one-way analysis of variance (ANOVA) was used to assess whether there was a significant difference ($p < 0.01$) between the stand volume projections for the original 1-ha plots and the stand-volume outputs simulated by the model using the 5000 m^2, 2500 m^2, and 500 m^2 plot sizes. The data were plotted to illustrate the differences in the means and standard deviations of the stand-volume projections for each of the plot sizes tested.

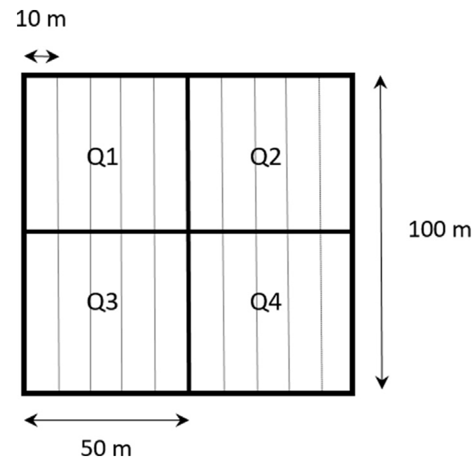

Fig. 2. Illustration of one 1-ha plot divided into four 2500-m^2 quadrats. Each quadrat is further subdivided into five 500-m^2 strips.

2.4. Simulation of A. angustifolia for a sustainable timber supply

Araucaria angustifolia is the most important tree species in this type of forest, and it is considered the most important conifer in Brazil. However, current law prohibits its harvest. Therefore, research on the sustainable harvesting and recovery of *A. angustifolia* after selective harvesting is still scarce. For a better understanding of the consequences of harvesting *A. angustifolia*, we simulated nine different harvesting scenarios by using an individual tree-growth model to evaluate which scenarios might be sustainable based on the basal-area recovery after harvest.

We set the growth model to run all 48 plots established on the 19 small farms simultaneously, initializing the model with the data collected in 2011. The harvest intensity and cutting cycles were varied to create nine different harvest scenarios to test (Table 1). All the scenarios were simulated for a period of 100 years to analyze *A. angustifolia*'s recovery after harvest in the long-term. The minimum cutting diameter (MCD) in the model was set to 40 cm for all harvest scenarios, as this was the diameter that the law required decades ago when harvesting *A. angustifolia* was permitted.

To be a sustainable harvesting scenario, the long-term simulations were required to show a clear recovery of the basal-stand area after the *A. angustifolia* had been harvested. To test a particular harvest scenario

Table 1
Scenarios tested to evaluate the recovery of *Araucaria angustifolia* after harvesting.

Harvest scenario	Cutting cycle (years)	Harvest intensity[a]
1	5	10%
2		15%
3		20%
4	10	20%
5		35%
6	20	35%
7		50%
8	25	50%
9	30	50%

[a] Percentage removal of the *A. angustifolia* basal area.

for sustainability, we assumed that the average *A. angustifolia* basal area ($m^2\,ha^{-1}$) of all 48 plots at the end of the 100-year simulation should be equal to or larger than the basal area at the beginning of the simulation ($7.48\,m^2\,ha^{-1}$ in 2011). However, if the basal area of a tested scenario was smaller at the end than at the beginning, we used a paired *t*-test to determine if the difference was significant. If there was no significant difference between the *Araucaria* basal areas at the beginning (Year 0) and end (Year 100) of the simulation, then that scenario was also considered sustainable.

2.5. Evaluating the different scenarios for harvesting native Araucaria forests on small farms

The scenarios considered sustainable for harvesting *A. angustifolia* were tested to simulate harvesting the forest as a whole, including angiosperm tree species. We included the angiosperms because if any eventual harvesting management plan is applied to small farms, not only would *A. angustifolia* be harvested, but so too would other important merchantable angiosperm trees.

Because we believe 30 years is an appropriate planning horizon for applying any eventual harvesting management plan to the small farmlands in southern Brazil, we ran 30-year simulations using all 48 plots. For those scenarios considered sustainable for harvesting *A. angustifolia*, we also tested a 10%, 20%, and 30% removal of the angiosperm stand basal area. Similar to the analysis performed for *A. Angustifolia*, a scenario was considered sustainable if the estimated stand volume at the end of the 30-year simulation was either larger than that at the beginning or the difference between the stand volumes at Years 0 and 30 was statistically insignificant. This should allow the merchantable timber volume in the forest to yield a non-declining even flow of timber.

