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Invasion of North American beaver (*Castor canadensis*) in the province of Magallanes, Southern Chile: comparison between dating sites through interviews with the local community and dendrochronology

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Abstract

Background: Twenty beavers *Castor canadensis* (Castoridae) were initially introduced in the Argentinean portion of Tierra del Fuego Island, from where they have occupied most of the Fuegian Archipelago and even reached the continent. This invasion is causing great damage to the subantarctic forest ecosystems, and it is not known how fast the species is spreading. While there is an estimation of this advance using interviews, it is not known how reliable these are and they cannot be made in remote areas.

On the mainland, where beavers were present, their date of arrival was estimated using interviews and dendrochronology, and the dates obtained by both methods were compared for each site.

Results: Differences were found among the groups of respondents, according to property size, in their ability to detect changes in the environment made by beavers.

The dates of arrival estimated through dendrochronology are 23 years prior to those determined through surveys, and they generate a potential route of arrival from the Fuegian Archipelago and migration in the mainland. This route is more parsimonious than the route of dispersal generated through interviews.

Conclusions: Since it was determined that there is no relationship between the dates estimated through surveys and dendrochronology, it is not possible to determine how much lag there is from the time when changes in the environment are produced by beavers and the time when people notice this change. Our results indicate that this lag may not be constant among different groups of people.

Keywords: Beaver; Dendrochronology; Dispersal; Cross dating; Surveys

Background

Biological invasions are a problem of great importance because they have been responsible for economic problems (Pimentel et al. 2000; Curtis and Jensen 2004) and losses of biological diversity (Sala et al. 2000; Vázquez 2002).

Castor canadensis (Castoridae) is an invasive species in southern South America, and it has been classified as a harmful species by the Chilean government (SERVICIO AGRICOLA Y GANADERO, Subdepartamento de vida silvestre DIPROREN 2011). The beavers are capable of completely modifying their habitat by building a lodge and a dam (Muller-Schwarze and Sun 2003), cutting down *Nothofagus* trees more than 20 m away from their pond (Anderson et al. 2009) to build dams that can measure up to 1.5 m tall and 100 m long (Baldini et al. 2008). While they do this, they generate changes to the riparian environment that are only reversible at rates much slower than its natural rate, because they change the plant community structure and succession patterns

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and prevent the natural regeneration of forests and aquatic ecosystems (Anderson et al. 2006; Martínez Pastur et al. 2006). In such conditions, only the seedlings of *Nothofagus antarctica* are capable to establish successfully, which could help the regeneration of the riparian forest, but only in the long term (Anderson et al. 2009).

Since 1946, when 20 beavers were released in a single event in the Argentine side of the Island of Tierra del Fuego (Pietrek and Fasola 2014), the population of beavers has expanded to the whole of the island, most of the Fuegian Archipelago and even to the South American continent (Skewes et al. 2006). On the Chilean side of Tierra del Fuego alone, the beaver population has been estimated at around 41,000 individuals (Skewes et al. 2006), with lower densities in steppe ecosystems and higher densities in *Nothofagus pumilio* (Nothofagaceae) forests (Skewes et al. 1999). This difference has been interpreted as a preference of the species for forested habitat environment over the steppe (Skewes et al. 2006).

Skewes et al. (2006) recounted the information of beaver sightings in Tierra del Fuego Island (both Chilean and Argentinean side) and Dawson Island. This study was complemented by Anderson et al. (2009) by incorporating information on sightings in Hoste and Navarino Islands and the mainland, thus providing a general idea of the possible dates of migration of this species. However, the information obtained from surveys and interviews has not been updated in recent years and/or validated by other methods and further quantitative studies to measure the progress of the invasion determining arrival of the specie or at least the settlement date and/or the first sign watching.

