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The effects of replacing native forest on the quantity and impacts of in-channel pieces of large wood in Chilean streams

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Abstract

Dead trees in rivers can significantly affect their morphological and ecological properties by increasing flow resistance, affecting sediment transport, and storing organic matter. Logs are usually recruited from banks or along the entire upstream basin. Although it is generally acknowledged that forested headwater streams feature higher volumes of in-channel pieces of large wood, the influence of forest type and forest management of the potential recruitment zone on the volumes and effects of wood have been less explored, especially in relation to the effects of replacing native forests with pine plantations. This paper presents a comparison of volumes of wood, and characteristics and effects on streams draining paired basins with comparable slopes, areas, and hydrologic regimes, but different in terms of land use. The five selected pairs of basins are located in the Coastal and Andean mountain Ranges in central Chile, in order to compare native forest and pine plantation basins. The results show that logs tend to be shorter and with larger diameters in streams draining native forest basins. Because of their smaller dimensions, logs and jams tend to be more mobile and oriented parallel to the flow. Volumes of in-channel wood in native forest basins are only slightly larger than in pine plantation basins, and no differences have been identified in terms of morphological effects on channel geometry. Also, fish type and biomass were comparable among pairs. Evidence highlights the importance of the width of riparian

buffers in mitigating the effects of land use change, especially the substitution of native forest with plantations.

Keywords: Native forest, pine plantation, large wood, wood jams, fish, Chile

1. Introduction

In forested basins, in-channel pieces of large wood (LW, i.e. logs coarser than 0.1 m and longer than 1 m) can significantly affect the morphological and ecological properties of rivers. Logs, especially if jammed, can create steps (Rosenfeld & Huato, 2003), increase flow resistance (Cadol & Wohl, 2013), store organic matter (Tank et al., 2010; Beckman & Wohl, 2014), and increase the connectivity with floodplains (Sear et al., 2010). It has also been demonstrated that in-channel wood increases habitats and biological diversity (Gerhard and Reich, 2000; Cordova et al., 2007; Vera et al., 2014), principally by augmenting morphological diversity and complexity (Gurnell et al., 2002). Indeed, the presence of LW can increases fish number and biomass (e.g. Schenk et al., 2015), and engineered LW is commonly used in river restoration practices in order to increase fish biomass (Abbe et al., 2003). On the other hand, when massively recruited and transported during extreme events, LW is potentially dangerous to human infrastructure (Mazzorana et al., 2009).

Trees can be delivered to the river by natural mortality or after episodic events such as wildfires, windthrow and forest diseases, or localized mass movements on slopes in the form of landslides or debris flows (Hassan et al., 2005). As well, logs can be recruited into river systems from riparian areas through toppling and bank erosion (Jeffries et al., 2003). When recruited, LW can be transported downstream for a distance that depends on the stream power (Merten et al., 2010), the relative size of the logs compared to the stream (Bocchiola et al., 2006; Wohl & Goode, 2008), and the degree to which logs are already jammed (Gurnell et al., 2002). Log recruitment and transport processes vary spatially and temporally depending on type, magnitude and frequency of processes occurring at the basin scale (Wohl & Jaeger, 2009). Several attempts have been recently made to organize this into conceptual (e.g. Benda & Sias, 2003) or numerical models (e.g. Mazzorana et al., 2010; Rigon et al., 2012). Generally, forested headwater streams (< 20 km^2) feature higher volumes of wood, and logs are less jammed than in downstream reaches. This has been related to the considerable recruitment of logs due to high connectivity with colluvial processes occurring on slopes, and with the transport-limited conditions for wood in such environments (Marcus et al., 2002; Abbe & Montgomery, 2003; Hassan et al., 2005; Wohl & Jaeger, 2009; Rigon et al., 2012).

The volume of LW in forested basins clearly depends on the type, age, and management of the forest cover. In general, old-growth forests feature a multi-layered canopy with taller and larger diameter trees that supply larger volumes of wood to rivers, which in turn can trap more floated logs, resulting in higher volumes of in-channel wood (Wohl & Beckman, 2014). Jackson & Wohl (2015) recently reported higher wood loads in old growth rather than in younger growth forests in the Southern Rocky Mountains (US). However, there is little evidence in the literature on the effects of land use changes on the loads of in-channel wood. For instance, Burrows et al. (2012) showed that streams draining clear-cut eucalyptus basins have greater abundance and volumes of wood than old-growth basins. Nevertheless, there is less field evidence for the effects of native forest replacement with exotic species. There has been extensive study of the effects of substituting native forests with exotic forest plantations on different biota and ecological processes (Lindenmayer et al, 2000; Brockerhoff et al, 2003; Vertessy et al, 2003; Vergara & Simonetti 2004; Arevalo & Fernández-Palacios, 2005) by comparing plots established on plantations and adjacent native forests. Evidence show that fish communities can also be affected by pine plantations due to changes in nutrient concentration, shading, amount and quality of organic matter inputs, and that these negative effects can be mitigated by the maintenance of a riparian vegetative boundary (Davies & Nelson, 1994; Lee et al., 2004). These studies have mainly reported reductions in biodiversity in plantations depending on the management and silvicultural methods. In spite of these studies, much less evidence is available on the impact of native forest substitution by forestry plantations at the basin scale, and especially on how this is reflected at the channel-reach scale. For example, Baillie & Davies (2002) compared basins with native and pine plantation forest covers in New Zealand and reported higher volumes of LW in pine plantation basins. However, eco-morphological effects appeared to have been greater in the native forest basins. Evidence on this for the Andean region is virtually absent. *Pinus radiata* D. Don (*P. radiata*) comprises almost 1.5 of the total 2.7 million hectares of planted forest (INFOR, 2009). Replacement of native forest by pine plantations in Chile has occurred mainly in Andean areas as native forests in coastal areas were largely eliminated before the development of plantations

(Donoso & Lara, 1995). Final harvest of *P. radiata* plantations in Chile is mainly based on clearcutting, as in most countries where this species is cultivated.

The main objective of this study is to assess the impacts of substituting native forests by pine plantations on in-stream large wood and related eco-morphological effects. To achieve that, we compared the characteristics of in-channel LW in streams draining paired basins that are different in terms of land use. The paired-basin study involved the use of five pairs of basins where the pairs were similar in terms of slope, aspect, soils, drainage area, climate, hydrologic regime, and located as close as possible to each other. Five pairs of basins were selected in this study to maximize the difference in terms of land use (native forest *vs.* pine plantation). This paper focuses on the impact of vegetation changes at the basin scale on the amount, size, and effects of in-channel wood in the Andean and Coastal Ranges of Chile.

2. Materials and methods

2.1. Field sites

The study was carried out on 5 pairs of basins, with draining areas ranging from approximately 2 to 20 km^2 (Table 1), located on the Andean and Coastal Ranges (3 and 2 pairs, respectively), with latitudes ranging from 35°32' to 37°34' (Figure 1). The drainage area, stream order, and main slope of the studied basins were determined with a digital elevation model (30 m size cells) using GIS software. The percentage of forest cover was derived from visual interpretation of recent aerial photos. Although most of the basins with native forest featured nearly the whole area covered with this forest type, nearby basins with plantation that could be selected in this study have areas covered by pine of about 60-75%. Basins with pure pipe plantations are rare in the area, especially because riparian areas are protected by law.

According to Gajardo (1994), all the studied sites are classified in the deciduous forest region, a temperate forest area dominated by deciduous species such as *Nothofagus obliqua*, *N. glauca*, *N. alpina*, and evergreen species like *N. dombeyi*, *Cryptocarya alba*, *Aextoxicon punctatum*, among others. All the watersheds with replacement, previous to planting *P. radiata* on the slopes, were covered with native vegetation, so that any changes registered in the watersheds are attributable to the replacement of native forests by plantations of pine trees and the activities associated with their management. At the time of the surveys, the plantations were between 12 and 18 years old and all had experienced only one rotation, or clear-cut and replanting. In all cases, the method of harvest is clear-cutting. Tress in the pine plantation areas have mean height of approx. 20 m and mean diameter of 25 cm. Although the height of trees is not available for all study sites, the mean diameter of trees in the riparian area and the slopes along the study reaches is reported on Table 2.

According to Gutierrez & Becerra (submitted) the most common native species present on the riparian areas of the 10 basins were *A. punctatum*, *Aristotelia chilensis*, *Citronella mucronata*, *Cryptocarya alb*a, *Lomatia dentata*, *Luma apiculata*, *Chusquea quila*, *Boquila trifoliolata*, *Cissus striata*, *Hydrangea serratifolia*, *Lapageria rosea* and *Lardizabala biternata*. The most common exotic species were *Rubus ulmifolius*, *Rosa moschata*, *Prunella vulgaris* and *Rumex acetosella*.