3. Results

3.1. Model performance estimating stand-volume growth in plots smaller than 1 ha

The mean stand volume estimated by the model for the original 1-ha plots ($10{,}000\,m^2$) was similar to that obtained for the smallest plot size tested ($500\,m^2$) in the 50-year simulation (Fig. 3). A one-way ANOVA found no statistically significant differences between the original 1-ha plots estimates and the three plot sizes used to evaluate the model's performance ($p = 0.386$). This indicates that the individual tree-growth model results in reliable stand-volume estimates when using plot sizes as small as $500\,m^2$.

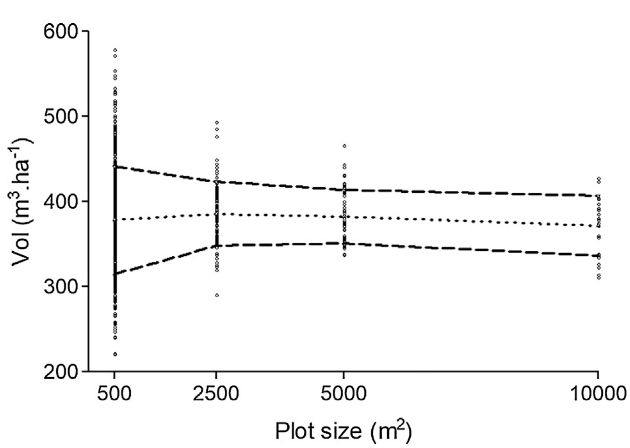

Fig. 3. Stand-volume estimates from the model for the different plot sizes after a 50-yr simulation. Dashed lines represent one standard deviation from the mean (dotted line).

3.2. Simulating the sustainable harvest of A. angustifolia

Among the nine harvesting scenarios tested, Scenarios 1, 4, 6, and 8 appeared to be sustainable for harvesting *A. angustifolia* (Fig. 4). For these four sustainable harvesting scenarios (black lines), the *A. angustifolia*'s basal areas at the end of the 100 simulated years were close to the values at the beginning of the simulations. The scenarios that were not considered sustainable (Fig. 4, gray lines) showed a trend of decreasing basal area throughout the 100-year simulation period, which indicated that the harvest intensity was above that which *A. angustifolia* can tolerate and recover from.

The *Araucaria* basal areas in Scenarios 1, 4 and 6 were larger at the end of simulations (Year 100) that at the beginning (Year 0), indicating their harvest intensities were appropriate for *Araucaria* species. In Scenario 8, the basal area at the end of the simulation ($7.07\,m^2\,ha^{-1}$) was slightly smaller than that at the beginning ($7.48\,m^2\,ha^{-1}$), but the paired *t*-test indicated no significant difference ($p = 0.893$). Therefore, the harvesting intensity in Scenario 8 was considered sustainable for *A. angustifolia*.

3.3. Evaluating harvesting scenarios for native Araucaria forests and angiosperms on small farms

The four scenarios considered sustainable for harvesting *A. angustifolia* (Scenarios 1, 4, 6, and 8) were tested to see if the scenarios would remain sustainable when the harvest included angiosperm tree species in the simulations in addition to the *A. angustifolia*. The simulations indicated that with the exception of Scenario 4, no more than 10% of the angiosperm basal area should be removed; Scenario 4 tolerated a 20% removal of the angiosperm basal area. The average cumulative-stand volumes ($m^3\,ha^{-1}$) for the *A. angustifolia* and angiosperms in the four sustainable scenarios are shown in Fig. 5. The estimated stand volume for each of the sustainable harvesting scenarios at the end of the simulation (Year 30) was close to that at the beginning (Year 0), approximately $154\,m^3\,ha^{-1}$. The paired *t*-test did not identify any significant differences in the estimated stand volumes between the beginning and end of the 30-year simulations: Scenario 1 ($p = 0.127$), Scenario 4 ($p = 0.194$), Scenario 6 ($p = 0.271$), and Scenario 8 ($p = 0.156$). Therefore, all the scenarios were considered sustainable, though it should be noted that Scenarios 1 and 4 had higher individual *A. angustifolia* volumes at the end of simulations than at the beginning.