Dendrochronological analysis is based on the seasonality of tree growth, determined by the annual cycle of climatic limiting factors resulting in time series of tree-ring width and density with annual resolution (Stokes and Smiley 1968; Cook and Briffa 1990; Boninsegna et al. 2009). Considering that woody species used by beavers in the region of Magallanes have only one ring per growing season, the determination of the dates of use of timber by beavers will be possible by cross dating of samples of dead trees with the series of growth rings of living trees whose age is known, since its last year of growth corresponds to the date on which the sample was collected. The dendrochronological approach is used to determine when a tree was cut by beavers, both during dispersal or when it has found a permanent establishment.

We hypothesize that if people perceive the changes in the environment produced by the beaver's damage, then the dates of arrival determined through interviews will match the dates of arrival determined by dendrochronological dating.

The specific objectives of this study were:

1. To estimate the dates of beaver arrival using interviews and develop a map of the putative progress of this species in areas of the Magallanes province.
2. To establish the relationship between different interviewed groups and the degree of success/failure in detecting beaver presence in the Magallanes province.
3. To determine the arrival of beavers by dendrochronological methods in sites of the Magallanes province with signs of beaver presence and make a map of beaver migrations.
4. To compare the information provided by dendrochronology and interviews.

In this paper, we compare the dates of arrival of the American beaver invasion to different sites within the province of Magallanes, determined by sightings of the species or their sign (gnawed trees, dams, and/or lodges) detected by people inhabiting contiguous areas and cross dating of affected trees through dendrochronology on sites with signs of beaver found in this area through surveys (Graells and Corcoran 2011).

Methods
Study area
The study was conducted in the Magallanes province corresponding to continental geographical area of the region of Magallanes and Chilean Antarctica (Figure 1). The area is characterized by atmospheric circulation, oceanic influence, and landscape factors that define the five climatic types: arid with steppe and cold (BSk), arid with desert and cold (BWk), temperate without dry season and warm summer (Cfb), temperate without dry season and cold summer (Cfc), and tundra (ET) (Peel et al.
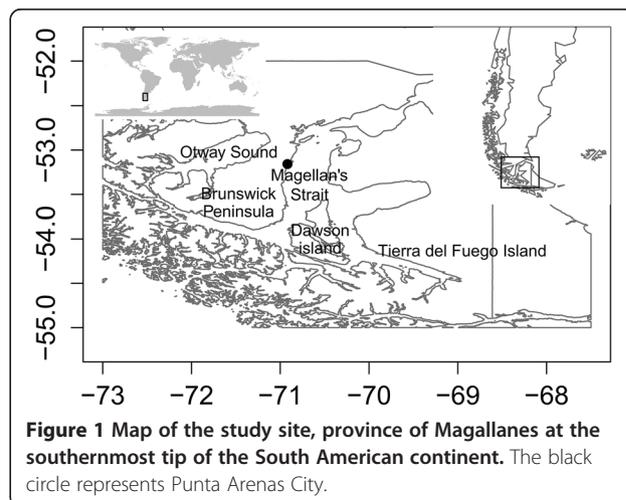

Figure 1 Map of the study site, province of Magallanes at the southernmost tip of the South American continent. The black circle represents Punta Arenas City.

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2007). The surveyed area considers the five climatic types. Sites dendrochronologically sampled were associated with cold-temperate environments (Ckc). The vegetation in these environments is represented by mixed forest of *N. pumilio* and *N. antarctica* (Nothofagaceae) in the upper band, Magellanic deciduous forest of *N. pumilio* and *Nothofagus betuloides* (Nothofagaceae) evergreen forest at the bottom (Correa 1998).

Interviews

We estimated the perception of the date of arrival of beavers on the South American continent through interviews made in the Punta Arenas County, since this was the only county with a confirmed presence of beavers (Graells and Corcoran 2011). We used a questionnaire followed by a semi-directive interview (Huntington 2000), with the objective to survey most of the properties in the County. In order to do this, we went door to door in every house where someone was found and interviewed them. The questionnaire inquired about the presence or suspected presence of beavers or their signs, the date they saw the first beaver sign, considering presence of cut trees, dams, and/or beaver lodges. We established an area of perception in a range of 10 km of each surveyed property. The interviews were conducted face to face at the moment of the visit without announcement with landowners, tenants, and workers in agricultural and livestock farms, workers engaged in tourism, officials of armed forces and police, among others. The main activity of the individuals was recorded. We did not use maps during our interviews, because according to our experience, people working in sheep ranching in Magallanes, who possess low educational level, are intimidated by maps and get confused within their own geographical space when they look at them.