Although the median size of trees is comparable on riparian forest along the streams draining basins with native forest and pine plantation, riparian forests in pine plantation basins feature lower density of trees, lower diversity of tree species, lower regeneration of tree species, and higher richness of exotic species than in watersheds without replacement of native forest (Gutierrez & Becerra, submitted).

The northernmost pair on the Coastal Range is located at the estuary of the River Itata (IT). The two basins are approximately 5 km^2, and are only 5 km apart. The basin with native forest (IT-NF) features a deciduous Mediterranean coastal forest but 38% of the basin area is covered by almost mature *Pinus radiata*. In the paired basin (IT-PP), the forest cover is dominated by pine plantation (75%), and a fourth of this area was bare due to a clear-cut that took place two years before the surveys. There is still native forest in 25% of the basin, especially in the lower part and along the river network, which is quite developed, considering that the stream is an order 4, despite the small size of the basin (5 km^2).

The second pair of basins on the Coastal Range is located in the Trongol Valley (TR). The native forest in this area (TR-NF) is completely covered by mixed deciduous coastal forest. Although there were no visible scars of landslides or debris flows in recent aerial and satellite images, field evidence (e.g. typical depositional levees, and the presence of large boulders) suggests that debris flows have occurred in the past in the main channel. The pair basin (TR-PP) is located 4 km apart from TR-NF, and 60% of its area is covered by mature pine plantation.

On the Andean Range, the southernmost pair of basins is located in the Rio Cato Valley, a tributary of the Ñuble River (NI). Some 71% of the surface area of the plantation pair

(NI-PP) is covered with pine plantation, 10% of which was clear-cut at the time of the surveys, mostly in its uppermost part.

A further pair on the Andean Range is located in the Achibueno Valley (PE). The basins are around 3 km^2, are at similar altitudes, and are less than 5 km apart. The native forest in this area (PE-NF) is completely covered by Andean Mediterranean deciduous forest. Its pine plantation counterpart (PE-PP) is planted with *P. radiata* on 66% of its surface, which had been clear-cut for the first time just a year before this study.

The basins of the last pair on the Andean Range the basins are approximately 30 km apart, and the range of elevations differs more than in the other pairs. Around 67% of the native forest basin (AN-NF) is covered by the Andean Mediterranean deciduous forest up to 1200 m a.s.l., above which the basin is almost bare. Pine plantations cover 68% of the pair basin (AN-PP), and native forest is concentrated on the highest part of the basin and along the river network.

2.2.Field data collection

A segment of at least 370 m of every studied basin was surveyed between November 2013 and February 2015 (see Table 2). Between 6 and 12 reaches were selected at every basin. The reaches were defined as uniform in terms of slope, channel width, channel morphology and abundance of in-channel wood. The lengths of the reaches were generally approximately 10 times the bankfull width (Table 2). Longitudinal profiles and three cross-sections per reach were surveyed using a laser distance meter with clinometer and a prisma pole. The cross-sections were measured in order to calculate the average bankfull width and depth, and the average fluvial corridor width of all the reaches. The longitudinal profiles were used to count the number of steps and pools and to calculate the longitudinal area of pools.

Pieces of wood lying both in the active channel and the adjacent active floodplain were measured if the diameter was greater than 10 cm and the length was greater than 1 m, as previously done in similar field studies (e.g. Comiti et al., 2008; Mao et al., 2008; Iroume et al., 2010; Wohl et al., 2010). Logs lying alone on the bed were classified as single logs, whereas if two logs were grouped or in contact, they were classified as jammed. All single logs and logs belonging to jams were measured. The length and mid-diameter of every log were measured with a tape and a tree caliper, respectively. The volume of each log was calculated from its mid-diameter and length, assuming a solid cylindrical shape. The size and volume of rootwads present were measured and the volume was added to the volume of the log.

Several other measurements were recorded for each piece of wood during the field survey, including the type of piece (log, rootwad, log with rootwads), tree species (broadleafs *vs.* conifers), orientation to flow (parallel, orthogonal, oblique), state of decay (fresh, semi-decayed or old log), and position (within or outside the bankfull line). The most probable recruitment mechanism that delivered the log into the channel was determined in the field as landslide, debris flow, bank erosion, natural mortality, artificial cutting, or transported from upstream.

Jams were defined following a simplification of the Abbe & Montgomery (2003) classification, which distinguishes autochthonous jams (i.e. key wood elements not fluvially transported from upstream), allochthonous jams (i.e. key elements previously transported from upstream) and combination jams (autochthonous key elements with racked transported pieces). For transversal logs and jams forming a step in the profile, the volume of the downstream pool and the volume of sediment stored upstream were estimated as a solid wedge by measuring their length, width, and depth using a tap measure.

At all the studied sites fish was sampled in the summer along a 100m-long reach blocked with nets at the up- and down-stream ends, using a standard double-pass electrofishing technique (HT-2000 Battery Backpack Electrofisher device, Halltech Aquatic Research Inc.). All fish were identified at the species level, measured for total length, and weighed before being returned to the river.

3. Results

3.1. Dimensions and type of log pieces in the studied rivers

The average diameters of in-channel logs ranged from 10 to 25 cm, while the maximum diameters range from 15 to 80 cm (Figure 2). Taking average diameter into consideration for comparing native forest- and pine plantation-dominated basins, a F-test confirms that the average diameter was significantly greater in native forest basins in the AN and NI pairs, while the maximum diameter was significantly coarser in the native forest basins of the TR, AN, and NI pairs (Figure 2, Table 3).

In-channel logs were generally longer in basins where pine plantations predominate. Figure 2 shows that the average length of logs surveyed in the studied rivers ranged from 2 to 4 m, and the average length of logs in basins with pine plantation was greater than those from natural forest basins (statistically significant differences in pairs IT and TR, Table 3). If we take into consideration the longer logs surveyed at the studied reaches, pine plantations basins had significantly longer logs only in the pairs IT and PE (Figure 2, Table 3). However, in all but one case, the longest logs per reach (generally between 5 and 20 m long) were always pine species, and the longest log surveyed was a pine species of over 30 m in the PE-PP channel.

With the exception of AN, the percentage of pine logs was higher in basins with pine plantation (Figure 3; Table 3). This is especially true for the IT pair, where in the pine plantation basin more than 80% of the in-channel logs were conifers (more rounded and straight than native species, and with smaller branches). Figure 3 also shows that logs in native forest basins were in a poorer state of conservation in three of the five study pairs (AN, PE, and NI).

3.2. Volumes, abundance, and degree of accumulation of logs in the studied rivers

Figure 4 shows the volume of large wood surveyed in the studied sites. To compare reaches of different lengths and widths, volumes are expressed in terms of channel area units (length and bankfull width of the reach). The volumes of wood at the studied reaches varied by a magnitude of two orders, ranging from 6 m^3 ha^{-1} in a reach of the IT native forest basin to 1780 m^3 ha^{-1} in a reach of the TR native forest basin. The volume of logs does not appear to depend on the location of the basins (Coastal vs. Andean Range), but in three of the five pairs (TR, PE and NI) LW volumes in streams draining native basins were nearly double that in the pine plantation basins (Table 3). However, LW volumes were significantly higher in the pine plantation basin of the IT pair (Table 3).

Volumes of wood in the studied sites can be compared to other evidence gathered in Chilean streams over the last decade. In particular, data on volumes of in-channel wood are available for five other basins comparable to the studied sites: Tres Arroyos (9 km^2, 64% with native forest; see Andreoli et al. 2007 and Comiti et al., 2008), El Toro (17.5 km^2; 100% with native forest, see Andreoli et al., 2007), Vueltas de Zorra (in the Coastal Range, 5.87 km^2, 75% with native forest; see Iroumé et al., 2011 and Ulloa et al., 2011), Pichun (a pine plantation basin of 4.3 km^2 in the Coastal Range; see Iroumé et al., 2011 and Ulloa et al., 2011), and Milico basin, (in the Andean Range, 1.5 km^2, 40% with native forest, being the rest above the timberline; Gomez, 2013). Figure 5 shows that in small mountain basins (< 15 km^2) in-channel volumes of large wood can vary by three orders of magnitude, ranging from 10 to 1000 m^3 ha^{-1}, with a weak tendency toward a reduction of large wood storage with greater basin area ($R = -0.12$; $p > 0.66$). Basins with dominant forest cover tend to feature higher volumes of LW (F test = 1.855; $p = 0.19$). However, basins with a higher percentage of native forest do not necessarily have higher volumes of LW, as volumes can vary quite dramatically (two orders of magnitude) even in basins with pure pine plantation.