The individual *A. angustifolia* and angiosperm values at the end of the simulations were also close to those at the beginning, indicating a sustainable supply of merchantable wood throughout the 30-year plan horizon. This suggests the four harvesting scenarios can be appropriately applied for timber production on the small farms in southern Brazil.

The individual mean volumes harvested ($m^3\,ha^{-1}$) for the *A. angustifolia* and angiosperm harvesting scenarios are shown in Table 2. The scenario that resulted in the largest harvested volume was Scenario 4, resulting in $322.75\,m^3\,ha^{-1}$ at the end of the 30-year horizon plan. In this scenario, the model applied a 20% removal rate for the *Araucaria* and angiosperm basal areas in 10-year cutting cycles. The second largest harvested volume was for Scenario 1, which harvested in 5-year cutting cycles. In contrast, the scenarios with the longest cutting cycles, Scenarios 6 and 8 (20 and 25 years, respectively), resulted in the smallest harvested volumes.

4. Discussion

The scenarios that applied short cutting cycles of 5 or 10 years (Scenarios 1 and 4, respectively) showed the largest harvest volumes at the end of the 30-year planning horizon. In fact, Scenario 4 showed the highest harvested volume among all scenarios tested due to the higher intensity of the angiosperm harvest (20% removal of the basal area). The other scenarios were unsustainable if the harvest intensity

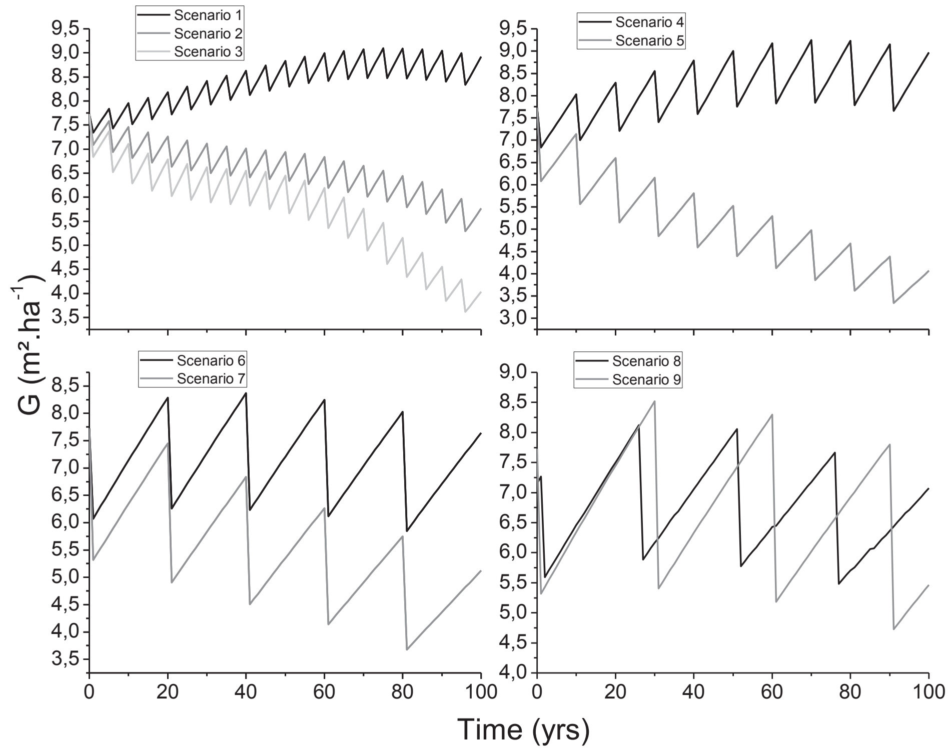

Fig. 4. Recovery of the *A. angustifolia* basal area ($m^2\,ha^{-1}$) under nine different harvesting scenarios in 100-year simulations. The harvesting scenarios considered sustainable are indicated with black lines, while gray lines show those considered unsustainable.

exceeded a 10% removal of the angiosperm basal area.