We used the oldest dates reported by the respondents as the estimated date of arrival for each river in the province and developed a map to visualize the possible route of arrival of beavers to the continent and their migration within it. For that purpose, we used the program DIVAGIS (Hijmans et al. 2004).

To estimate the relationship between the activity of the inhabitants and their success in detecting the presence or absence of beavers, we analysed 62 surveys. The surveyed people were categorized according to their main activity: owner of a small property (≤5 hectares), worker of a small property, owner of a large property (>5 hectares), worker of a large property, and visitor to a large property. We quantified the number of successes and errors at detecting the presence or absence of beaver sites by verifying suspicions by prospecting the river on foot (Graells and Corcoran 2011).

To establish if the ability to detect the presence of beavers is independent of the activity of the inhabitant or the size of the property, we performed a Fisher's exact independency test to see if there is a relationship between activities carried out by the respondents and the degree of correspondence of the responses to the presence of beavers and their actual presence. We also perform a chi-square test to determine differences in the correspondences of responses in large or small farms.
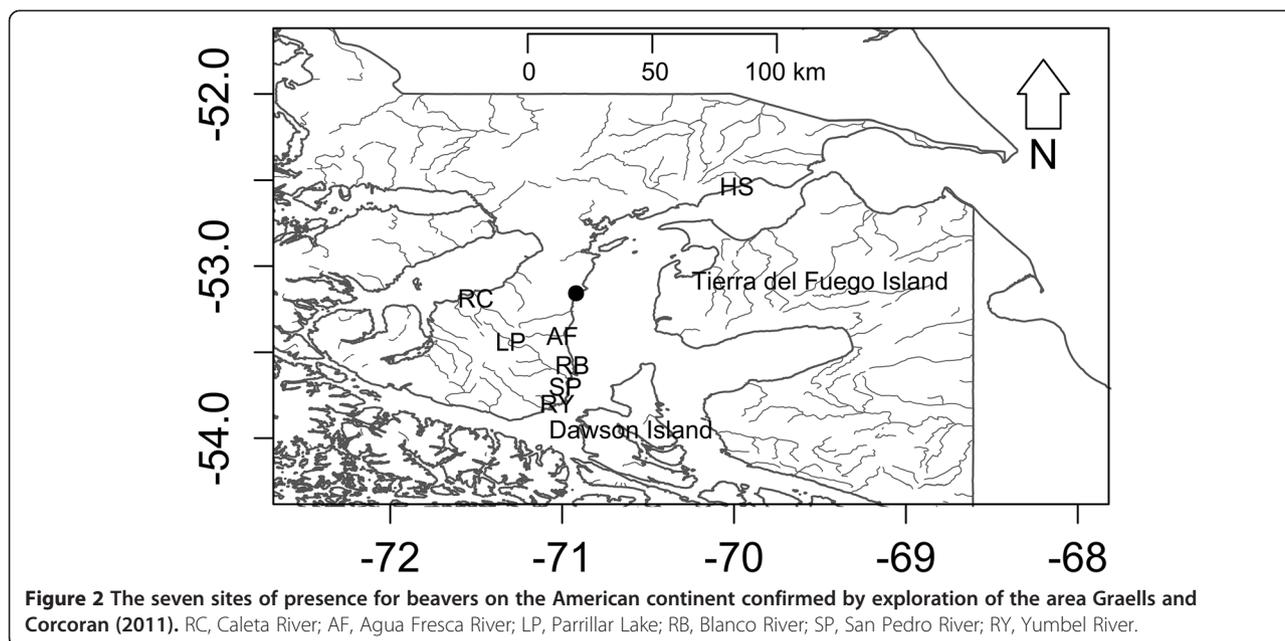
Dendrochronology

To estimate empirically the time of arrival of beavers into the Magallanes province, we sampled six of the eight sites prospected by Graells and Corcoran (2011), leaving out the Sanhueza Hotel (HS) as the only steppe site which did not have *Nothofagus* stumps and the sector of San Juan River (SJ), which was less than 10 km away from the San Pedro site and was far more difficult to sample because the beaver lodge was in the middle of a peat bog (Figure 2).