There were no significant differences in single log volumes between the native forest and pine plantation forest pairs at any of the five sites (Figure 4, Table 3). As well, no significant differences between native and pine plantation basins were found in terms of volumes of jammed logs, and significantly higher volumes of jammed LW were only found in the NI native forest.

Because LW volumes depend on both the number and dimension of logs, it is worth considering the number of logs and jams. Figure 6 shows that there were no significant differences between native forest and pine plantation basins in terms of the number of isolated logs, except for the TR basin (Table 3). The only site with a significant difference in the number of log jams was AN, where the number of log jams was higher in the plantation forest site.

Figure 7 shows the percentage of logs recruited from the banks/slopes or from upstream reaches (i.e. floated by previous flood events). It appears that in the IT, TR, and NI pairs, a higher percentage of the logs were most likely to have been transported in streams draining native forest basins than from the plantation forest basins. Figure 7 also shows that in four of the five pairs, logs in native forest basins tend to be more parallel than those in pine plantation basins (statically significant differences were found for the IT and AN pairs; Table 3).

Figure 8 shows that jams tended to be more autochthonous in pine plantation basins in the AN, NI, and TR pairs, but this difference was statistically significant only for NI. As to the orientation of jams, Figure 8 shows that logs tended to accumulate in a direction parallel to the flow in native forest basins of the TR, AN, and PE pairs (the difference is statistically significant only for AN; Table 3).

3.3. Eco-morphological effects of in-channel logs

In the studied sites, no clear evidence of differences were observed between streams draining native forests or pine plantations in terms of the number or dimensions of steps and pools. Retention of sediments due to jams was not significantly different in native forest vs. pine plantation basins. Indeed, Figure 9 shows that the ratio between the volume of trapped sediments and the volume of jammed logs is between 1 and 3, with no significant differences among basins, except for TR. The remarkable value (around 7) obtained for the native forest basin of the TR pair is due to the massive amount of sediments coming from debris flows and trapped by jams.

A total of three fish species were encountered in all ten watersheds, namely rainbow trout (*Oncorhynchus mykiss*), brown trout (*Salmo trutta*), and the Chilean catfish (*Nematogenys inermis*). Two of the three species were encountered in all watersheds, except for Las Arañas (TR-NF), where no fish were found. Rainbow trout (*O. mykiss*) were found in all sites except TR-NF, brown trout (*S. trutta*) were encountered in six sites (IT-NF, NI-NF, NI-PP, PE-NF, PE-PP, and TR-PP), and Chilean catfish (*N. inermis*) were found in two sites (AN-PP and IT-PP). If the fish biomass per unit effort (BPUE: g 250 m^{-2}) is considered, a total of 1250.7 g of fish per 250 m^{-2} of stream were found in native forest streams, whereas 1088.8 g of fish per 250 m^{-2} of stream were found in pine plantation streams (Figure 10). The difference in biomass (161.9) is not significant (two-sample t-test = 0.42; p = 0.69) between the two land uses. In assessing the associations between fish BPUE and LW volumes, sites TR-NF and NI-PP were both excluded as outliers. The volume of large in-channel LW did not correlate significantly with the number of species or BPUE in any of the watersheds, regardless of dominant land use. Only two factors appear to be significantly related to fish BPUE, namely maximum log diameter (F=7.57, P=0.03, R^2=0.58) and maximum log length (F=3.75, P=0.10, R^2=0.42) (Figure 10).

4. Discussion

4.1. Dimensions and type of log pieces in native forest vs. pine plantation basins

The results of the comparative analysis of paired native forest *vs.* pine plantation basins suggest that pieces of large in-channel wood tend to have larger diameters in the native forest basins. This can be related to the fact that native forest basins naturally tend to feature older and coarser plants that are unlikely to be left growing in basins with pine plantations. Indeed, in four of the pairs the mean diameter of standing trees on the slopes is larger in the native forest than in the pine plantation basins. Even if the riparian area is left untouched, it is generally less likely to include very old and large plants in close proximity to the channel (due to higher frequency of flood disturbances) rather than on the slopes. In fact, in four of the pairs the mean diameter of trees growing in the riparian area is larger in the native forest than in the pine plantation basins On the other hand, in-channel logs tend to be longer in basins with pine plantation. This is probably due to the fact that many pine logs are recruited from the slopes or after clearcutting (many pine logs were artificially cut), and were therefore generally longer than native species, and in a better state of conservation. There was generally a higher percentage of in-channel logs in a poor state of conservation in native forest basins (i.e. without branches and bark, and with porous/rotted wood), which makes it easier for the flow to break up longer logs during floods. In support of this observation, field evidence suggest that at least in three of the five pairs, logs are predominantly transported from upstream reaches in native forest basins, whereas in pine plantation basins logs were recruited more from banks and slopes than transported from upstream. There is no clear explanation as to why the AN and PE pairs feature more floated logs in the pine plantation basins, but at least for the AN pair this could be due to the generally smaller dimensions of logs in the pine plantation basin.

Overall, there are weak indications that logs tend to be more parallel to the flow (i.e. logs have been transported from upstream, e.g. Francis, 2007) in native forest basins, while logs in pine plantation basins tend to be more oblique or perpendicular to the flow, indicating that they have been in the channel for less time and are close to the point of recruitment from the banks or slopes. However, the results obtained in our field investigation do not provide unequivocal evidence that there were more transport or combination jams in native forest basins, and that log jams were not predominantly oriented parallel to the flow in native forest basins, as one might expect if logs were relatively smaller and more mobile in native forest basins. Beside, the presence of complex branches in broadleaf species of native forest basins could reduce the mobility of logs if compared with conifers (Dixon and Sear, 2014).

Results show that there were no significant differences between native forest and pine plantation basins in terms of volumes of jammed logs or the number of log jams. The number of log jams per ha of stream ranged from o to more than 200, and significant differences could be identified among pairs. In AN, the very low number of jams in the native forest basins could be caused by the higher discharges (due to the larger basin area) and more likely by the wider bankfull, which reduces the chances of large logs being trapped by the banks and creating jams (as logs tend to be more mobile at smaller piece length/channel width ratios, e.g. Bocchiola et al., 2006; Dixon & Sear, 2014). The considerably higher number of jams in both TR pair basins (around 100 jams/ha; i.e. around 80 jams/km) helps explain the high LW volumes in both, even though log diameter and length were comparable to those in the other studied pairs. This high longitudinal frequency of jams is due to high recruitment of logs and to the presence of potential “trapping” sites. Montgomery et al. (2003), the number of logs per unit of channel length decreases with increasing basin area, and has been reported to be as high as 400 jams/km. The very high number and volumes of LW elements could be related to the fact that the two TR basins are the smallest among the selected pairs. Following the conceptual model of longitudinal distribution of wood proposed by Wohl & Jaeger (2009), higher LW volumes are likely to be found in narrower and steeper streams, and LW volumes tend to decrease downstream. Wohl & Jaeger’s (2009) model also suggests that the percentage of jammed wood increases with drainage area and channel width due to the higher capacity of logs to be transported. The fact that the TR pair featured the highest number of jams may thus be related to an unlimited transport capacity condition due to extreme events such as debris flows that transport large amounts of sediments and logs. This seems especially true for the native forest TR basin, where some reaches were depleted of logs while others had large debris jams (*sensu* Abbe & Montgomery, 2003). As expected, the percentage of floated logs reached 80% of the total number of logs in the native basin of the TR pair, which is affected by debris flows.

4.2 Volumes of logs in native forest vs. pine plantation basins

Results from the studied basins showed that LW volumes varied considerably among basins and sites and by more than two orders of magnitude among reaches (from 1.8 to 639 m^3/ha in two reaches of the IT PP basin). Indeed, as previously demonstrated, the volume of logs in a river can vary dramatically among reaches depending on the local slope and width (e.g. Wohl & Jaeger, 2009) or the location of log recruitment points (e.g. Comiti et al., 2006). However, if volumes are averaged among reaches, evidence from the field indicates that native forest basins had larger volumes than pine plantation basins. This is true for at least three of the five pairs of basins (NI, PE, TR). Exploring the reasons this did not hold in the other two pairs (AN and IT) could shed light on the processes involved in determining these differences in volumes.

The AN basin covered with native forest is the highest, largest and steepest of the studied sites, and almost half of it is above the timberline. Here the LW volume was small, probably due to frequent high magnitude floods, and especially to the lower log length to channel width ratio. The AN pine plantation basin featured a wider riparian area along the studied reaches (more than 60 m), and this seemed wide enough to isolate the channel from the processes and land use changes occurring at the basin scale. In fact, even if the pine plantation was close to the studied reach (less than 20 m from the riparian buffer and less than 40 m from the upper part of the studied reach), no conifers or chainsaw-cut pieces were found in the AN pine plantation basin.

