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Willows in Patagonia:

the challenge of understanding and controlling invasions

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A B S T R A C T

Exotic willows are widely spread throughout Patagonia due to their vegetative multiplication, rapid growth, and ease for establishing themselves in environments with fluctuating hydric regimes, so they most commonly overgrow in riverside environments and wetlands. We identified exotic willow species on the Futaleufú and the Chubut rivers basins, which cover roughly 65,000 km^2 in the Chubut Province of Argentina. We also surveyed and determined the western distribution boundary of *Salix humboldtiana* – the only native willow in the Southern Hemispere. In addition, we documented occurrences of natural hybridization between *S. humboldtiana* and *Salix* x *fragilis*. An important objective of the survey included developing control methods for *S.* x *fragilis* to prevent regrowth. We shared such research activities with socially interested groups through extension, release, and other related activities. The involvement of scientific and technical sectors in socio-environmental issues enables the use of friendly tools geared towards the sustainable development of local domestic economies while preserving the environment's biological diversity.

K e y w o r d s
Salix invasion, *Salix* x *fragilis*, invasion management, regrowth control methods.

INTRODUCTION

Biological invasion processes threaten biodiversity, especially when they involve species that are considered to be ecosystem engineers. Such species either native or exotic generate biotic and abiotic conditions that shape the structure of ecosystems (e.g. trees in forests). Sometimes exotic species in a new ecosystem become invasive and change its structure; either by changing habitats, light conditions, humidity, sedimentation rates, heat, available water, etc. These changes can have profound effects on the native biota, on their interactions, trophic webs and on their disturbance regimes (Mack & D´Antonio, 1998; Crooks, 2002).

Over the past two decades, willow invasion has been widely documented in riparian areas, wetlands, valleys, and grasslands of the Southern Hemisphere. Some examples are: the invasions of *Salix* x *fragilis* (formerly *Salix* x *rubens*) in Australia, New Zealand and Argentina; *Salix euxina* (formerly *Salix fragilis*) in South Africa and Chile; *Salix babylonica* in South Africa; *Salix nigra* and *Salix cinerea* in Australia, among others (Henderson, 1991; Cremer, 1999; Greenwood *et al*., 2004; Budde *et al*., 2010; Lewerentz *et al*., 2019). In Australia and New Zealand, *S.* x *fragilis* is considered a pest and eradication programs are carried out since the late 1990s (Cremer, 1999; Cremer, 2003; Kusovkina & Belyaeva, 2018).

Willow invasion occurs in transition areas between terrestrial and aquatic environments and can alter the exchange of matter and energy and their functioning (Ewel *et al*., 2001). Changes in the riparian vegetation can affect levels of light, heat and the contribution of organic matter both in quantity and composition, as well as its breakdown rate (Naiman & Décamps, 1990, 1997; Stohlgren *et al*., 1999). For instance, in Patagonia there is evidence that the decomposition rate of *S. fragilis* (actually *S. euxina*, but probably *S.* x *fragilis)* is slower than in the native species *Ochetophila trinervis* (Serra *et al*., 2013). In Australia, there is also evidence of changes in the composition and abundance of terrestrial arthropods in riparian areas invaded by willows (Greenwood *et al*., 2004). Likewise, in willow-invaded areas, there is a loss of herbivorous macro-invertebrates and an increase in the number of generalist species. Changes are also seen in functional feeding groups with autotrophic pathways where algae predominate, into heterotrophic pathways where there is a predominance of detrital organisms (McInerney *et al*., 2016). Changes in food webs can have important effects on higher-order consumers (Greenwood *et al*., 2004; Yard *et al*., 2004; McInerney *et al*. 2016).