In each of the six sites, two cores were taken from each of 12 living trees ($n = 144$) using increment borers (HAGLOF, Sweden), and 7 to 12 cross sections of trees cut by beavers (depending on availability of the site and the conditions in which they were by the decomposition of wood) were collected. There were two types of sampling sites: In areas where beaver dams and/or lodges were found, samples were taken from living trees and stumps within a radius of 20 m from the lodge. When no beaver lodge or dam was found, we choose randomly a stump and sampled on an approximate 20-m radius from it.

Core samples were stored in plastic straws and cross sections in paper bags and properly identified per site; both were taken to the Dendrochronology Laboratory of CEQUA, a regional research center based on Punta Arenas.

The increment cores were mounted in wooden supports (Stokes and Smiley 1968; Phipps 1985) and fixed using a water-soluble glue, maintaining the correct alignment between the mount and the cells in the core. The core was hold in place with adhesive tape while the glue sets. Finally, increment cores and cross sections were prepared using a rotary-sanding tool through a range of grit size from 100 to 700 (Pilcher 1990).

After obtaining a clear exposition of the growth rings, their measurements were performed under a stereomicroscope using a ×15 magnification. The width of each ring was measured and recorded digitally (VELMEX, New York, USA). The ring-width series obtained from living and dead trees were analysed using the program COFECHA (Holmes 1983). This computer program allowed us to detect errors in assigning ages of samples, generate a reference series or average for samples of living trees, and compare growth patterns of living trees (of known age) and dead (age unknown), allowing

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Figure 2 The seven sites of presence for beavers on the American continent confirmed by exploration of the area Graells and Corcoran (2011). RC, Caleta River; AF, Agua Fresca River; LP, Parrillar Lake; RB, Blanco River; SP, San Pedro River; RY, Yumbel River.

us to assign the date of death to the latter (Stokes and Smiley 1968).

The dates of the invaded sites obtained by dendrochronology were used to make a map with DIVAGIS. Using these dates, the likely route of arrival of the beavers to the mainland and their migration routes were inferred.

Comparing surveys and dendrochronology

To compare the oldest dated years obtained by both methods for each sample site, the years obtained by dendrochronology were considered as the independent variable and the dates obtained by surveys, as the dependent variable. The degree of dependency was tested by simple linear regression, considering an α of 0.05.

Results

Interviews

A total of 62 surveys were conducted in the Magallanes province. Nine of the respondents reported at least a suspicion of beaver presence. Reported dates of the first sightings for suspected or confirmed presence of beavers were available for six sites (Table 1). These dates were considered as the tentative arrival dates of beavers at each site and were used to generate a hypothetical map of beaver dispersal from known points of presence on the islands of Tierra del Fuego and Dawson and movement across the continent (Figure 3)
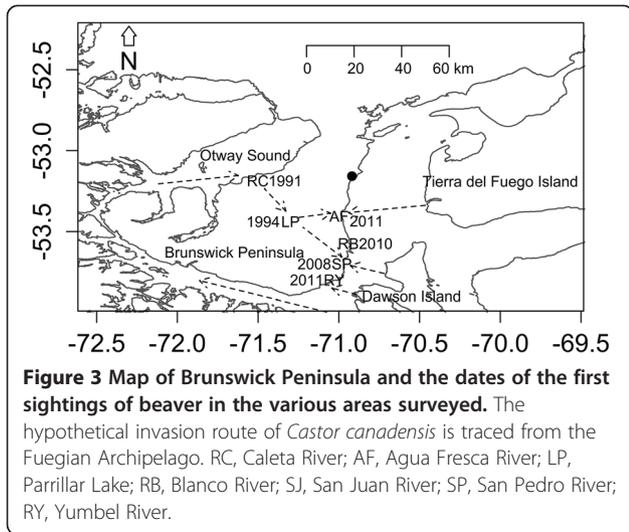
The map created from the dates obtained from the surveys suggests a possible migration route from Caleta River to the Strait of Magellan. The migration of *Castor canadensis* would have occurred from Caleta River

crossing through Parrillar Lake and then dispersed by rivers that flow into the Strait of Magellan. The data do not rule out the possibility of beavers crossing from the islands of Tierra del Fuego and Dawson.