As in the AN pair, the native forest covered basin of the IT pair feature less in-channel wood. In this case, the pine plantation is also very close to the studied reach, but more importantly the riparian buffer along the reach is as narrow as 20 m (one of the narrowest among the studied sites), and the clear-cutting of the pine plantation occurred mostly in 2013, thus dramatically increasing recruitment from the slopes. This is corroborated by the observation that nearly 90% of in-channel logs were pine and most of them appeared cut by chainsaw. A further indication that the proximity and connectivity of pine plantation patches to the main channel is important in determining the presence of in-channel pine logs is provided by the native forest basin of the TR pair, where the percentage of pine plantation is very low (i.e. only 1% of the basin area), but conifers represent almost 18% of the in-channel logs as the patch of pine plantation is close to the studied reach (around 25 m).

Results show that volumes of large wood in the mountain basins of the Andean and Coastal ranges of Chile tend to be smaller on streams draining larger basins. Higher volumes of large wood in headwater streams have been related in literature with the fact that logs are only occasionally transported as they have high length to channel width and diameter to water depth ratios, limiting their mobility (e.g. Baillie et al., 2008; Wohl & Jaeger, 2009). Volumes of large wood in small forested basins of Chile range from 10 to 1000 m^3 ha^{-1}, with an average value or around 100 m^3 ha^{-1} for basins of 5 km^2, being the Tres Arroyos an outlayer with more than 1000 m^3 ha^{-1} (Andreoli et al., 2007). This range of volumes is lower than values reported for the Pacific Northwest (Nakamura & Swanson, 1993; Czarnomski et al., 2008) or Colorado (Jackson & Wohl, 2015), but are similar to other unmanaged mature hardwood forests (e.g. Gurnell, 2003), and higher than managed basins in the Europe, which feature volumes < 100 m^3 ha^{-1} (e.g. Comiti et al., 2006, Diez et al., 2001).

4.3 Eco-morphological effects of in-channel logs in native forest vs. pine plantation basins

Regarding the morphological effects of wood, no clear evidence has been found of significant differences between native forest and pine plantation basins, either in terms of pool formation or sediment retention. There are only a few examples in the literature of direct comparison of large pieces of in-channel wood in basins with different land uses, the most interesting being a study comparing large wood volumes and morphological effects on native forest and pine plantation streams in the Nelson Region of New Zealand (Baillie & Davies, 2002). Baillie & Davies (2002) found that logs were relatively shorter and had a more parallel orientation to the flow in native forest basins, due to the fact that pieces has more time to break down and be transported fluvially. They found higher volumes of LW in pine plantation basins, but logs in native forest exerted significantly more morphological effects, especially creating more numerous and deeper pools. This is related to the fact that *P. radiata* wood is generally more degradable than that of *Nothofagus* species. However, the morphological effects of in-channel logs do not necessarily depend only on the large wood volume, as the slope and width of the channel and the size of sediments are also important. For example, Scott et al. (2014) recently showed that the height of log steps strongly depends on the size of sediments in the channel, demonstrating that logs in second-growth basins can form log steps high enough to exert morphological influences on the channel comparable to old growth forest basins if coarse sediments are available in the channel. Jackson & Wohl (2015) also showed that that streams draining old-growth forests feature higher volumes of in-channel wood and more and larger jams. Even if un our study we could not compare unmanaged *vs.* managed forests of the same type native trees are not used for artificial plantations for commercial use in Chile, the main findings of the present study are also corroborated by the study of Benda & Bigelow (2014) of different practices of forest management in small mountain basins of northern California. They showed that forest management influences stream wood dynamics, logs being smaller and less abundant in managed forests. Because in our study the native forest were always unmanaged, in

In terms of the fish populations in the studied basins, there appears to be little difference between dominant land use and fish biomass in the studied Chilean headwater systems. The total number of species in any given sampled headwater was necessarily low, due to relatively limited available habitat, the relatively low level of diversity in Chilean rivers (e.g. Dyer, 2000; Habit et al., 2006), and the invasive role that trout play in Chilean streams (Habit et al., 2010).

Because the pairs of basins lied at approximately the same elevations and have comparable slope, size, and order, the dominant physical conditions affecting fish species presences are likely to be very similar. As well, riparian vegetation along the streams is at least 20 m wide, providing heavy shading to the watercourses, meaning that the waterways experienced very little heat gain in both pine plantation and native forest basins, providing both with low and stable water temperatures. Thus, although differences in forest cover at the basin scale are likely to change the allochthonous energy sources between native forests and pine plantations, this is not reflected in statistically significant differences in the amount of fish biomass, number and diversity of fish between native and pine plantation basins within the studied sites.

4.4 Management implications

Among other authors, Whiles & Wallace (1997) have shown that converting native forest to an exotic monoculture can influence benthic taxonomic composition. For instance, in low-order streams in central Chile, Mancilla et al. (2009) found significantly higher diversity of macroinvertebrates in channels draining basins with native vegetation than in basins with exotic species. Similarly, studying mountain streams of Argentinian Patagonia, Miserendino & Masi (2010) found that shredders were more abundant in native forest rather than in pine plantation basins, and Valdovinos (2001) found more shredders in native forest than in *P. radiata* basins in Chilean streams. Martinez et al. (2013) found lower densities of shredders in streams of the Cordillera Cantábrica (Spain) where native vegetation had been replaced by pine plantation. However, all these studies stress the importance of riparian vegetation along the river network, which can buffer the effects of land use changes at the basin scale, especially by providing coarse particulate organic matter to the streams, including large wood.

Studying wood recruitment and transport processes in small forested mountain basins of California, Benda & Bigelow (2014) found that most wood recruitment occurs in a buffer narrower than 50 m along channels, and that landslides can extend the main source distance. Jensen et al. (2014) also showed that the volume of wood in small streams (< 30 km^2) of the Upper Little Tennessee River strongly depends on the type and dimension of trees in the riparian area. They further suggested that the 10-m-wide buffer around reaches is the most important source of wood recruitment. Other authors (Diez et al., 2001; Roth et al., 1996) have recommended wider buffers (20 to 30 m) in order to allow abundant recruitment of large and coarse logs to rivers.

Current Chilean legislation recognizes the importance of protecting riparian areas in order to preserve the multiple ecosystem services they provide. Romero et al. (2014) noted that references to the protection of riparian vegetation in Chilean legislation date back to 1931 (e.g. Pellet et al. 2005). However, legislation on this topic is now abundant, but fragmented, and lacking coherence (Romero et al., 2014). Current riparian conservation regulations for plantations of *Eucalyptus* spp. and *Pinus radiata* D. Don require a buffer of 25 m on both sides of the channel. The width of this protected area for rivers in forested areas is 30 and 15 m on both sides for permanent and intermittent rivers, respectively (Gayoso & Gayoso, 2003; Pellet et al. 2005). This buffer extends to 200 m for steep basins with risks of slope instabilities. Still, it is possible to better define these buffers and to specify standards for restoring riparian areas (Romero et al., 2014). As well, there is no legislation regulating the removal of logs from channels. Evidence suggests that maintaining a wide riparian forest is crucial for maintaining positive ecological functions of channels and for allowing abundant recruitment of large woody elements of native species that can exert strong geomorphic influence on channels. Accordingly, snag removal should be discouraged, especially from small streams that supply wood to downstream reaches, and where transport of potentially risky large elements is less likely due to the high ratios between log diameter and water depth and between log length and channel width (see Gurnell et al., 2002; Ulloa et al., 2011). Indeed, as reported by Mao et al (2013), log removal and riparian vegetation clear cuts are not effective strategies for reducing hazards since high-magnitude events are able to recruit trees from hillslopes due to mass wasting processes (Lucía et al., 2015). A valuable alternative is wood retention measures such as rope net barriers and filter dams (e.g. Mao et al., 2013) to protect sensitive local infrastructure.

5 Final remarks

This paper presents novel evidence gathered from field surveys in five pairs of basins in Chile on how land use changes, and in particular the substitution of native forest by pine plantation, can affect the volume and degree of organization of large wood in the streams draining these basins. The results show that in streams draining native forest basins, logs tend to be coarser and shorter, and tend to be oriented parallel to the flow as they are more easily transported. Volumes of in-channel wood tend to be higher in native forest basins. However, although streams in native forest basins tend to feature more jams, no significant differences were detected in terms of the number or dimension of pools, or volumes of trapped sediments. As well, fish species and biomass were not significantly different from those in streams draining pine plantation basins.