Although exotic *Salix* species probably were introduced during late 18th or the first part of the 19th centuries, the spread of *S. fragilis* was only reported during the first decade of the 21st century (Faggi 1999; Orellana *et al*., 2010; Rey 2010). Budde *et al*. (2010) did a regional-scale study that analyzed the genetic composition of willows in the basins of the Limay, Negro, Manso and Puelo rivers, finding high frequency of a single female clone of *S.* x *fragilis* which propagated by vegetative reproduction creating dense stands reaching linear distribution ranges of almost 800 km long. Budde *et al*. (2010), and later, Kusovkina & Belyaeva (2018), point out a common mistake that persists in publications, even after 2010. Authors, in mentioning "*S. fragilis*" in Patagonia, should have referred instead to "*S.* x *fragilis*", which is a hybrid created from *S. alba* x *S. euxina*. In this paper we use the nomenclature for willows as proposed by Belyaeva (2009). *S. alba*, *S. euxina* and *S.* x *fragilis* are common in the riverside environments of Europe where they are native species (De Cock *et al*., 2003).

In 2009 we began research in the river basins of the Futaleufú and the Chubut rivers, both located in Chubut province. This work attended the requests of Los Alerces National Park (PNLA), the Association of Producers of the Valley 16 of October, and the Municipality of Trevelin city, all locally emplaced. Main concerns were: the persistent growth of willow-infested areas; the periodic flooding of productive valleys; and the formation of dams in watercourses due to the accumulation of willow biomass. All resulted in problems such as smaller crop yields, loss of soil quality, damaged infrastructure, and lack of access to water sources for fishing.

We set three objectives: **a)** identify the exotic willows species in the Futaleufú and Chubut river basins, **b)** determine the natural area of distribution of southernmost populations of *Salix humboldtiana*, the only native species of willow in the southern hemisphere; **c)** develop effective cutting methods for exotic willows controlling regrowth.

Study Area

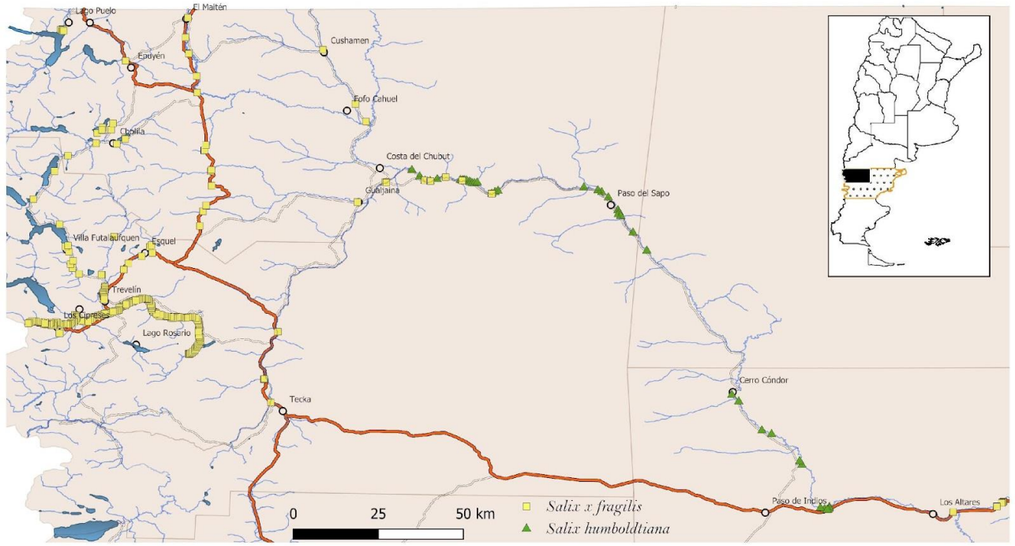

Figure 1.

Study area in the Northwest of the Chubut Province. On the left is the Futaleufú River basin: from Cholila to Trevelin, throughout Los Alerces National Park, we mainly find *S.* x *fragilis*. To the center left is the Chubut River Basin that includes the tributaries that National Route 25 crosses, from El Maitén to Tecka and the Chubut River from Cushamen to Los Altares. In this basin the surveys were oriented to detect *S. humboldtiana* populations, so we omitted to survey more points for *S.* x *fragilis*, although its presence is continuous throughout the basin.

The Futaleufú river basin with 7.630 km^2 includes among others Los Alerces National Park, a designated Natural World Heritage Site and the Valley 16 de Octubre, where substantial agricultural activities take place (Méndez Casariego, 2008). The Chubut river basin occupies the northern part of Chubut Province, from east to west, covering an area of 53.234 km^2 (SSRH, 2002) (Fig.1).