Of the 62 survey respondents, there were 25 owners of small properties, 5 workers of small properties, 15 owners of large properties, 14 workers of large properties, and 3 visitors to large properties. Statistical analysis indicated that the ability to assess beaver presence was dependent on the activity of the respondent ($P = 0.00033$). Owners of larger properties were more successful at properly assessing beaver presence than other groups, with 93% of accuracy (Figure 4). On the other hand, owners of small parcels were the least successful group, with only 36% of the group properly evaluated the presence of beavers. Most differences were false negatives, i.e., the respondents were unaware of beaver presence within their premises or nearby areas.

Table 1 The sites for which respondents indicated the presence of beaver on the Brunswick Peninsula

Site	Estimated time of arrival through surveys (year)
Los Patos Brook	2011
Blanco River area	2010
San Pedro Rriver area	2008
Yumbel Rivera area	2008
Parrillar Lake	1994
Caleta River	1991

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Figure 3 Map of Brunswick Peninsula and the dates of the first sightings of beaver in the various areas surveyed. The hypothetical invasion route of *Castor canadensis* is traced from the Fuegian Archipelago. RC, Caleta River; AF, Agua Fresca River; LP, Parrillar Lake; RB, Blanco River; SJ, San Juan River; SP, San Pedro River; RY, Yumbel River.

Dendrochronology

Of the 144 cores collected, 135 were used to develop the reference series for each of the six sites. Nine cores were discarded because excess moisture and/or state of decay. Using those reference series, 107 trees cut by beavers were successfully cross dated. The average correlation with the reference series obtained for each site was 0.418. At least eight trees were used on each site for the reference series determination (9.5 trees on average). On average, 17.83 trees cut by beavers were cross dated on each site, but only the samples that showed a correlation of 0.320 or higher were kept, resulting in a range of two to eight dated samples per site (Table 2).

For each site, the oldest date of the samples with a correlation index of 0.330 or higher was determined (Table 3). On the eastern shore of the Brunswick Peninsula (closest continental coastline to Tierra del Fuego), the San Pedro River had the oldest recorded beaver activity with trees being cut in 1968 (correlation with the reference series of 0.660). Then, proceeding from oldest to most recent sites, we have Blanco and Yumbel Rivers since 1976 ($r = 0.485$ and 0.780, respectively) and the Agua Fresca River from 2010 ($r = 0.840$). Inland of the Brunswick Peninsula, Parrillar Lake cut trees indicate beaver activity at least since 1996 ($r = 0.330$). On the western shore of Brunswick Peninsula (further away from Tierra del Fuego Island), we only have the Caleta River, where the oldest recorded activity was determined to be in 1986 ($r = 0.380$).

The oldest dates found for tree cutting from each site were considered as an estimation for the date of arrival to the area. Arrival dates were used to infer a map of beaver dispersal from nearby points with known presence of beaver on Tierra del Fuego and Dawson Islands and movement across the continent (Figure 5).