The simulation results suggest that in the event harvest management plans are applied on small farms in southern Brazil with native *Araucaria* forest coverage, then the shorter cutting cycles should be adopted (5 or 10 years) as they are on small farms in the Amazon region, where 10-year cycles are used in a low-impact animal-drawn harvesting system with a cutting rate of $10\,m^3\,ha^{-1}$ (D'Oliveira and Braz, 2006). In simulations for secondary tropical forest fragments following agricultural abandonment, 10-year cycles with the removal of up to 20 trees with a 30-cm MCD yielded more than 30-year cycles with

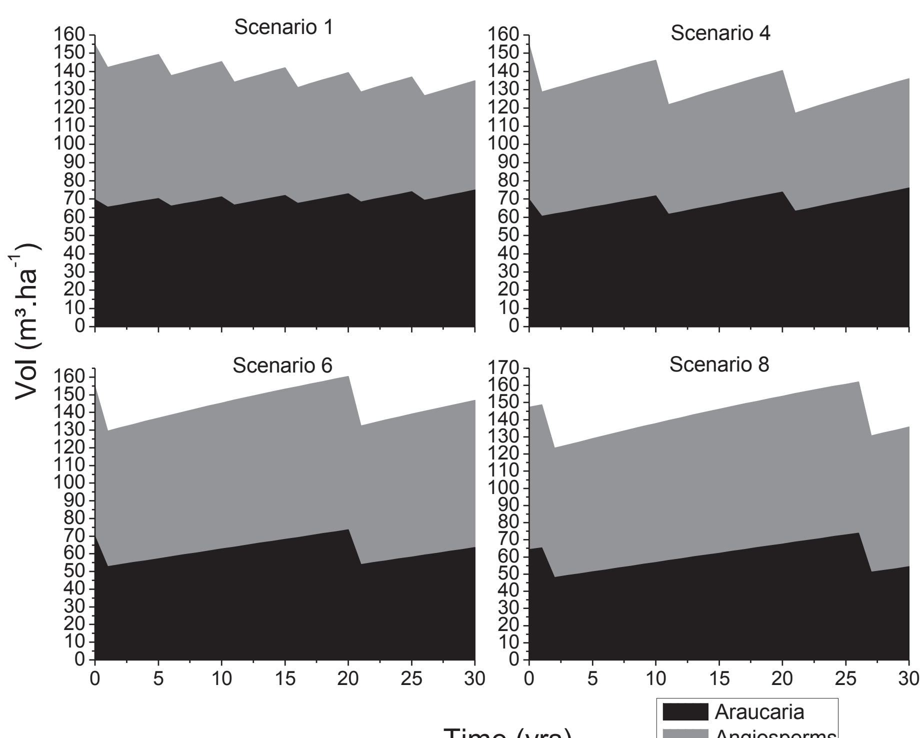

Fig. 5. Cumulative volume of the *Araucaria angustifolia* and angiosperm harvest from 30-year simulations for the four scenarios considered sustainable for harvesting native *Araucaria* forests: Scenario 1, Scenario 4, Scenario 6, and Scenario 8.

Table 2

Volume harvested ($m^3 ha^{-1}$) over 30 years for the four sustainable *Araucaria angustifolia* harvest scenarios when additional angiosperm tree species are harvested.

Scenario	Species group	Cutting						Volume harvested (30 yrs)	Total volume harvested (30 yrs)	Volume harvested (per yr)
		1	2	3	4	5	6			
1	*A. angustifolia*	25.43	23.68	22.59	20.97	19.88	18.89	131.44	300.39	10.01
	Angiosperms	44.76	35.85	29.07	23.74	19.49	16.05	168.95		
4	*A. angustifolia*	50.86	45.94	40.39	–	–	–	137.19	322.75	10.76
	Angiosperms	89.51	57.76	38.29	–	–	–	185.56		
6	*A. angustifolia*	89.00	74.70	–	–	–	–	163.70	243.02	8.10
	Angiosperms	44.76	34.56	–	–	–	–	79.32		
8	*A. angustifolia*	91.89	86.32					178.21	258.86	8.63
	Angiosperms	45.82	34.83					80.66		

a 35-cm MCD (Kammesheidt et al., 2002). These results corroborate our simulations, which also found 10-year cutting cycles to be more productive than the longer cutting cycles of 20 and 25 years tested in our study.

