Pine Plantations and Invasion Alter Fuel Structure and Potential Fire Behavior in a Patagonian Forest-Steppe Ecotone

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Abstract: Planted and invading non-native plant species can alter fire regimes through changes in fuel loads and in the structure and continuity of fuels, potentially modifying the flammability of native plant communities. Such changes are not easily predicted and deserve system-specific studies. In several regions of the southern hemisphere, exotic pines have been extensively planted in native treeless areas for forestry purposes and have subsequently invaded the native environments. However, studies evaluating alterations in flammability caused by pines in Patagonia are scarce. In the forest-steppe ecotone of northwestern Patagonia, we evaluated fine fuels structure and simulated fire behavior in the native shrubby steppe, pine plantations, pine invasions, and mechanically removed invasions to establish the relative ecological vulnerability of these forestry and invasion scenarios to fire. We found that pine plantations and their subsequent invasion in the Patagonian shrubby steppe produced sharp changes in fine fuel amount and its vertical and horizontal continuity. These changes in fuel properties have the potential to affect fire behavior, increasing fire intensity by almost 30 times. Pruning of basal branches in plantations may substantially reduce fire hazard by lowering the probability of fire crowning, and mechanical removal of invasion seems effective in restoring original fuel structure in the native community. The current expansion of pine plantations and subsequent invasions acting synergistically with climate warming and increased human ignitions warrant a highly vulnerable landscape in the near future for northwestern Patagonia if no management actions are undertaken.

Keywords: fire severity; forestry; fuel build-up; restoration; wildfire

1. Introduction

Fire regimes are being altered by climate warming as well as by synergisms between changes in climate and land use [1,2]. Changes in fuel load and vegetation structure, due to a variety of factors

including fire exclusion [3], livestock grazing [4] and invasion of non-native plant species [5], have crucial implications on fire activity, possibly altering fire propagation, and the severity and extension of fire events. For instance, anthropogenic fuel build-up can sharply alter fire behavior in fuel-limited systems, increasing the difficulty of fire control, and thus raising the amount of resources needed for suppression. Disruption of fire regimes due to changes in fuel loads and structure can ultimately result in altered or delayed successional trajectories.

Both planted and invading non-native plant species can alter fire regimes through changes in fuel loads and in the structure and continuity of fuels, potentially increasing or decreasing the flammability of native plant communities [6,7]. Well studied cases, such as the invasion of cheatgrass (*Bromus tectorum* Huds.) into the US Great Basin, show that invaded areas burn nearly four times more frequently than native vegetation types due to the higher flammability and faster recovery of cheatgrass compared to native species [8]. Although there is a significant body of knowledge on the relationship between invasive grasses and fire activity, much less is known about the consequences of non-native woody species on fire regimes [7]. Non-native and fire-prone tree species, such as certain eucalypts and pines, are expected to alter fire behavior in sites where they are planted or invading, potentially increasing fire severity [9,10]. On the contrary, other non-native woody species, such as *Hakea sericea* Schrad. and J. C. Wendl and *Acacia saligna* (Labill.) H. L. Wendl. in South Africa can suppress fire occurrence due to understory fuel reduction, higher fuel moisture in their tissues or more densely packed fuel compared to native vegetation [11]. Therefore, the potential response of fire behavior associated to non-native woody plants is complex and unpredictable, and deserves system-specific studies. Careful evaluation of native and non-native fuel attributes is needed in order to understand and predict potential changes in fire regimes in those ecosystems where non-native species are planted or invading.

In several regions of the southern hemisphere, such as New Zealand, South Africa and South America, pines have been planted in native treeless areas for forestry purposes and have subsequently invaded the native environments [12]. In these open environments with naturally low fuel loads (grasses and short shrubs), exotic trees represent a significant alteration in the load and structure of fuels. For example, in northwestern Patagonia, Argentina, pines have been planted along the forest-steppe ecotone since the late 1970s [13] and escaped pines from plantations have rapidly become biological invaders in several formerly treeless areas [14]. In this region, the most commonly planted species is *Pinus ponderosa* Douglas ex C. Lawson and the most widespread invasive pine species is *Pinus contorta* Douglas, both of which experience frequent fire in their native environments and thus have life-history traits that generally make them well adapted to fire [15]. Furthermore, both species have fast growth rates and thus rapid fuel load accumulation, particularly in the introduced range [16,17]. Lastly, frequent observations of fires originating or spreading rapidly in non-native plantations and neighboring invaded areas are generating concerns as to whether pine plantations and invasions increase native vegetation's flammability and may qualitatively alter the historical fire regime [9,18].

Arguments supporting the high flammability of pine stands seem reasonable. Nonetheless, the heterogeneity of fuel loads and structures in pine plantations and invaded areas, as well as the various native plant communities that are replaced, create complex scenarios that prevent generalizations on the relative flammability and the ecological consequences of fire. For instance, well managed plantations where tree thinning treatments were rigorously conducted seem less prone to high severity fires compared to those that were not thinned [19]. Similarly, pine invasions only seem to generate positive fire-invasion feedbacks after certain pine density thresholds are surpassed [16]. Thus, it is necessary to evaluate the relative fire hazard of pine plantations under different scenarios of management and different stages of invasion in comparison to the native vegetation being replaced.

Despite the pervasive presence of pine plantations and invasions in many regions of the southern hemisphere, where currently millions of hectares are occupied by plantations and invasions [10,12], there are remarkably few studies that have evaluated changes in the flammability of the native

vegetation caused by pines. Only recently, two studies have explored the changes in fuel loads and structure generated by pine invasions in southern South America [16,20]. However, neither addressed changes in flammability caused by plantations, which are also a main component of these landscapes, nor did they assess the impacts of different management practices on the relative flammability of these scenarios. The objective of this study is to evaluate changes in fuel structure and potential fire behavior due to pine plantations and invasions of two *Pinus* species (*Pinus ponderosa* and *Pinus contorta*) in the northwestern Patagonian forest-steppe ecotone. Although changes in fuel loads may seem obvious (especially above the height of steppe's vegetation), alterations in potential fire behavior originated from fuel build-up are not easily forecasted. We quantified the amount and spatial arrangement of fine fuels in four contrasting scenarios: native steppe, pine plantations, pine invasions and mechanically removed pine invasions. We also compared fuel structure among three levels of invasion with progressively higher basal areas and older ages of establishment and between plantations with pruned basal branches vs. unpruned plantations. We used fuel characterizations and additional quantifications of fuel loads to evaluate the effects of pine-induced fuel changes on fire behavior under two fire danger scenarios of contrasting fuel moisture and wind speed utilizing the modeling software BehavePlus 5.0.5 (US Forest Service and Systems for Environmental Management, Missoula, MT, USA) [21,22]. This will allow the assessment of the relative ecological vulnerability to fire of the most common forestry and invasion scenarios in the region.