The inferred migration route (Figure 5) indicates that the first beavers to reach the Brunswick peninsula probably crossed to the area of San Pedro River from Dawson Island on 1968, the Yumbel and Blanco River could also be crossings from Dawson or Tierra del Fuego or from a secondary migration from the San Pedro River. The
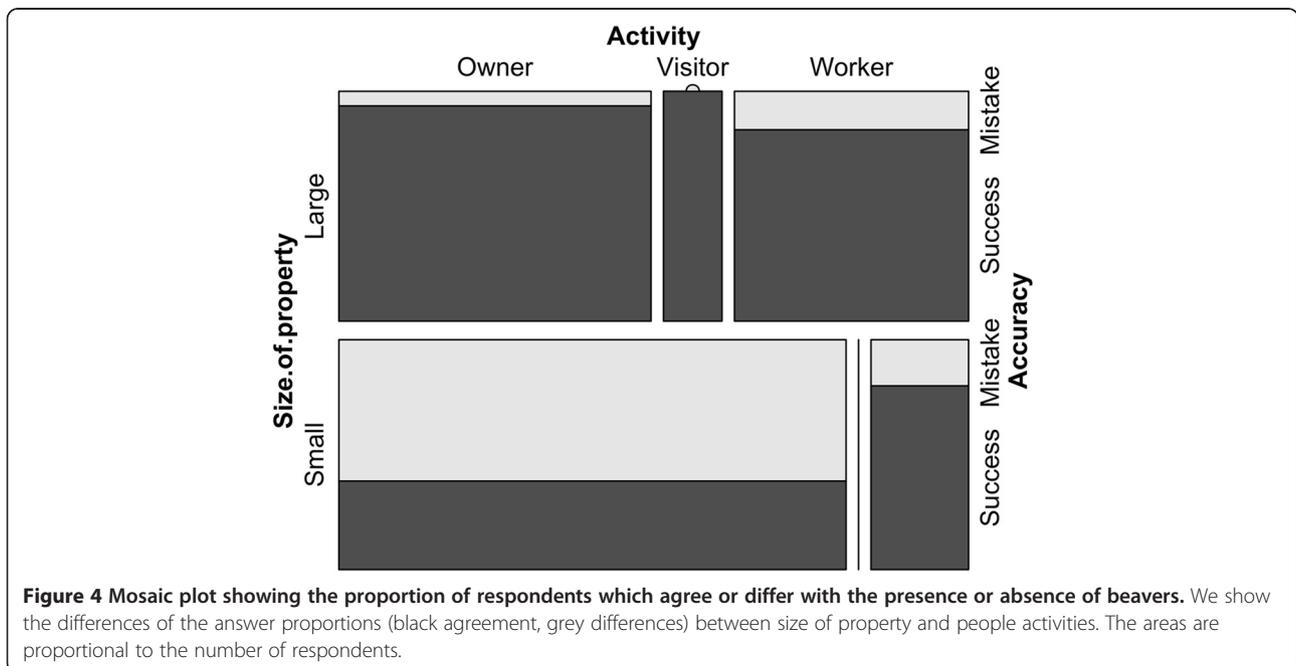

Figure 4 Mosaic plot showing the proportion of respondents which agree or differ with the presence or absence of beavers. We show the differences of the answer proportions (black agreement, grey differences) between size of property and people activities. The areas are proportional to the number of respondents.

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Table 2 Summary of the six sites where the dendrochronological sampling for living trees and beaver stumps was performed

Site	Number of living trees samples	Correlation index with the master series	Number of living trees used for cross dating	Number of samples from stumps	Number of samples with a correlation index >0.330
Caleta River	23	0.365	10	16	6
Parrillar Lake	24	0.324	9	16	2
Agua Fresca River	22	0.405	10	20	2
Blanco River	22	0.473	8	18	8
San Pedro River	24	0.397	10	16	7
Yumbel River	20	0.408	10	21	8
Total	135	-	57	107	33
Average	22.5	0.418	9.5	17.8	5.5

Sample numbers and correlation coefficients obtained by cross dating are indicated.

Caleta River was probably reached using a transpeninsular route going through Parrillar Lake since there is no presence of beaver in nearby islands. The migratory route suggests that the presence of beavers in the Agua Fresca River could be due to a migration from Parrillar Lake or a late crossing from Tierra del Fuego in 2010.