The average harvestable yields for the four sustainable harvesting scenarios were well above those found in some other tropical forests. Projections with the SYMFOR growth model for the Amazon revealed that even with adopting low-impact harvest systems, 30-year cutting cycles, and a harvest intensity of 35 to 40 $m^3 ha^{-1}$, the harvests of commercially valuable species would be increasingly reduced (Valle et al., 2007; van Gardingen et al., 2006). This suggests that even in the Amazon, cuts nearing 1 $m^3 ha^{-1} year^{-1}$ are still heavy and incompatible with timber sustainability in the long term. In tropical forests in the northern state of Queensland in Australia, sustainable timber production calls for cutting only 0.4 $m^3 ha^{-1} year^{-1}$ (Vanclay, 1993), while in the Tapajos National Forest in Amazonia, no more than 0.3 $m^3 ha^{-1} year^{-1}$ should be cut for a sustainable wood flow (van Gardingen et al., 2006). In the simulations performed in this study, the sustainable wood flow in the best scenario was 10.8 $m^3 ha^{-1} year^{-1}$, with the worst scenario yielding 8.1 $m^3 ha^{-1} year^{-1}$ (Table 2).

The higher yields found in our research compared to other tropical forests may be related to the minimum diameter for cutting adopted in the simulations (40 cm). In the Amazon region, the MCD imposed by Brazilian law is 50 cm for most tree species (Macpherson et al., 2012), with a few species having their own particular MCDs. Another factor that may have resulted in higher yields in this study is that, unlike what occurs in the Amazon forest, the native *Araucaria* forests have not been exploited for timber for many decades due to the harvest restrictions imposed by law. Therefore, most forests on the small farms have large trees, resulting in a greater availability of wood for harvesting in the first cutting for each of the four sustainable harvesting scenarios (Table 2). In other tropical regions such as the Amazon, forest management for timber production has been implemented continuously for several decades, and large trees with commercial value are now rare in many tropical forests. This may explain why some tropical forests have yielded less harvestable wood than our simulations found for the native *Araucaria* forests. However, comparing yields in different tropical forests is difficult for reasons such as the number of commercial species, their growth rates, and the minimum cutting diameters used in the different studies on different forest types. Nevertheless, as this is the first study performed to evaluate harvestable timber scenarios in Brazilian native *Araucaria* forests, we compared our results with other tropical studies to illustrate the potential for managing this forest type for timber.

The results of our study indicate that native *Araucaria* forests have great potential and should be explored for timber production. *Araucaria angustifolia* was shown to have a good basal-area recovery in four of the nine harvesting scenarios tested. This suggests that *A. angustifolia* has the potential to be used for farming wood, as this tree species also has one of the highest diameter-growth rates in this type of forest. Of the tree species with more than 10 individuals in the study area, only *Piptocarpha angustifolia* has a slightly higher mean diameter growth rate (0.5 $cm\ yr^{-1}$) than *A. angustifolia* (0.41 $cm\ yr^{-1}$).

Araucaria angustifolia has good physical and mechanical wood properties (Hillig et al., 2012), and the number of stems per hectare is relatively high, with an average of 80 trees per hectare (DBH > 10 cm) on the small farms evaluated in this study (Appendix A). Moreover, the regeneration of *A. angustifolia* in mature stands is rare (Caldato et al., 1996; Longhi et al., 2018; Rosa et al., 2016; Vicente-Silva et al., 2016), although the species can successfully regenerate under increased light levels (Souza et al., 2008). This suggests that opening gaps by removing a few individuals under selective logging practices would promote regeneration.

A few plots in this study had a low number of *A. angustifolia* trees (Appendix A). However, promoting assisted-regeneration techniques and species enrichment (Macpherson et al., 2012; Walters et al., 2005) on those plots would also provide for a sustainable wood flow in the medium and long term. Similar to the Amazon forests that provide commercially important seeds (Klimas et al., 2012), native *Araucaria* forests are rich in NTFPs such as *A. angustifolia* seeds (pine nuts) that could be sustainably harvested, giving small farmers an alternative source of income (Figueiredo Filho et al., 2011) and providing more opportunities for the farmers in southern Brazil.