2. Materials and Methods

2.1. Study Area

This study was conducted in northwestern Patagonia, Argentina, on the eastern side of the Andes from 39°55′ S to 41°58′ S. Low foothills and plains dominate the landscape and the climate in the region is temperate with a Mediterranean precipitation regime where most precipitation occurs during May–September as rain or snow. The elevations of the selected sites ranged from 765 to 950 m above sea level and mean annual precipitation ranges from 700 to 800 mm [23]. Vegetation in the study areas is typically ecotonal with a mosaic of low shrublands and steppes of tussock grasses (e.g., *Festuca pallescens* (St. Yves) Parodi, *Pappostipa speciosa* (Trin. and Rupr.) Romasch.) and scattered low shrubs (e.g., *Mulinum spinosum* Pers., *Acaena splendens* Gillies ex Hook. and Arn., *Berberis buxifolia* Gillies ex Hook. and Arn.). Wildfires and grazing are the two most important broad-scale disturbances in the northwestern Patagonian forest-steppe ecotone, with most fires being anthropogenic in origin [24]. The selected study sites are representative of the typical environments in which pine plantations and invasions are located in the region. Pine plantations in the Andean Patagonia are distributed from ~36° S to ~44° S; typically on steppe areas and less frequently on mixed shrublands or secondary successions of Chilean cypress (*Austrocedrus chilensis* (D. Don) Pic-Serm. and Bizzari) [13]. Most planted species in the ecotone area are *P. ponderosa* followed by *P. contorta* (80% and 7.5% of the planted area respectively) [25,26]. The latter species is an aggressive invader in multiple locations across the southern hemisphere including the steppe in northwestern Patagonia, while *P. ponderosa* is considered less invasive [27].

2.2. Study Design

We conducted the study at five different locations (Table S1) that exhibited various levels of pine invasion from adjacent plantations (from ca. 25 to 40 years old). In each location, we selected a minimum of four 20 × 20 m plots with the following vegetation conditions (hereafter referred to as treatments): (i) native vegetation consisting mostly of steppe with scattered low (<1 m) shrubs, (ii) mature (reproductive) pine plantations dominated by *P. ponderosa* and with variable proportions of *P. contorta*, (iii) invaded native vegetation mainly by *P. contorta* (>95% composition), and (iv) removed (clearcutted) *P. contorta* invasions (Table 1, Figure S1). The group of four plots was replicated two to four times at each site for a total of 14 groups, thus totaling 56 plots. Additionally, we classified

the invaded and their paired removed invasion plots into three different categories based on their basal area: (a) low invasion (<5 m^2/ha) (and low removed invasion) (5 plots each), (b) intermediate invasion (from 5 to 20 m^2/ha) (and intermediate removed invasion) (4 plots each), and (c) high invasion (>20 m^2/ha) (and high removed invasion) (5 plots each) (Table 1, Figure S1). The plantations were divided into those that exhibited pruning of basal branches (9 plots, pruned) and those that were not pruned (5 plots, unpruned) (Table 1, Figure S1). Basal branches were pruned up to a height of 2 to 3 m and the removal of forestry residues was variable among plantations. Pine invasion removal was conducted one year before fuel sampling in plots with similar densities and basal areas as their paired invasion plots. Pines were cut at basal height and removed from the plot. Year of invasion initiation on each plot was estimated by counting tree rings on basal discs that were obtained from three to five harvested individuals per plot which presented the largest diameter.

Table 1. Number of sampled plots with each vegetation condition classified according to the level of invasion (invaded plots) or the pruning status (plantations) totaling nine treatments.

Vegetation Condition	Control	Low Invasion	Intermediate Invasion	High Invasion	Pruned	Unpruned	Total
Native steppe	14	-	-	-	-	-	14
Pine plantation	-	-	-	-	9	5	14
Pine invasion	-	5	4	5	-	-	14
Removed pine invasion	-	5	4	5	-	-	14

We measured fuel characteristics in mixed plantations dominated by *P. ponderosa*, and in invasion stands dominated by *P. contorta*. It is important to note that this work is not aimed at describing the specific characteristics of fire behavior in different *Pinus* species stands, which have been quantified in previous studies (e.g., [28,29]), but to describe the most common scenarios in the studied region and evaluate their relative vulnerability to fire. *Pinus ponderosa* plantations are ubiquitous in northwestern Patagonia and also in other countries such as New Zealand [12,30]. On the other hand *P. contorta* invasions are by far the most common pine invasions in the region and in the southern hemisphere [12]. We acknowledge that plantations dominated by *P. ponderosa* may have a different structure to plantations dominated by *P. contorta*, and the same can be said for their invasions. However, neither pure plantations of *P. contorta* nor *P. ponderosa* invasions are common in the area. Therefore, our analysis provides useful information on fuel changes originated by pines for Patagonia and other regions (e.g., New Zealand, Chile) where these scenarios of plantations and invasions are a ubiquitous part of their landscape.

2.3. Fuel Characterization

We used two sampling strategies: one designed to characterize vertical and horizontal fine fuel (i.e., 1 h fuels; <0.6 cm diameter twigs and leaves) structure and the other aimed at creating fuel models to simulate potential fire behavior using BehavePlus 5.0.5 [21]. To quantify fine fuel structure at each treatment, we followed the point-intercept method [4,31]. We limited fine fuel characterization up to a height of 4 m, which includes surface fuels and the lower portion of the canopy of the evaluated stands. We set a grid of 30 points (5 × 6) equally spaced by 2 m intervals (i.e., 10 × 12 m) in the center of each of the 56 plots. At each point, a 4 m long pole with subdivisions every 25 cm (16 height segments) was vertically placed and we recorded the number of segments that were in contact with dead or live fine fuels. Species identity of the intercepted fuel was also recorded. To characterize canopy height and canopy base height, we visually estimated these variables for the closest tree to the pole as the maximum tree height and the height to the lowest portion of the crown, respectively.