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TABLES

Table 1. Main characteristics of the studied basins (NF stands for native forest and PP for pine plantation)

Pair	IT		TR		AN		PE		NI	
Stream	Manqui	Mela	Arañas	Cerezas	Piuquenes	Potrerillos	Sin Puerta	Duende	Queñes	Cabras
Code	IT-NF	IT-PP	TR-NF	TR-PP	AN-NF	AN-PP	PE-NF	PE-PP	NI-NF	NI-PP
Coordinates (S-W)	36°23'15" 72°44'20"	36°21'48" 72°46'38"	37°34'28"73°13'19"	37°34'56" 73°16'53"	35°49'03" 71°11'05"	35°32'20" 71°11'58"	36°04'19" 71°19'16"	36°03'49" 71°20'45"	36°40'21" 71°34'37"	36°41'17" 71°37'42"
Basin area (km²)	4.92	4.83	1.43	2.54	11.86	9.13	2.35	3.53	10.21	11.22
Max elev. (m a.s.l.)	571	558	982	730	2087	865	1153	1078	1551	1168
Min elev. (m a.s.l.)	78	75	560	224	660	452	520	530	565	576
Mean basin slope (%)	18.6	9.4	26.2	17.8	28.2	10.5	26.1	26.8	12.9	10.6
Basin orientation	S	O	S	S-O	S	S-O	N-O	N-O	N-O	N-O
Channel order	4	4	2	2	3	2	2	3	3	3
Hydrologic regime	pluvial	Pluvial	pluvial	pluvial	Pluvial/ nival	Pluvial	Pluvial	Pluvial	Pluvial/ nival	Pluvial/ nival
Mean annual precip. (mm)	1100		1500		1640		1710		1490	
Climate	Temperate Mediterranean		Temperate Mediterranean humid		Temperate Mediterranean sub-humid		Temperate Mediterranean humid		Temperate Mediterranean	
Dominant forest type	Maule deciduous forest		Concepcion deciduous forest		Deciduous mountain forest		Maule deciduous forest		Deciduous mountain forest	
% native forest	62	25	99	40	100	32	100	34	98	29
% pine plantation	38	75	1	60	0	68	0	66	2	71
Width of the riparian buffer (m)	57.6	22.0	50.1	34.1	53.9	66.3	29.2	22.5	82.9	40.9
Distance from the closest plantation to the riparian area (m)	46.0	11.7	26.1	11.83	-	11.64	-	16.1	98.6	12.1
Distance from the closest plantation to the studied reach (m)	53.8	10.9	53.2	21.8	-	37.4	-	12.5	145.2	30.6

Table 2. Main characteristics of the surveyed channels

Pair	IT		TR		AN		PE		NI	
Stream	Manqui	Mela	Arañas	Cerezas	Piquenes	Potrerillos	Sin Puerta	Duende	Queñes	Cabras
Code	IT-NF	IT-PP	TR-NF	TR-PP	AN-NF	AN-PP	PE-NF	PE-PP	NI-NF	NI-PP
Number of reaches	10	9	12	8	6	8	6	6	7	7
Length of the studied segment (m)	667.8	656.6	822.4	375.4	781.7	907.9	543.3	715.3	801.4	718.8
Average channel slope (m m^{-1})	0.080	0.029	0.168	0.073	0.086	0.016	0.047	0.046	0.043	0.015
Average channel bankfull width (m)	5.0	4.5	4.1	4.6	13.3	3.7	2.7	3.1	8.9	8.5
Number of pools (pools km^{-1})	102.4	112.5	149.9	127.8	64.5	55.4	174.2	125.2	86.1	51.4
Dominant channel morphology	Cascade steps-pools	Riffles-pools	Riffles-step-pools	Riffles-pools	Steps-pools	Riffles -pools	Riffles steps-pools	Riffles steps-pools	Riffles-steps-pools	Riffles-pools
MDBH* of trees in the riparian area	24.40	16.00	23.95	8.90	14.70	11.40	11.86	14.92	16.59	12.44
MDBH* of trees on the slopes	31.88	25.08	20.62	15.06	17.47	22.03	9.96	3.55	16.26	19.84

*MDBH: Mean Diameter at Breast Height

Table 3. Statistical differences between native forests and pine plantation basins for each pair (F test, numbers in bold are significant at $p < 0.05$)

	IT	TR	AN	PE	NI
Average log diameter (m)	1.721	0.379	**0.392**	1.811	**24.427**
Maximum log diameter (m)	0.335	**2.185**	**0.392**	0.402	**50.674**
Average log length (m)	**2.397**	**4.438**	0.001	0.039	0.046
Maximum log length (m)	**1.746**	0.943	0.636	**3.138**	0.065
% Conifers vs broad-leafed logs	**105.758**	**31.486**	0.734	**16.836**	**37.972**
% Decayed vs. fresh and semi-decayed logs	2.720	0.311	**3.2003**	**9.201**	**33.022**
LW volume (m^3 ha^{-1})	**3.149**	**1.863**	0.064	**0.081**	**12.232**
Single logs volume (m^3 ha^{-1})	1.729	0.531	0.006	0.995	2.644
Jammed logs volume (m^3 ha^{-1})	0.841	2.014	1.569	1.761	**9.767**
Number of log jams (jams ha^{-1})	2.969	0.539	**12.213**	0.355	0.359
Number of single logs (logs ha^{-1})	0.464	**3.524**	2.449	2.256	0.065
% Logs floated vs. input from slopes and banks	**17.635**	**15.334**	**16.421**	**8.556**	**14.482**
% logs perpendicular vs. parallel to the flow	**3.554**	1.779	**3.681**	1.972	0.143
% transport/combination vs. autochthonous jams	0.836	2.977	0.1224	**13.333**	**13.938**
% Jams perpendicular vs. parallel to the flow	0.085	**1.468**	**5.882**	**0.773**	0.001

FIGURE CAPTION

Figure 1. Location of the studied sites (PP and NF refers to pine plantation and native forest basins, respectively).

Figure 2. Average and maximum diameter and length of all logs (either laying alone or jammed) measured within the bankfull channel in the study basins. The box-plots are produced using data acquired on various reaches per studied basin. The solid line indicates the range between the 25th and 75th percentiles, the square icon indicates the median, the whiskers indicate the maximum and minimum non-outlier values, the solid circles indicate outliers, and the diamond indicates extreme value.

Figure 3. Percentage of logs recognised as conifers or broad-leaved species (on the left) and as in a decaying or good state of conservation (on the right) in the study sites.

Figure 4. Volumes of in-channel wood at the studied sites. The graphs show the overall LW volume per ha of channel (a) and the volumes of single (b) and jammed logs (c). The box-plots are produced using data acquired on various reaches per studied basin. The solid line indicates the range between the 25th and 75th percentiles, the square icon indicates the median, the whiskers indicate the maximum and minimum values, the solid circles indicate outliers, and the asterisk indicates extreme value.

Figure 5. Volumes of large wood in mountain basins as a function of the basin area (on the left) and the percentage of native forest cover (on the right).