Some studies have reported conflict among stakeholders in the use of tree species (e.g., Guariguata et al., 2010; Herrero-Jáuregui et al., 2009). This can happen when a particular tree species is valued both for its timber and a NTFP. When the extractions are made by different stakeholders, the conflict becomes even greater (Guariguata et al., 2010). Ultimately, the role the non-timber use plays in the livelihoods of the stakeholders and the commercial value and ecological resilience of the species will determine the nature and intensity of the conflict (Herrero-Jáuregui et al., 2009). Nevertheless, it would be sensible to allocate forest areas solely for seed collection when there are seeds are of commercial interest (Guariguata et al., 2010).

Another issue of importance when managing species-rich forests is concern for the local fauna. Logging practices have long been reported to impact local fauna (Azevedo-Ramos et al., 2006; Burivalova et al., 2014; Ghazoul, 2002; Hill and Hamer, 2004), especially birds (Felton et al., 2008; Imbeau et al., 1999; Wunderle Jr. et al., 2006). However, because current law restricts the management of these forests and government oversight of their maintenance is poor, many small farmers have been illegally clear-cutting their forest patches to convert them to other land-uses, which has an even greater impact on the local fauna and endangered species. Changing the law to provide greater opportunities to manage native *Araucaria* forests, mainly by allowing timber harvesting, would benefit the small farmers who play a fundamental and critical role in conserving the native forests (Rockwell et al., 2007). This would avoid the illegal conversion of forest to annual crops, pasturelands, or commercial tree plantations, hence expanding the coverage area of native *Araucaria* forests, and consequently, increasing the presence of local fauna on these larger forest patches. This study aims to achieve these goals by providing an overview to eventually implement a forest management plan for timber harvesting purposes on the small farms in southern Brazil with native *Araucaria* forest coverage.

5. Conclusions

Among the nine harvesting scenarios tested, four were shown to allow sustainable harvesting of *A. angustifolia* for timber production. These four scenarios were also sustainable when angiosperm tree species were included in the harvest of the native *Araucaria* forests and are therefore appropriate for application on the small farms covered by such forests.

The mean harvestable timber volumes accumulated by the end of a 30-year horizon plan were approximately 10 times higher than those found in other studies conducted in tropical forests. Even in the worst sustainable harvesting scenario, the simulations still estimated a harvestable volume eight times higher than the 1-$m^3\,ha^{-1}$·yr harvest intensity found, on average, to be sustainable in the Amazon region. The simulations indicate that *A. angustifolia* and the native *Araucaria* forests in southern Brazil hold great potential for harvesting timber.

In recent decades, the restrictions on forest management imposed by current law have led to a reduction in native forest coverage and the loss of many endemic species. Therefore, the first step to save the native *Araucaria* forests from illegal conversion and consequent increased species loss is a change in the law to permit harvesting *A. angustifolia* and other commercial tree species. This step, coupled with harvesting non-timber products, would give small-farm owners a different view of the forested areas on their property, which they currently consider idle.

A change in the law is also necessary to increase the minimum area of native vegetation on small farms, which in southern Brazil today corresponds to 20% of the total area. The law should be directed toward encouraging connections among the fragments on the small farms, which would then become ecological corridors, thereby avoiding a reduction in genetic diversity. Finally, forest management plans should also include the enrichment of rare and commercial species. Total protection as imposed by current law is actually leading to forest extinction, while these proposed measures would prevent the further loss of native *Araucaria* forest coverage and species. Although the outputs of this study originated from simulations using a growth model, this study is the first attempt to evaluate the potential for managing forests for timber production in this forest type.