To model potential fire behavior, we quantified fuel load variables and constructed custom fuel models in BehavePlus 5.0.5. Because BehavePlus 5.0.5 assumes homogeneous horizontal distribution of fuel loads, fuel models were only created for those treatments with reasonably homogeneous horizontally distributed fuels (including litter) in most height classes: native vegetation, pruned and

unpruned pine plantations, high invasion and its paired removed high invasion. Low and intermediate invaded areas exhibited discontinuous horizontal fuel arrangements above 0.5 m, preventing their use in BehavePlus 5.0.5. We selected one representative plot per treatment to collect fuel data for the parameterization of each model. To estimate surface fuel loads on each treatment, we delimited 10 1 × 1 m micro plots within an area of ~0.25 ha and we harvested and weighted all fuels classified into dead (sub classified into 1 h fuels, 10 h fuels or 0.6 to 2.5 cm diameter twigs, and 100 h fuels or 2.5 to 7.5 cm branches) and live (sub classified into herbaceous and woody). Fuels were weighted in the field with a portable digital field scale and subsamples of dead fuel were oven dried at 60 °C for four days to calculate dry weight. Canopy bulk density (kg/m^3) in *P. contorta* invasions and *P. ponderosa* plantations was estimated using values in Scott and Reinhardt [32]. Live fuel moisture corresponds to values from February (i.e., mid fire season) recorded over three growing seasons for *P. ponderosa* foliage and two of the most representative steppe species (*M. spinosum* and *P. speciosa*) that were subsequently averaged. Live fuel moisture was calculated as follows [(fresh mass–dry mass)/dry mass] × 100. *Pinus contorta* live fuel moisture was assumed to be similar to that of *P. ponderosa* based on Qi, et al. [33].

2.4. Fire Behavior Modeling

We used the fire behavior modeling software BehavePlus 5.0.5 [21] to estimate differences in potential fire behavior among the five selected treatments. This simulation software is based on Rothermel's mathematical model of wildfire spread [34] and has been widely used to characterize potential fire behavior (e.g., [35,36]). BehavePlus 5.0.5 was used in this study to assess an envelope of possible fire behaviors rather than as a precise predictor of fire characteristics. We focused the comparison of fire behavior on the following variables: (i) surface and crown rate of spread (ROS, m/min), (ii) surface flame length (m), (iii) transition ratio to crown fire (dimensionless), and (iv) heat per unit area (kJ/m^2). Rate of fire spread and flame length are useful indicators of the difficulty of fire control, potential for fire escapes, and equipment required for suppression [37]. The transition ratio to crown fire indicates the probability of a surface fire to transition into a crown fire; and values equal to or above one suggest enough intensity to reach the canopy. Crown fires are inherently more difficult to control and imply a radical change in fire behavior in the native steppe. Heat per unit area is the heat energy released within the flaming front and is closely related to severity, providing an indication of the ecological effects of fire on vegetation and other organisms [38].

Fuel models for the five selected treatments were created by substituting fuel parameters into standard fuel behavior models [39]. Specifically, we used the low load, dry climate grass-shrub model (GS1) for the steppe, the long-needle litter model (TL8) for the pruned and unpruned plantations and the short needle litter model (8) for the high invasion and the removed high invasion sites. These models were selected due to the similarity to fuel conditions within each treatment. Except for the GS1 model used for the steppe, these standard fuel behavior models were originally created for North American conifers and thus are adequate for the fuel types and species found in pine plantations and invasions in Patagonia. We defined two contrasting fire danger scenarios: a high danger scenario with fine fuel moisture content of 5% and a 7-m wind speed of 20 km/h, and an extreme danger scenario with fine fuel moisture of 1% and a 7-m wind speed of 40 km/h. These scenarios were based on observed meteorological conditions during documented fires in the region [40]. The slope was set to 5% for all simulations because most plantations are typically located in flat or low angle slope terrain. Fuel load data for models were collected in October (i.e., austral spring) and not during peak fire season. Nevertheless, because of the virtual absence of live annual fuels within the closed canopy of plantations and high invasion levels, and the perennial condition of dominant species at the steppe, there is limited seasonal variation in fuel loads in these environments. Comparisons of potential fire behavior among the five selected treatments were conducted qualitatively because we only characterized one representative site per treatment.

2.5. Data Analysis

To relate fuel amount and structure to pine plantations and invasion, we computed mean fuel intercepts and mean horizontal fuel continuity using the fuel data collected with the point-intercept method. Mean fuel intercepts (%) for a given height class were calculated as the number of segments of that height class that were intercepted by fine fuels over the amount of points in the grid (30 points). We calculated this value for all the fuel types together, for live and dead fuels separately and for pine and non-pine species fuels separately. Mean horizontal fuel continuity corresponds to the mean distance between adjacent fine fuel intercepts in a given height class transformed to a percentage, where 2 m (minimum possible distance between two adjacent intercepts) is 100% connectivity and 10 m (maximum possible distance between two adjacent intercepts) is 0% connectivity. We calculated this value by pooling all fine fuel intercepts and species together (total fine fuels). Mean fuel intercepts and mean horizontal fuel continuity values were then averaged per height class among plots of the same treatment to plot their vertical distribution.

We used generalized linear mixed-effects models to compare the vertical classes of fuel and horizontal fuel continuity as response variables, and treatments (i.e., steppe, plantation, invasion and removed invasion) as a fixed factor. We also compared height classes between pruned and unpruned plantations, among the three levels of invasion and among the three levels of removed invasion. To simplify statistical analyses, original 0.25 m height classes were grouped into three broader height classes (i.e., 0–0.50 m; 0.51–2.00 m; 2.01–4 m). All models included "sites" as a random effect. Based on graphical analysis (i.e., residual vs. predicted values), all models satisfied the underlying statistical assumptions, including linearity and the expected relation of the variance to the mean given the nature of the dependent variable error distribution. The multiple mean comparison between treatments and conditions was conducted with Tukey tests (a = 0.05). All models were implemented with the statistical software R version 3.4.1 (R Core Team, R Foundation for Statistical Computing, Vienna, Austria) [41] using the function nlm from the package nlme [42] and the function glmer from the package lme4 [43].