Comparison of surveys and dendrochronology

There were five sites where dating by both methods was possible Yumbel (RY), Blanco (RB), San Pedro (SP), and Caleta (RC) Rivers in addition to Parrillar Lake;

Table 3 Sites of beaver presence in Brunswick Peninsula and stimated date of arrival obtained by dendrochronology

Site	Code of the sample	Correlation index of the simple with the master series	Estimated time of arrival through cross dating
Caleta River	RC1V1	0.380	1986
Parrillar Lake	LP1V5	0.330	1996
Agua Fresca River	AF1V4	0.840	2010
Blanco River	RB1V1	0.485	1976
San Pedro River	SP1V4	0.660	1968
Yumbel River	RY1V6	0.780	1976

Figure 5 Brunswick Peninsula map and estimated date of arrival of beavers in the various areas surveyed. The hypothetical invasion route of *Castor canadensis* is traced from the Fuegian Archipelago. RC, Caleta River; AF, Agua Fresca River; LP, Parrillar Lake; RB, Blanco River; SJ, San Juan River; SP, San Pedro River; RY, Yumbel River.
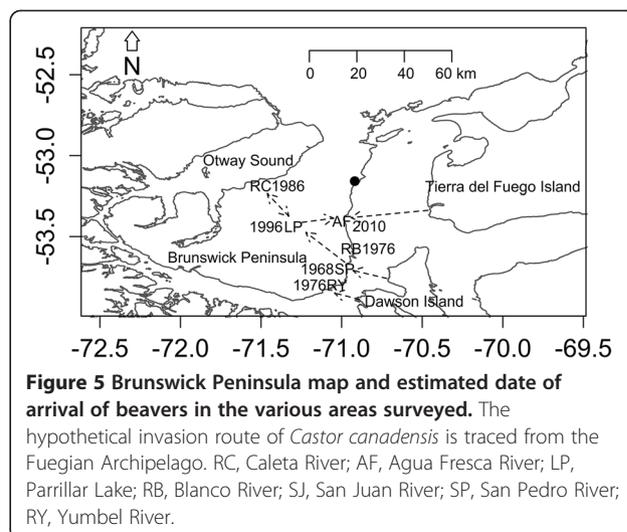
consequently, it was possible to make a methodological comparison through a simple linear regression. Although the relationship between dates determined by the two methods showed a negative trend, it was not significant ($P = 0.238$).

Discussion

The invasion of *Castor canadensis* is a good model to monitor the development of a biological invasion. First, beavers leave a trail of dams and cut trees which are samples suitable for dendrochronological analysis (Muller-Schwarze and Sun 2003). Also, the Magellanic forest, either evergreen or deciduous, is almost monospecific with dominant species like *N. pumilio* and *N. betuloides*, which do not regenerate from stumps (Pisano 1977), thereby facilitating species identification, and an ideal system for cross dating in order to estimate the beaver migration paths. This system allowed us to date invaded sites that previously were dated only through surveys (Skewes et al. 2006; Anderson et al. 2009).

Although surveys provide valuable information on the perceptions of the community, the time required for people to notice changes in nature has not been considered, and this work shows that there is a significant but not constant delay. Estimated dates of first sighting and dendrochronology were mismatched. Even though both solutions are possible, the migration route established through the dates obtained by dendrochronology is shorter than that of obtained by interviews. According to the principle of parsimony (Baker 2003; Baker 2007; Mayo-Wilson 2009), the route determined by interviews could be considered it less likely than the one determined by dendrochronology. Moreover, the analysis of surveys indicates that the activity of a respondent is predictive of the congruence of dates between dendrochronology and

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the interviews (Figure 4). While the owners and employees of large and small properties alike usually inspect their property, owners of large properties go through more area, giving them a sampling advantage over owners and employees of small sites.