S. x *fragilis*, in its female form, is the most frequent taxon found in the Futaleufú river basin. The highest densities there are located in the Corinto and Futaleufú rivers. Other *Salix* species: *S. euxina* (female); S. alba; *S. alba* var. *vitellina* (female); *S. caprea* (female and male); *S. babylonica* and *S. viminalis*, all exist in low numbers, while *S. humboldtiana* does not grow in the Futaleufú basin (Fig.1 and Fig. 2). Currently we are using Simple Sequence Repeats (SSRs) and Internal Transcribed Spacer (ITS) techniques to confirm prior morphological findings and to review the genetic properties of *S.* x *fragilis* populations in both basins. Partial results are published as Orellana *et al*. (2015 a) and Orellana *et al*. (2016).

S. x *fragilis* was also found throughout the Chubut River and its tributaries and more frequently than the other species. In the Chubut River we also found *S. euxina*; *S. alba*; *S. alba* var. *vitellina*; and *S. caprea* in low numbers (Fig. 2; Orellana *et al*., 2015 b; Orellana *et al*., 2016). In addition, between the locations of Costa del Chubut and Paso de Indios along Chubut river's southern bank we surveyed 41 stands of *S. humboldtiana*, counting 492 adult individuals. In most of the

stands we found between 1 and 10 adult individuals (Fig. 1). Dense stands exist between the locations of Cerro Cóndor and Paso Berwyn, coinciding with a historical low human population density. In all of the *S. humboldtiana* natural distribution areas, abundant specimens of *S.* x *fragilis* were recorded, and in lesser proportion, *S. alba* var. *vitellina* was also seen. In 7 out of 41 studied populations, we detected a new female hybrid between *S. humboldtiana* (male) and probably *S.* x *fragilis* (female) (Orellana *et al*., 2021). One of the most undesirable consequences of *S.* x *fragilis* overgrowth is its hybridization with *S. humboldtiana* (Bossi *et al*., 2012) thereby contributing to gene dilution, a process that establishes a new, additional threat to the conservation of valuable *S. humboldtiana* populations (Gallo *et al*., 2020).

Such information allowed us to learn details of composition and distribution of both the exotic and native willow species, and thereby, determine on which species or taxon to focus when engaging in actions related to their control or their conservation respectively. We developed specific control methods for *S.* x *fragilis* - the main invader in the Futaleufú and Chubut basins. We also incorporated new survey projects to further define the characteristics and structure inherent to *S. humboldtiana* stands (2017). Finally, we were able to raise funds for joint work with area residents of river Chubut in order to recover fragile *S. humboldtiana* populations still remaining there (2019).