3. Results

3.1. Fuel Characterization

Fine fuels in the native steppe were limited to the first 1.5 m and were more abundant and horizontally continuous within the first 0.5 m (Figures 1a and 2a). At the lowest height class (i.e., 0 to 0.5 m), fuel amount and horizontal continuity in the steppe were significantly higher than in the plantations and the removed invasion but similar to the invasion treatment (Figure 3a,b). Conversely, at higher height classes (>0.5 m) fuel amount and horizontal continuity were significantly lower in the steppe compared to the plantations and the invasion treatment, but similar to the removed invasion treatment (Figure 3a,b). For instance, for the 0.51–2.00 height class, mean fuel intercepts were 1% in the steppe and 4% and 17% in plantations and invasions respectively, while mean horizontal fuel continuity for the same height class was 5% in the steppe and 12% and 37% in plantations and invasions respectively (Figure 3a,b). Plantations had the lowest amount of fine fuels and horizontal continuity within the lower 0.5 m (except for litter) compared to all other treatments (Figure 3a,b). Pruned plantations exhibited a significantly lower amount of fuel across height classes compared to the unpruned plantations (Figure 3c). However, while there was no difference in mean horizontal fine fuel continuity between pruned and unpruned plantations in the 0–0.5 m height class, fine fuels were significantly more continuous horizontally for the higher height classes in the unpruned plantations (Figure 3d).

There were no significant differences in the amount of fine fuels across the vertical distribution and the horizontal continuity between low and intermediate invasions (Figure 3e,f). Low and intermediate invasion levels, each with mean (±SE) basal areas of 3.6 ± 0.2 and 12.1 ± 1.7 m^2/ha, and mean (±SE) ages of establishment of 12.4 ± 0.9 and 15.5 ± 1.4 respectively, did not form a closed canopy, generating a similar amount and horizontal continuity of fine fuels in the lower segments as in the uninvaded