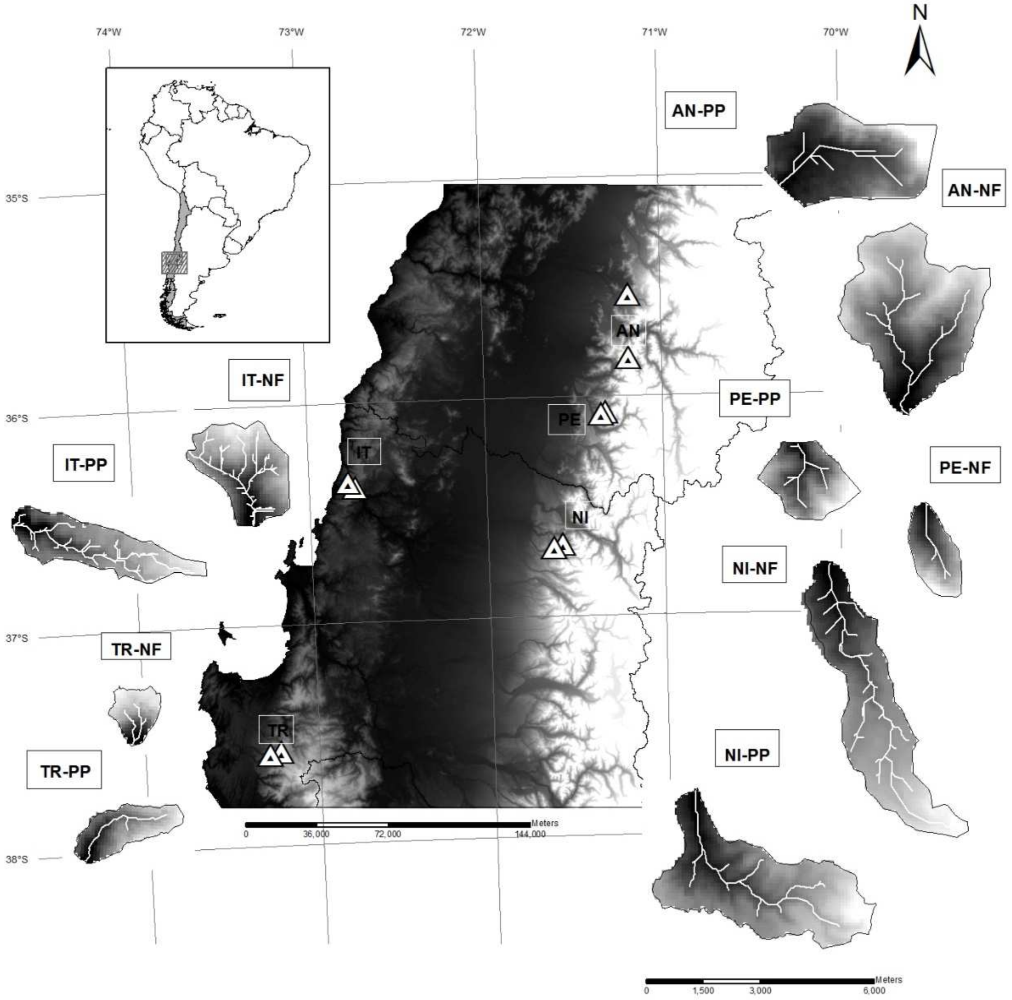
Figure 6. Number of log jams and single logs (dimensionalized per ha of bankfull channel) in the studied sites. The box-plots are produced using data acquired at various reaches per studied basin. The solid line indicates the range between the 25th and 75th percentiles, the square icon indicates the median, the whiskers indicate the maximum and minimum non-outlier values, the solid circles indicate outliers, and the asterisk indicates extreme value.

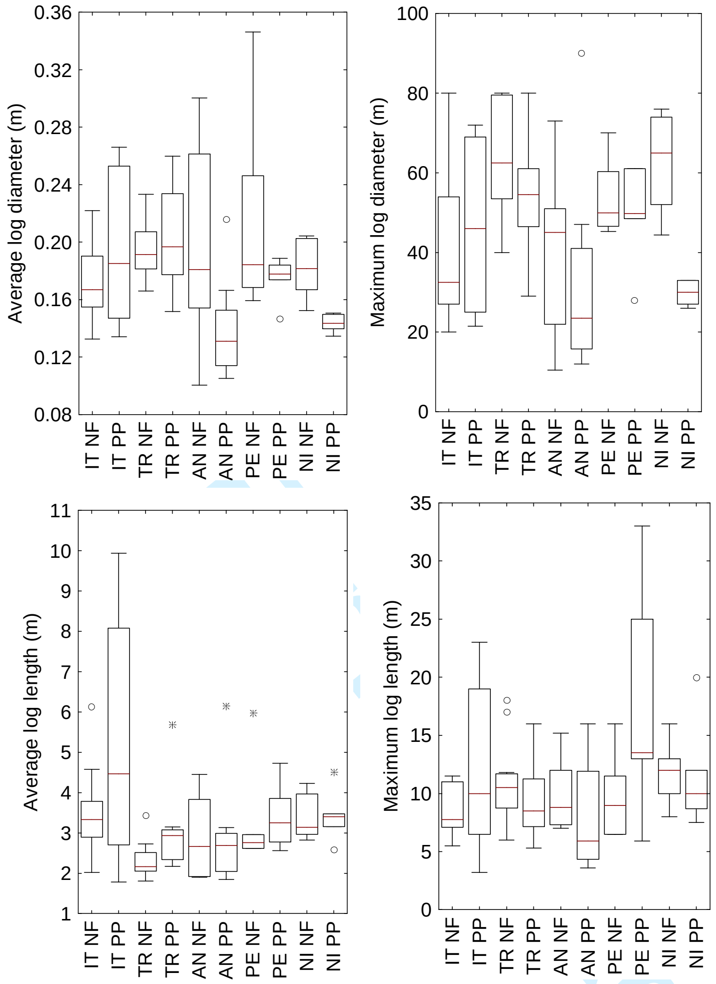
Figure 7. Percentage of logs recognised as having floated from upstream reaches or as being recruited from the slopes or banks within the reach (on the left), and percentage of logs found lying perpendicular or parallel to the flow (on the right).

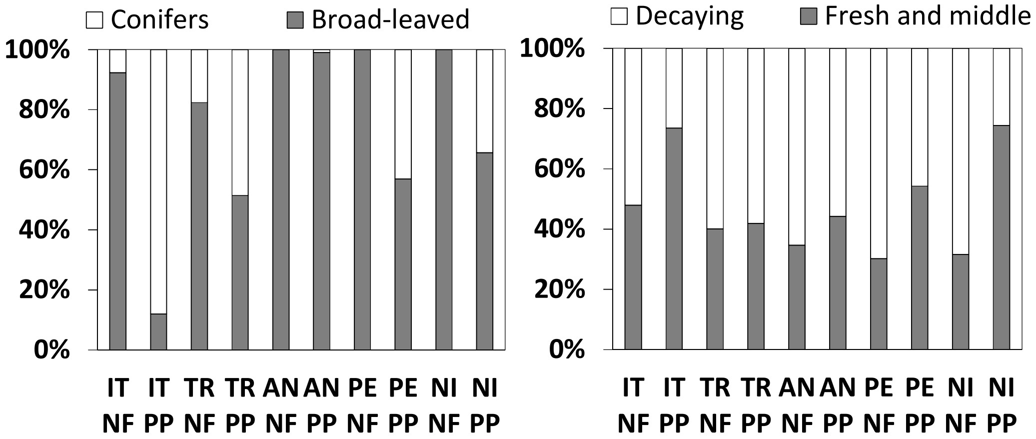
Figure 8. Percentage of log jams classified as having transport, combination or autochthonous origins (on the left), and percentage of jams found predominantly perpendicular or parallel to the flow (on the right).

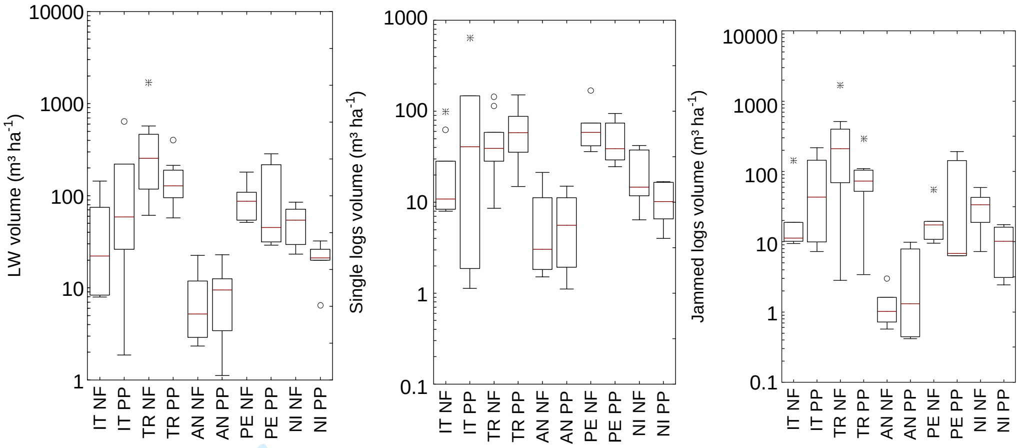
Figure 9. Ratio of volumes of sediments trapped by jams and jammed wood in the studied basins.

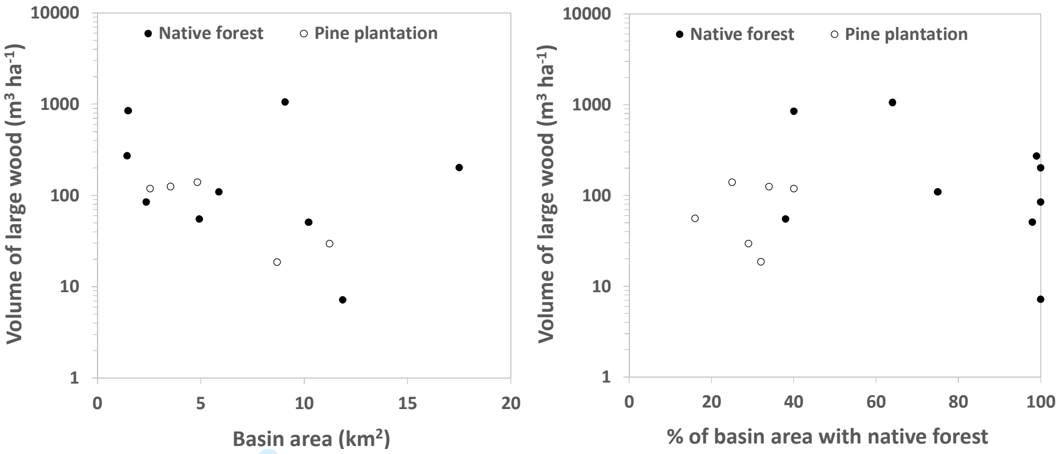
Figure 10. Comparison of biomass per unit effort between streams in native forests (NF) and pine plantations (PP) (on the left), and the correlations of biomass per unit effort against maximum log diameter and maximum log length (on the right).