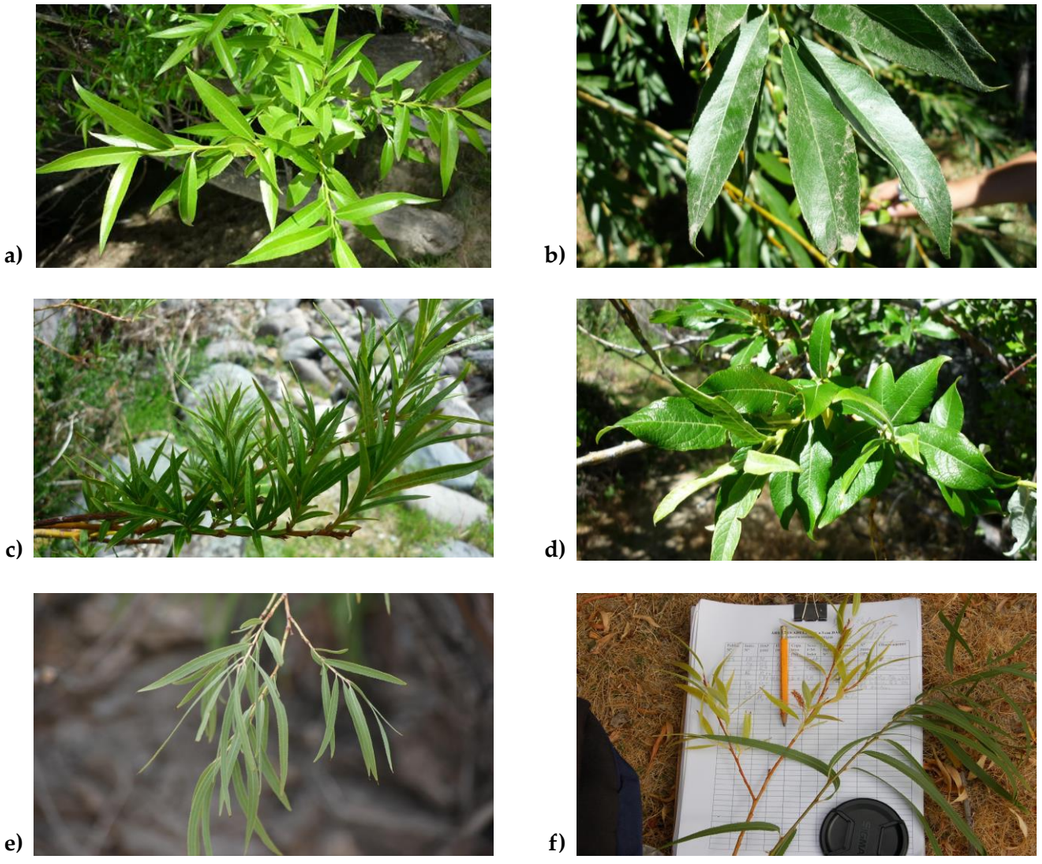

Figure 2.
a) *S.* x *fragilis*, **b)** *Salix alba* var. *vitellina*, **c)** *Salix viminalis*, **d)** *Salix caprea*, **e)** *Salix humboldtiana* and **f)** the new hybrid between S. x fragilis (female) and S. humboldtiana (male) on the left and S. humboldtiana on the right.

In 2013 we received a subsidy from Argentina's Ministry of the Environment and Sustainable Development. Based on control methods performed in Australia, we applied several trials to avoid regrowth in *S.* x *fragilis*, by combining cutting and the application of agrochemicals. We selected those herbicides that had the least impact on health and the environment. To do so, we used Argentina's Phytosanitary Guide which bases its recommendations on those of the World Health Organization. For herbicides approved for use in the country they accept four toxicity categories, category IV being the least toxic (CASAFE, 2011). We also considered the viewpoint of the National Commission for Research on Agrochemicals Decree 21/2009 (CONICET, 2009). We selected glyphosate ("Roundup") and aminopyralid ("Tocón"); both classified as category IV herbicides back in 2012. To apply them, we developed a method based on localized applications and lower concentrations than those used in Australia.

In trees with a DBH (Diameter-at-Breast-Height) greater than 5 cm we first cut the trunk and applied aminopyralid 2% diluted in water, with a brush, on the fresh cut. Another trial included cutting and applying glyphosate 7.5%, with the same method. A third trial consisted on glyphosate injections at 30% to standing trees; with 10 ml of product applied per hole. In a fourth trial we sprayed a dilution of glyphosate at 3% on young plants (DBH <5 cm). As control trial we only cut the trees with no further treatment. As seen in Figure 3, the most effective treatment to control regrowth was by injection (0% regrowth) regardless of when it was applied. The spray treatment, applied to plants with thin branches, was more effective when applied in spring (20% regrowth) than when applied in autumn (70%).