steppe (Figure 1d,e and Figure 2d,e). On the contrary, high levels of invasion, with a mean ($\pm$SE) basal area and age of establishment of 27.8 ± 2.6 m^2/ha and 20.0 ± 2.7 years respectively, generated a closed canopy with vertically and horizontally continuous fine fuels largely composed of pine needles and twigs but less fine fuels within the first 0.5 m (except for needle litter) than the low and intermediate invasion levels (Figures 1f, 2f and 3e,f). Fuel amount and horizontal continuity of fine fuels at high invasion levels were significantly higher than those of low and intermediate invasions in the height classes above 0.5 m (Figure 3e,f). In the removed invasion treatments, regardless of the original invasion level, vertical and horizontal distribution of fine fuel resembled that of the native steppe but with significantly less fuels and less horizontal continuity (Figure 3a,b). Fuel amount was not significantly different among the three levels of removed invasion (Figure 3g) but horizontal continuity was significantly higher in the removed low invasion (Figure 3h).
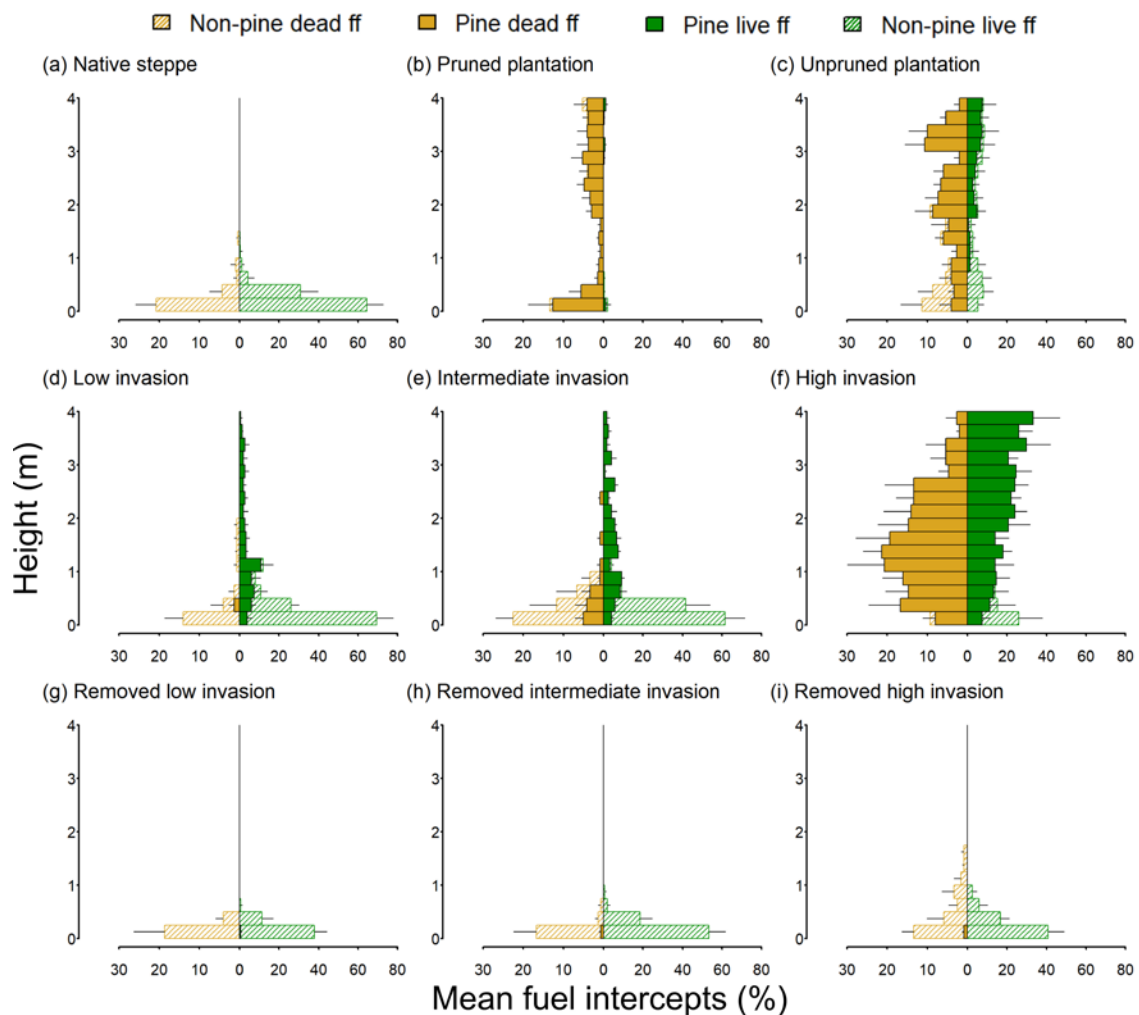
Figure 1. Vertical distribution of the mean fuel intercepts ($\pm$SE) at each of the nine treatments divided into 0.25 m height classes: native steppe (**a**), pruned plantation (**b**), unpruned plantation (**c**), low invasion level (**d**), intermediate invasion level (**e**), high invasion level (**f**), removed low level invasion (**g**), removed intermediate level invasion (**h**), and removed high level invasion (**i**). Bars represent mean dead and live fine fuel (ff) intercepts classified into pine and all fuels together.
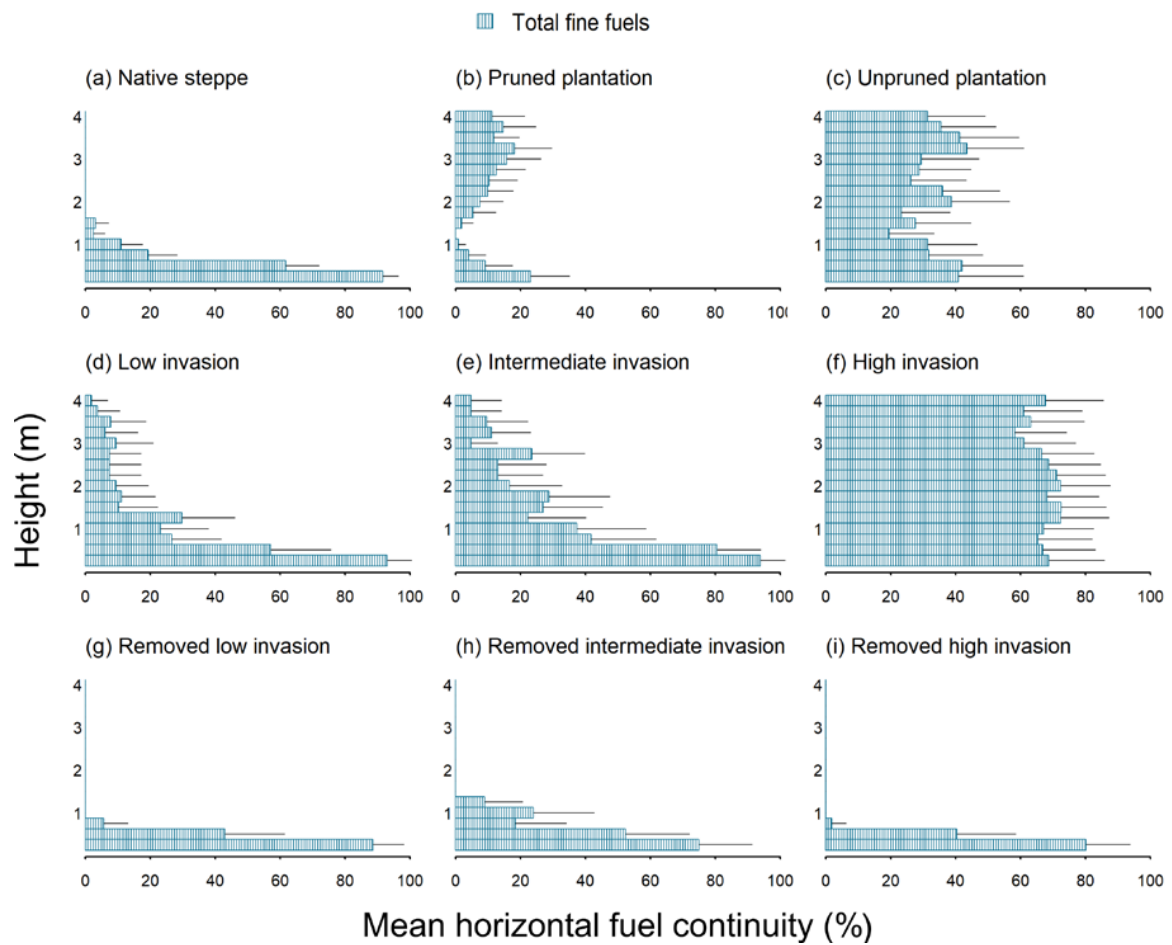
Figure 2. Mean horizontal total (live and dead) fuel continuity (expressed as a percentage) (±SE) for each 0.25 m height class at each of the nine treatments: native steppe (**a**), pruned plantation (**b**), unpruned plantation (**c**), low invasion level (**d**), intermediate invasion level (**e**), high invasion level (**f**), removed low level invasion (**g**), removed intermediate level invasion (**h**), and removed high level invasion (**i**).
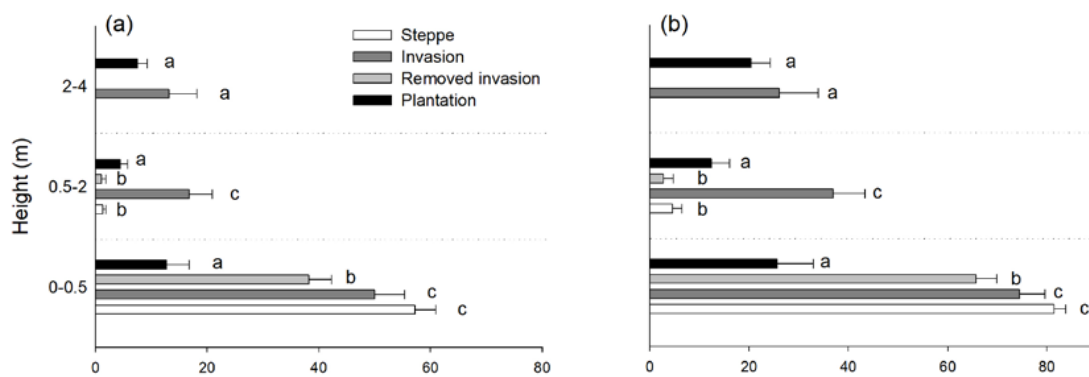
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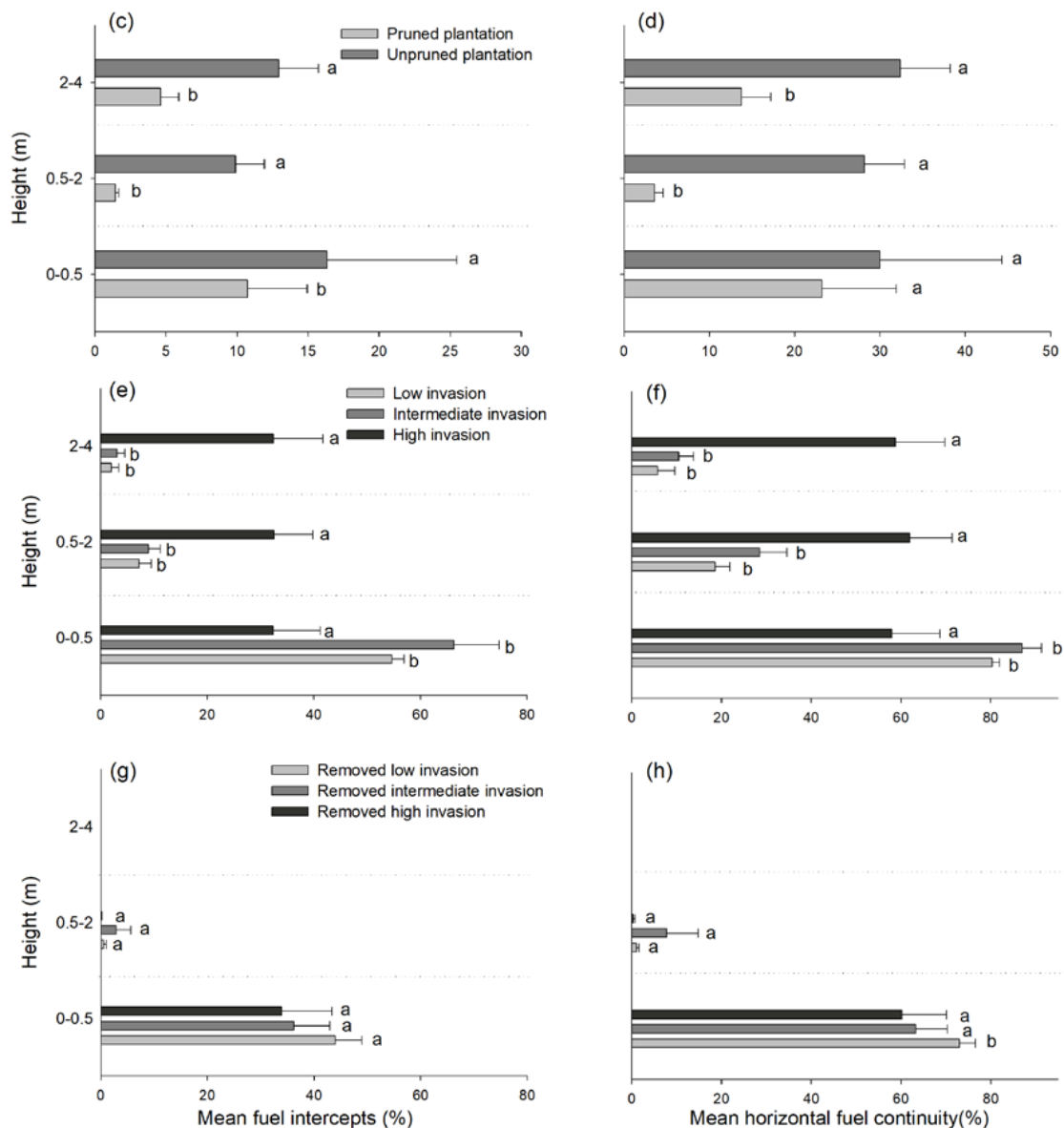
Figure 3. Vertical distribution of the mean fuel intercepts and mean horizontal continuity (±SE) of each treatment grouped into three height classes. Bars represent mean total (live plus dead) fine fuel intercepts. We evaluated the differences in fuel structure among steppe, invasion, removed invasion, and plantation treatments (**a**,**b**); between pruned and unpruned plantations (**c**,**d**); among the three levels of invasion (**e**,**f**); and among the three levels of removed invasion (**g**,**h**). Different letters indicate significant statistical differences ($p < 0.05$) among treatments within each height class based on the generalized linear mixed-effects models.