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Appendix A. . Variables that describe forest structure for *Araucaria angustifolia* and angiosperms collected from 48 plots established on the 19 small farms used to simulate harvest scenarios

Small farm	Plot	Plot area (m^2)	*A. angustifolia*			Angiosperms			Total	
			Mean DBH (cm)	N ha	G/ha ($m^2\,ha^{-1}$)	Mean DBH (cm)	N/ha	G/ha ($m^2\,ha^{-1}$)	N/ha	G/ha ($m^2\,ha^{-1}$)
1	1	2000	42.2	65	11.3	19.5	695	24.4	760	35.7
2	2	2000	36.5	10	1.4	21.5	375	18.6	385	20.1
	3	1600	37.3	19	2.1	18.4	700	21.4	719	23.5
3	4	2000	33.0	130	13.3	18.4	670	19.7	800	33.0
	5	2000	27.2	250	17.6	16.7	440	10.6	690	28.2
	6	2000	34.2	90	9.3	17.7	1010	27.5	1100	36.8
4	7	2000	70.0	10	3.9	21.4	500	20.4	510	24.3
5	8	1600	33.7	6	0.6	19.9	406	16.1	413	16.7
6	9	2000	25.3	220	13.4	16.2	510	12.2	730	25.6
	10	2000	24.8	260	16.3	16.8	435	11.0	695	27.2
	11	2000	24.5	100	6.5	16.8	590	15.8	690	22.3
	12	2000	23.4	195	10.9	19.7	450	16.9	645	27.8
	13	2000	29.1	105	9.2	19.9	540	20.5	645	29.8
	14	2000	30.8	60	4.8	23.0	585	29.7	645	34.6
7	15	2000	–	0	0.0	18.7	865	28.3	865	28.3
	16	2000	–	0	0.0	16.5	825	19.7	825	19.7
8	17	2000	45.3	25	4.5	17.6	595	16.8	620	21.3
	18	2000	31.2	20	2.0	22.4	510	25.7	530	27.7
	19	2000	28.0	50	4.4	20.7	560	22.7	610	27.1
	20	2000	26.6	120	17.5	23.4	475	28.9	595	46.4
9	21	2000	24.5	10	0.5	19.6	380	16.1	390	16.6
	22	2000	21.6	5	0.2	20.4	280	11.1	285	11.3
10	23	2000	37.8	55	6.9	23.5	540	33.6	595	40.5
	24	1600	29.7	88	6.6	24.9	275	16.0	363	22.6
11	25	1000	–	0	0.0	18.2	890	25.5	890	25.5
12	26	800	–	0	0.0	23.9	338	18.4	338	18.4
	27	800	–	0	0.0	20.6	550	22.5	550	22.5
13	28	2000	30.8	75	7.4	17.8	580	16.4	655	23.8
	29	2000	37.0	160	21.5	19.0	530	18.4	690	39.8
	30	2000	24.0	35	1.9	17.7	980	29.5	1015	31.4
	31	2000	51.2	115	25.6	17.3	495	13.8	610	39.3

14	32	2000	29.3	195	14.5	16.5	835	19.8	1030	34.3
	33	2000	38.7	60	7.9	20.1	750	28.4	810	36.3
	34	2000	25.0	100	6.0	17.8	1025	29.5	1125	35.5
	35	2000	30.5	165	13.5	17.3	735	19.7	900	33.3
	36	2000	33.3	95	10.4	19.6	775	28.3	870	38.6
	37	2000	36.2	95	11.0	21.6	435	18.3	530	29.4
15	38	2000	39.8	10	1.3	21.3	675	29.9	685	31.2
16	39	2000	33.2	95	9.4	18.8	785	24.5	880	33.9
	40	2000	36.5	100	11.8	18.2	785	23.2	885	35.0
17	41	2000	29.8	55	4.8	19.0	660	21.9	715	26.7
	42	2000	20.0	160	5.5	19.2	460	19.6	620	25.1
	43	2000	23.2	170	8.5	19.9	420	18.4	590	26.9
18	44	1200	17.6	42	1.1	24.1	450	23.1	492	24.2
	45	1600	25.5	56	3.4	24.2	375	24.1	431	27.5
	46	1200	61.6	8	2.5	28.0	383	31.1	392	33.6
19	47	2000	40.2	55	7.7	19.9	500	20.3	555	28.1
	48	2000	34.5	40	4.5	19.3	645	22.3	685	26.7

Appendix B. Supplementary material

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.foreco.2018.07.057.

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