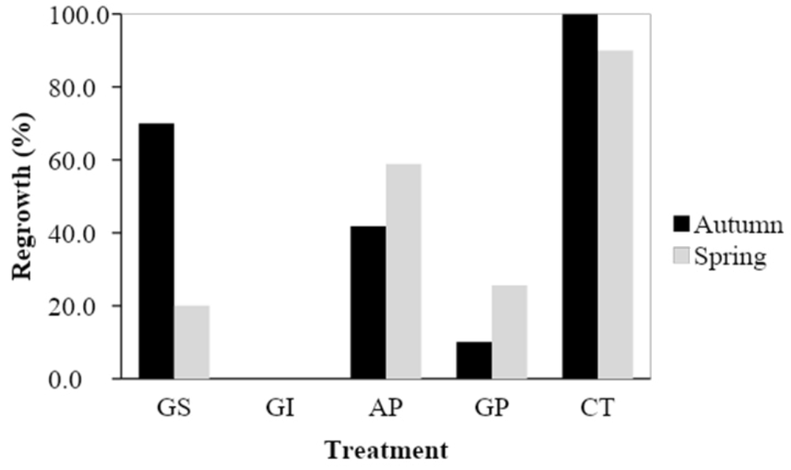

Figure 3. *Regrowth average (%) per plant per plot, for treatments applied in spring of 2013 and fall of 2014, evaluated in spring of 2015, n = 5 sites. GS = Glyphosate Spray; GI = Glyphosate Injection; AP = Aminopyralid Paint; GP = Glyphosate Paint; CT = Control.*

Willows are timber resource at local scale, so the cutting and herbicide application trials allowed us to quantify the yield in useful wood coming out of *S.* x *fragilis*. From 1 ha invaded it is possible to obtain: 80 rolls, 327 posts and 233 rods for fences, and 317 m^3 of firewood (Orellana *et al*., 2016). Some of these results have been published in local extension magazines, to make them available in Spanish for the local audience (Amico & Orellana, 2014). We also participated in several radio interviews for the benefit of the local rural audience.

Local environmental authorities can use the results of the trials to promote the willow control tools with rural residents, who will in the end, not only benefit of an improved environment and recover valuable invaded land and water resources, but also take advantage of the productive potential attained when controlling and extracting exotic willow stands. With this in mind, in 2015 with the municipality of Trevelin, we organized a "Show of Willow Wood Products" within the framework of a production regional fair in the city of Trevelin. Sixteen local carpenters and artisans participated, with a focus on *S.* x *fragilis* wood used to build objects, crafts and furniture. The great interest of the public and the high quality and aesthetics beauty of the work presented by them illustrated the possibility of using willow wood to add value (Figure 4).

Figure 4.
Wooden furniture by local carpenters and artisans made with S. x fragilis, during the "Willow Wood Products Show" within regional fair of the production of Trevelin in 2015.

Innovation based on uses for: basketry, as a substrate for growing edible mushrooms, as animal forage, in the development of systems such as biomass for bioreactors, and alternative uses as retaining walls and quality wood for furniture, constitute possibilities of local interest for improvements in small family economies. The promotion of uses needs to be emphasized in willow-invaded areas, never to promote the multiplication of willows in new areas. Only in this way the use of willow wood for alternative uses should be promoted.

After little more than a decade of research, design and control programs for *S.* x *fragilis* invasions continue to be a priority. Such programs must be permanent. Strong eradication is not advisable as most times it causes damage to the environment. Managing and controlling invasions requires a sustained, joint commitment of the entire local society. Management authorities and institutions could be local basin boards or commissions since they bring together representatives of multiple society organizations (Fig. 5).

The nature of willow invasions, where willow cuttings are continually spread through waterways also reinforces the need for basin-scale management planning. Such programs should incorporate the cleaning of riverbeds and riverbanks at the farm scale, prioritizing the cleaning of areas where the riverbed is obstructed with undertow and the extraction of living trees established in the water. In line with the logging of willows, the role of woodcutters is key to controlling invasions. Cutting alone is not useful to control regrowth; herbicide applications and the adequate care and deposition of the branches must follow. Such willow control activities add cost, which could be covered for example, by establishing minimal fee charges for extraction, or a state subsidy for tasks dedicated to willow invasion control. Currently there is no formal recording of willow wood usage. Such records are also needed necessary when planning the comprehensive management of willow invasion at the basin level. Their incorporation into the management systems of institutions that monitor the use of forest resources should be considered (Fig. 5).