3.2. Fire Behavior Modeling

The most noticeable differences between the fuel model for the native steppe site and the fuel models for the pine stands (both invasion and plantations) stem from the absence of trees and the presence of grasses and short shrubs in the former (Table 2). The pruned plantation had a higher canopy base height compared to the unpruned plantation site (Table 2). The high invasion level site had higher tree density but lower basal area and shorter canopy base height compared to the plantation sites. The steppe site exhibited the lowest simulated surface ROS, flame length and heat per unit area compared to the plantations, the high invasion level and the removed high invasion (Table 3). Slightly higher fine fuel loads and fuel bed depth were recorded in the pruned plantation

compared to the unpruned plantation site, which originated higher flame length in the former. Despite the slightly higher flame length in the pruned plantation, the transition ratio to crown fire was larger in the unpruned plantation due to its lower canopy base height (Table 3). The high invasion site showed lower surface ROS, flame length and heat per unit area compared to the plantation sites. However, the low canopy base height of the high invasion stand resulted in a transition ratio to crown fire well above 1 in both fire danger scenarios, which is notoriously higher than in the plantations, implying high chances for fire crowning even if conditions are not extreme. Simulated crown fires in the three pine-dominated sites (i.e., high invasion, pruned and unpruned plantations) involved a ~30-fold increase in total heat per unit area (i.e., surface plus canopy) compared to the native steppe and exhibited three times faster crown ROS than the surface ROS in the steppe. The removed high invasion treatment had similar but slightly higher values of ROS, flame length and heat per unit area compared to the steppe (Table 3).