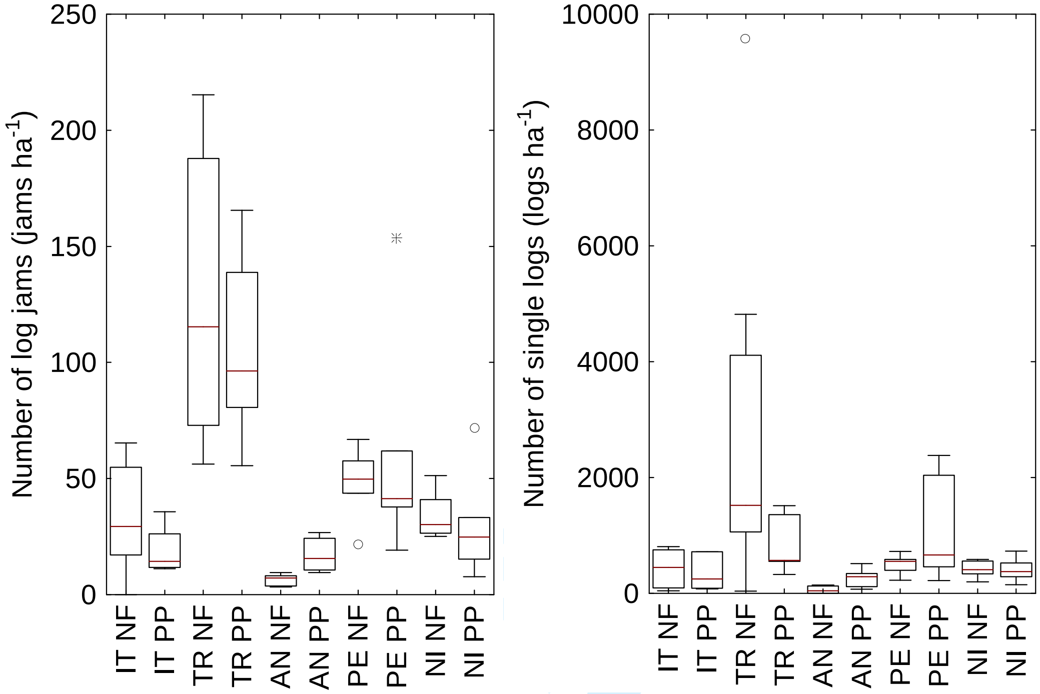

N
74°W
73°W
72°W
71°W
70°W
35°S
36°S
37°S
38°S
AN-PP
AN-NF
AN
IT-NF
IT-PP
IT
PE-PP
PE-NF
PE
NI-NF
NI-PP
NI
TR-NF
TR-PP
TR
Meters
0
36,000
72,000
144,000
Meters
0
1,500
3,000
6,000

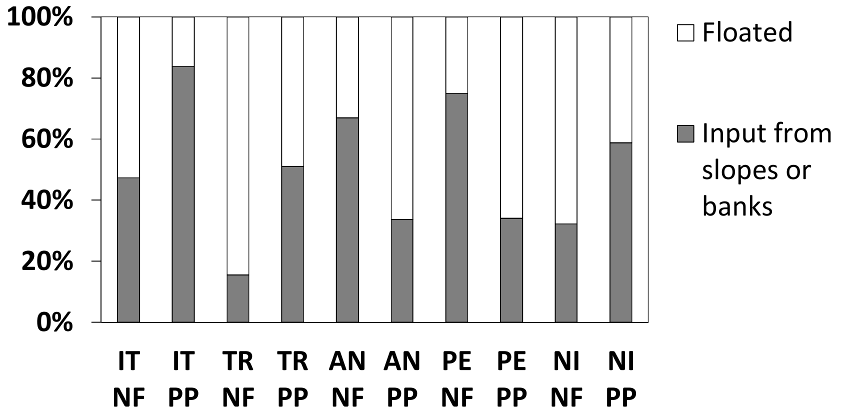

Average log diameter (m)
0.36
0.32
0.28
0.24
0.20
0.16
0.12
0.08
Maximum log diameter (m)
100
80
60
40
20
0
Average log length (m)
11
10
9
8
7
6
5
4
3
2
1
Maximum log length (m)
35
30
25
20
15
10
5
0
IT NF
IT PP
TR NF
TR PP
AN NF
AN PP
PE NF
PE PP
NI NF
NI PP

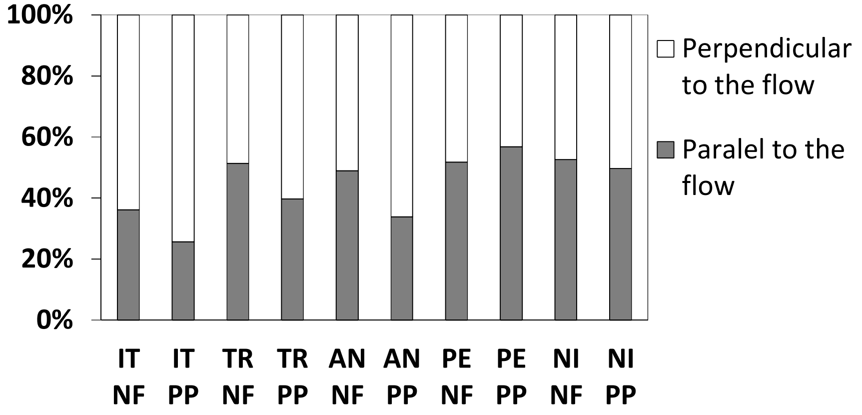

☐ Conifers
▨ Broad-leaved
100%
80%
60%
40%
20%
0%
IT NF
IT PP
TR NF
TR PP
AN NF
AN PP
PE NF
PE PP
NI NF
NI PP
☐ Decaying
▨ Fresh and middle
100%
80%
60%
40%
20%
0%
IT NF
IT PP
TR NF
TR PP
AN NF
AN PP
PE NF
PE PP
NI NF
NI PP

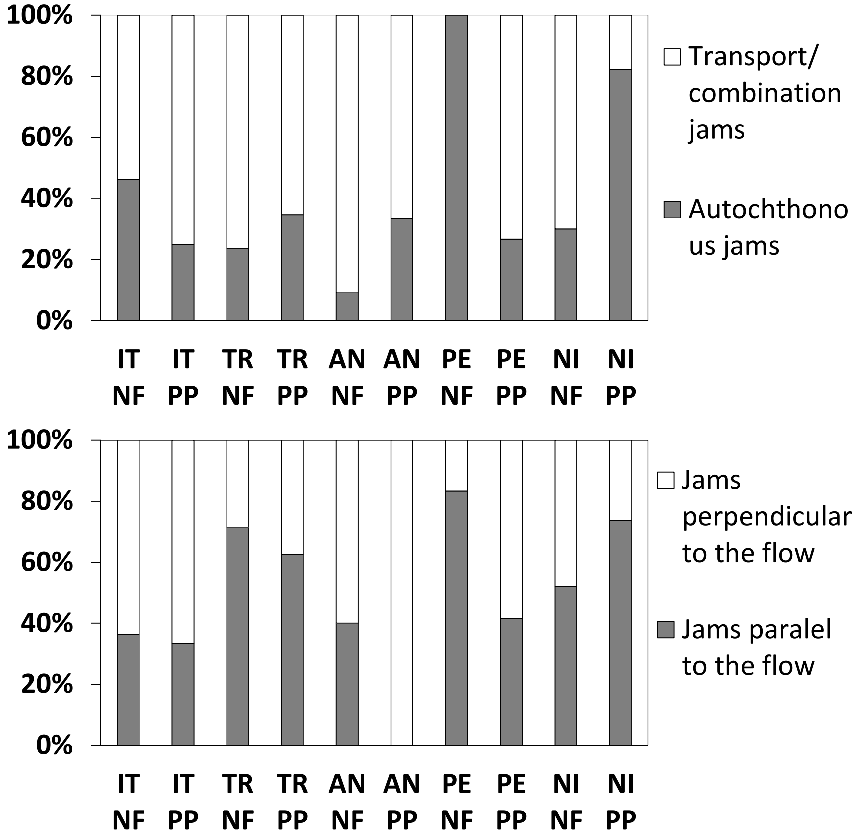

LW volume (m³ ha⁻¹)
10000
1000
100
10
1
Single logs volume (m³ ha⁻¹)
1000
100
10
1
0.1
Jammed logs volume (m³ ha⁻¹)
10000
1000
100
10
1
0.1
IT NF
IT PP
TR NF
TR PP
AN NF
AN PP
PE NF
PE PP
NI NF
NI PP