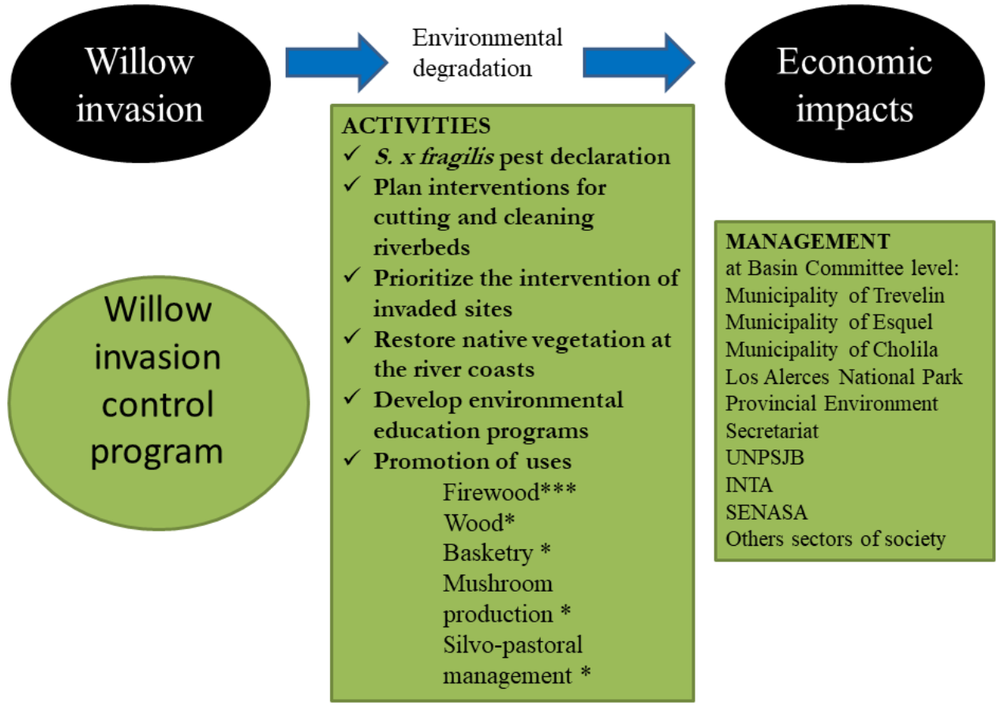

Figure 5. *Considerations for structuring willow control management program at large scale for the Futaleufú river basin. *** Cut for firewood, with herbicides applications and an adequate deposition of the branches could have significant contribution to the control of willow invasions. * Small contribution to the control of invasions.*

How does our work contribute towards actions favourable to environmental biodiversity and sustainability?

Complementary to science research and divulgation activities, it is imperative to promote knowledge of willow invasion and actions aimed at controlling it by means of education and extension activities at the local community level. In 2018 we organized and delivered a Certified Willow Management Course, for local staff at environmental institutions, in this case the national parks' and the environmental secretariats of Andean municipalities along the Chubut province. In addition, in 2019 we added to the contents of a training course for Fishing Guides a section on "Willows, their Origin and Characteristics". In 2020 we participated in an exchange network with other research groups and technicians of municipalities of the provinces of Río Negro and Neuquén, who face the same issues with willow overgrowth.
In 2021 together with Los Alerces National Park (PNLA) technicians, we provided a course for residents at the PNLA, a field guide booklet with basic information about willows, and a survey to find out their perception on willows. An important part of the mission of Argentina's national parks is focused on biodiversity conservation and environmental education, which makes willow management education for the PNLA inhabitants a must.

The herbicides used in 2012/2013 were selected because they made the least environmental impact. However, now there are restrictions on glyphosate uses in Chubut Province. The herbicides used also went into other categories: glyphosate is placed under category II b (moderately dangerous) and aminopyralid, in category III (slightly dangerous). For this reason, this year in PNLA practices, we evaluated using other substances as salts, and aminopyralid injection to avoid regrowth. The PNLA also has an herbicides use manual (Menvielle *et al*., 2020), which provides a formal framework for their application. We hope that the outcome of these experiences will contribute to a future broader range of willow control alternatives.

Scientific work, paired with strong practical follow-up practices contributes to the good management of natural areas. Technical science specifically applied to fully engage with other sectors of society generates paths in harmony with the environment.

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