In order to verify if the simulated fire behavior was reasonably realistic for the treatments, we contrasted our results with available information collected during actual fires. Specifically, we compared ROS with reports conducted by firefighters which were gathered and analyzed by Sagarzazu and Defossé [40]. The simulated ROSs for the steppe and pine plantations are reasonable based on the estimated range of ROS of actual fires occurring in the region on similar vegetation types. For instance, estimated surface ROSs for actual fires on shrubby steppe (Río Percey, 1979 and Rinconada, 1998) were 2–3 m/min on a <5% slope with 20 km/h winds and 10–12 m/min on a <5% slope with 50 km/h winds [40]; while simulated surface ROSs in this study for similar conditions were 5.9 and 11.2 m/min respectively. For an actual fire in a pine plantation (Lago Puelo, 1987), estimated crown ROS was 30–46 m/min on 15% to 40% slopes with 40–50 km/h winds [40], while our simulated crown ROS for a 5% slope and similar wind conditions was 32.1 m/min.

Table 2. Description of the five selected treatments sampled for constructing the fuel models to simulate fire behavior. Fuel load values correspond to surface fuels only (<2 m height). nd: no data

Site/fuel variables	Steppe	Pruned Plantation	Unprunned Plantation	High Invasion	Removed High Invasion
Dominant Species	*M. spinosum/ P. speciosa/ A. splendens*	*P. ponderosa*	*P. ponderosa*	*P. contorta*	*P. speciosa*
Tree age (years)	-	~30	~26	~3 to 29	-
Tree density (ind/ha)	-	1220	1330	8400	-
Basal Area (m²/ha)	-	85.4	59.7	25.1	-
1 h fuel load (ton/ha)	0.45	1.61	1.41	1.22	0.96
10 h fuel load (ton/ha)	0	0.31	0.45	0.05	0.09
100 h fuel load (ton/ha)	0	0	0	0	0
Live herbaceous fuel load (ton/ha)	0.32	0	0	0.03	0.08
Live woody fuel load (ton/ha)	0.61	0	0	0.02	0
Fuel bed depth (m)	0.35	0.11	0.09	0.05	0.08
Canopy height (m)	-	13.8	12.3	11.2	-
Canopy base height (m)	-	3.25	1.62	0.27	-
Canopy bulk density (kg/m³)	-	0.16	0.16	0.18	-
Mid-season live woody moisture (%)	80	100	100	100	-
Mid-season foliar/herbaceous moisture (%)	140/62/nd	135	135	135	62

Table 3. Potential fire behavior in two contrasting fire danger scenarios (high and extreme danger) for the five selected treatments. High danger consists of a scenario with fine fuel moisture content of 5% and a 7-m wind speed of 20 km/h, while extreme danger implies fine fuel moisture of 1% and a 7-m wind speed of 40 km/h.

Fire Behavior Variables	Steppe		Pruned Plantation		Unpruned Plantation		High Invasion		Removed High Invasion	
	High	Extreme	High	Extreme	High	Extreme	High	Extreme	High	Extreme
Surface rate of spread (m/min)	5.9	11.2	16.6	38.8	11.4	24	7.4	17.1	7.7	16.5
Surface flame length (m)	0.6	1.0	1.6	2.6	1.3	2.0	0.9	1.6	0.6	1.4
Transition ratio to crown fire	-	-	0.49	1.45	0.89	2.35	6.66	20.19	-	-
Crown rate of spread (m/min)	-	-	9.9	32.1	9.9	32.1	9.9	32.1	-	-
Surface heat per unit area (kJ/m^2)	1033	1331	2549	3264	2306	2946	1870	2461	1478	1906
Canopy heat per unit area (kJ/m^2)	0	0	31435	31435	31822	31822	36638	36638	0	0

4. Discussion

Pine plantations and their subsequent invasion in the Patagonian native steppe produce sharp changes in vegetation structure and fuel loads. As expected, we found that pine plantations and invasion increase the amount and continuity of fine fuels above ~0.5 m height. Most interestingly, these changes in fuel attributes have the potential to affect fire behavior, increasing fire intensity (measured as heat per area) ~30 times compared to the intensity of fires in the native steppe. However, significant changes in fuel structure do not occur until advanced stages of invasion in which fire hazard, measured as transition to crown fire and total heat per unit area, surpasses that found in plantations. Our results also show that pruning of basal branches in plantations can substantially reduce fire hazard by lowering the probability of fire crowning, and that mechanical removal of invasion seems effective in restoring original fuel structure in the steppe, at least in the short term. Overall, pine plantations and invasions significantly alter the amount and structure of fuels in the native steppe, potentially allowing more severe fires. Nevertheless, adequate silvicultural practices and invasion management techniques can contribute to reduce fire hazard in these areas.

Pruning of basal branches was effective in reducing potential fire severity in *P. ponderosa* plantations by reducing the probability of fire transition to the crown. However, the slightly higher surface fuel loads found in the pruned plantation compared to the unpruned plantation originated from longer flames and higher ROS in the pruned vs. the unpruned plantation, most likely because pruned branches were left on the site for some time after their removal, thus increasing the amount of needles on the ground. This implies that pruning treatments without immediate removal of the residuals created by such activity may exacerbate fire hazard rather than ameliorate it [44]. Accordingly, adequate silvicultural management is needed not only to improve the quality of wood and the logistics of timber production but also for fire hazard mitigation [19,45]. Basic methods for fire mitigation in tree stands involve reduction of surface fuels, increasing the height to live crown and decreasing crown density [44]. Equally important for fire hazard mitigation in a plantation is the removal or thinning of adjacent invasions since these provide effective ladder fuels, substantially increasing the chances of a crown fire in the plantation. Thus, to mitigate fire hazard associated with plantations, an integrated approach is needed that not only includes management of the plantation itself but also control of the escaped individuals in the surroundings.