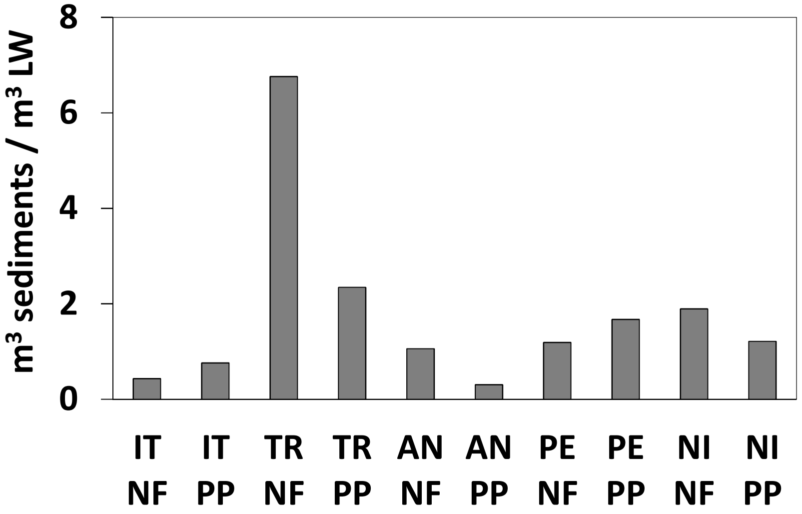

10000
1000
100
10
1
Volume of large wood (m³ ha⁻¹)
● Native forest
○ Pine plantation
0
5
10
15
20
Basin area (km²)
0
20
40
60
80
100
% of basin area with native forest

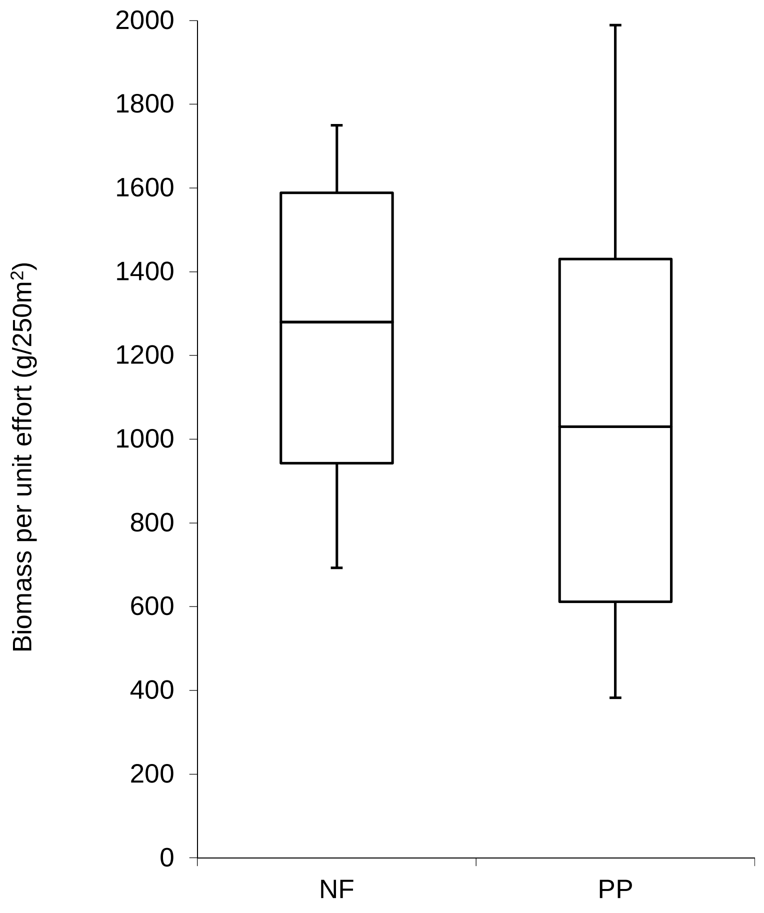

250
200
150
100
50
0
Number of log jams (jams ha^{-1})
IT NF
IT PP
TR NF
TR PP
AN NF
AN PP
PE NF
PE PP
NI NF
NI PP
10000
8000
6000
4000
2000
0
Number of single logs (logs ha^{-1})
IT NF
IT PP
TR NF
TR PP
AN NF
AN PP
PE NF
PE PP
NI NF
NI PP

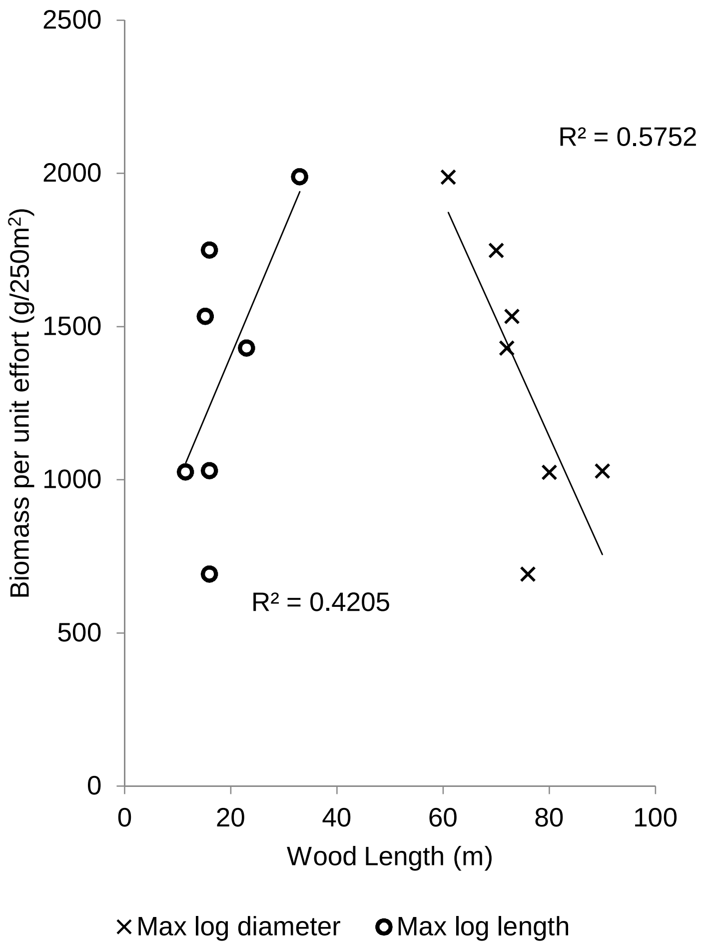

100%
80%
60%
40%
20%
0%
IT NF
IT PP
TR NF
TR PP
AN NF
AN PP
PE NF
PE PP
NI NF
NI PP
☐ Floated
▨ Input from slopes or banks


100%
80%
60%
40%
20%
0%
IT NF
IT PP
TR NF
TR PP
AN NF
AN PP
PE NF
PE PP
NI NF
NI PP
☐ Perpendicular to the flow
▨ Paralel to the flow


100%
80%
60%
40%
20%
0%
IT NF
IT PP
TR NF
TR PP
AN NF
AN PP
PE NF
PE PP
NI NF
NI PP
☐ Transport/ combination jams
■ Autochthonous jams
100%
80%
60%
40%
20%
0%
IT NF
IT PP
TR NF
TR PP
AN NF
AN PP
PE NF
PE PP
NI NF
NI PP
☐ Jams perpendicular to the flow
■ Jams paralel to the flow


m³ sediments / m³ LW
8
6
4
2
0
IT NF
IT PP
TR NF
TR PP
AN NF
AN PP
PE NF
PE PP
NI NF
NI PP


Biomass per unit effort (g/250m^2)
2000
1800
1600
1400
1200
1000
800
600
400
200
0
NF
PP


2500
2000
1500
1000
500
0
Biomass per unit effort (g/250m^2)
R² = 0.5752
R² = 0.4205
0
20
40
60
80
100
Wood Length (m)
× Max log diameter
○ Max log length