Pine invasion did not significantly alter fuel structure until advanced stages of invasion. A closed pine canopy was only observed at the high invasion level, with an average age of establishment of 20.0 ± 2.7 years. This is only 4.5 years more than the average age of establishment at intermediate invasion levels, which showed extremely low horizontal continuity at height classes above 0.5 m. This is consistent with a recent study conducted in native grasslands in the Chilean Patagonia, where fuel build-up generated by *P. contorta* invasions started growing exponentially between 15 and 20 years after invasion initiation [16]. Although we did not simulate fire behavior in low and intermediate levels of invasion, their fuel characteristics implies a much lower fire hazard compared

to high invasion levels [46]. The relatively rapid change in fuel conditions suggests the existence of a threshold in fuel build-up below which there is apparently no significant increase in fire hazard. However, once this proposed threshold is surpassed, fires may radically increase their intensity and severity in pine-invaded areas. The existence of this threshold for *P. contorta* invasions in the Patagonian steppe was previously shown by Taylor et al. [16], where simulated soil heating due to fire drastically increased after the invasion reaches 10 years [16]. In addition to increased fire hazard, high invasion levels significantly raise pine removal costs [47] and magnify the chances of positive fire-vegetation feedbacks [16], thus decreasing the probabilities of successful restoration of the native community. Therefore, it is critical to plan for an early control of pine-invaded areas before fuels reach the critical threshold.

Although the current area planted with pines in northwestern Patagonia is still relatively small (ca. 100 thousand ha), there are strong socioeconomic incentives to continue planting over an extensive area of ca. 800 thousand ha in the Patagonian steppe, near the ecotone at the Andean foothills [25]. Concurrently, pine invasions in northwestern Patagonia are at an incipient state but show strong trends of rapid expansion and densification [10,18]. Most densely invaded areas are still nearby plantations (i.e., a few hundred meters), but long-distance seed dispersed individuals (i.e., a few kilometers) that have already reached reproductive maturity are increasingly common across the landscape (pers. obs.). Furthermore, a large proportion of established plantations have not reached a reproductive stage yet, so more sources of invasion will be available in the near future [18]. These rapid changes in landscape cover will likely surpass landscape flammability thresholds in the future if no actions are taken. At this initial stage of plantations expansion and invasion spread, management practices have a realistic chance of lessening the potential consequences of increased fire hazard at a relative low cost compared to control measures applied at advanced stages.

Despite several native plant species in the forest-steppe ecotone showing post-fire regeneration strategies, elevated temperatures due to pine-promoted high intensity fire may still kill individuals of native species or slow down their rate of recovery [48]. This may promote further invasion and/or conversion from steppe to pine forest stands, as extirpation of native species due to death of belowground resprouting structures eliminates competition and favors pine establishment [49]. Moreover, many of the pine species planted and invading in Patagonia have fire-adapted life-history traits (e.g., serotiny) that enhance their colonization of post-fire native areas [50]. In pine-invaded sites or plantations, there are already documented reductions in the abundance and richness of native plant species. For example, in southern Chile, plantations and invasions filtered out most specialist and endemic plants [51,52], while in the forest-steppe ecotone of NW Patagonia in Argentina richness of herbaceous species has decreased almost 50% and abundance has decreased 70 times within plantations compared to the native steppe [53]. Therefore, the native steppe ecosystem becomes even more vulnerable to biodiversity loss considering the potential higher fire severity of pine stands, which may further eliminate the few surviving individuals of native species inside the planted or invaded stands.

Pine plantations and invasions are not only threatening the forest-steppe ecotone but also adjacent fire-sensitive native ecosystems. Increased connectivity and flammable landscape elements may threaten native forests in several ways. Pines are being planted near fire-sensitive tree species such as *Austrocedrus chilensis* and *Nothofagus pumilio* (Poepp. and Endl.) Krasser which may favor fire spread into these forests. Also in the region, native fire-resistant tree species such as the endangered monkey puzzle tree *Araucaria araucana* (Molina) K. Koch [54], are threatened by changes in fuel structure due to *P. contorta* invasions [20]. Therefore, spatially explicit models of fire spread are necessary to identify critical levels of invasion that may increase landscape level vulnerability of native ecosystems. Furthermore, spatially explicit models of fire spread can be used to test for the accuracy of fire behavior simulations by contrasting actual fire extension (size and shape) against modeled fires. Future research in Patagonia should combine quantification approaches of the effects of stand

structure and composition on fire behavior with the spatial characterization of fire spread and severity, especially in the context of climate warming.

Current climatic trends and forecasted warming scenarios for the southern hemisphere are associated with large and more severe fires [55,56]. The upward trend observed in the Southern Annular Mode (SAM), linked to current warming conditions, is tightlty coupled with fire activity in southern South American forests and woodlands, resulting in increased fire synchrony and activity [56]. Clearly, increased warming in Patagonia promotes low fuel moisture levels, favoring extreme fire danger conditions, such as the scenario described in this work, which in turn may allow more intense and severe fires. These changes occur in synergy with land use trends, such as the expansion of the wildland–urban interface and the increase in non-native plantations, implying increased anthropogenic ignitions and greater exposure of societies to wildfire hazards [9,57,58]. Adaptation measures such as fuel reduction in both planted and incipiently invaded sites following adequate silvicultural practices may sensitively diminish ecological and socioeconomic vulnerability to these altered fire regimes. Furthermore, these practices may reduce the probability of transition from native to novel pine-dominated states that could further result in more frequent and severe fire events.

5. Conclusions

Pine plantations and invasions in the Patagonian forest-steppe ecotone originate significant increases in fuel loads and produce changes in fuel structure affecting the potential behavior of fire. Wildfires in pine plantations or areas with high levels of pine invasion can increase the potential fire intensity ~30 times compared to the native steppe. This drastic rise in intensity may have profound impacts on post-fire regeneration due to the likely extirpation of the few native resprouting species in the understory. Pruning of basal branches can contribute to reducing fire hazard within plantations by lowering the probability of fire crowning. Likewise, the mechanical removal of invasion can result in a similar fuel structure to that of the native steppe. As pines are becoming ubiquitous in southern hemisphere landscapes and fire activity is increasing, active management to prevent unnaturally severe fires is urgently needed.

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