Dendrochronological analysis provides a systematic methodology that resulting in absolute dates of beaver arrival, where each sample of a tree cut by beavers is cross dated with a reference series of living trees, giving a correlation value. Although we worked using high correlation values (0.330 or higher), there are parameters that can limit the sampling methodology. For example, in two of the sites studied (Caleta River and San Pedro River), all the trees cut by beavers were sampled (while in Yumbel River and Parrillar Lake approximately 10% of the trees were sampled, with 50% and 20% of the trees on the Blanco River and Agua Fresca River sites, respectively). When the arrival dates were estimated, we assumed to have sampled the oldest felled tree, but as the percentage of trees sampled decreases so does the probability of finding the oldest cut tree. We tried to minimize this possible flaw by selecting the oldest looking stumps and sampling cut trees located closer to the river. Despite these considerations, Parrillar Lake presented sampling issues, because we were only able to sample an estimated 10% of the trees, resulting in a 10% probability of finding the oldest tree. This problem resulted in the oldest date determined by dendrochronology (1996) being later to the date detected by surveys (1994), probably because the oldest cut tree was not among the selected samples.

Considering this source of bias, the sampling of sites with low numbers of felled trees, in which all trees cut by can be accomplished, generates a greater dating accuracy of the migration route. However, loss of information can also occur from moisture conditions that accelerate the process of rotting stumps (possibly the oldest trees cut on each site) or by increasing the probability of error measuring growth rings due to adverse weather conditions (six of the eight samples had this problem in Parrillar Lake). Despite the potential drawbacks of the method, which determines the specific dates for each sampled tree, the oldest date among them is selected as an estimation of the date of arrival of beavers on a site, independent of the presence, activity, or concerns of the human inhabitants. Also, the net effect of these biases will always result in underestimation of antiquity of the date of arrival at a given site, that is, we can only make one type of mistake: by estimating that beavers arrived to a site later than the real date of arrival. Using these specific dates, we were able to establish a map that presents a plausible migration path which is more parsimonious than the map developed using surveys. This migratory route, besides being the shortest, shows a relationship with the geography of the peninsula, where the progress of migration is related to the connection between the basins. Thus, the arrival of beavers between 1968 and 1976 and its progress towards Parrillar lagoon after the arrival in Caleta River and Parrillar and to Agua Fresca River is more likely than the dispersion from Rio Blanco directly to Rio Agua Fresca where there are no rivers that communicate them.

Conclusions

Given the differences between dates established via dendrochronology and interviews in the province of Magallanes, we can assume in general that the dates established for Tierra del Fuego using surveys (Skewes et al. 2006; Anderson et al. 2009) should also have a delay in their estimation of the time of arrival for beavers. Therefore, the only reliable dates for the invasion would be the date of introduction to Tierra del Fuego in 1946 and the dates of arrival to the province of Magallanes in 1968. This work succeeds in presenting the first reliable map of migration for this invasive species in the Brunswick peninsula, showing an error of 26 years in the arrival of this species to the continent, rejecting previous hypothesis about continental settlement beavers.

Dendrochronology is a potential tool that has several uses for policy makers, eradication, and conservation planners, because the number of trees killed by this specie for a specific year and area could serve as an indicator of the abundance of this species or another species causing tree mortality.

Considering beavers alone, this technique could be useful in monitoring populations in eradication programs for the specie which are being planned for Europe (Lorvelec and Pascal 2005; Genovesi et al. 2012; Parker et al. 2012) and South America (Choi 2008; Parkes et al. 2008; Menvielle et al. 2010), to monitor the advance and activity of the same invasive species in Asia (Saveljev and Safonov 1999) and to monitor the reintroduced populations of both *Castor canadensis* and *Castor fiber* (Macdonald et al. 1995; Halley 2011; Baldwin 2013; Gibson and Olden 2014). This could also help in studying the populations of pest species which attack woody species such as bark beetles (Hadley and Veblen 1993; Fettig et al. 2006; Schwilk et al. 2006) or other herbivores and/or pathogens producing tree mortality (Augspurger 1984; Schowalter et al. 1986; Christensen et al. 1995; Cannicci et al. 2008).

Authors' contributions
GG conceived the study and the design, worked in the acquisition of data, analysis and interpretation of data, and did most of the drafting of the manuscript. DC participated in the study's design, coordination, data acquisition, and analysis and helped to draft the manuscript. JCA has been involved in drafting the manuscript and revising it critically for important intellectual content and has given final approval of the version to be published. All authors read and approved the final manuscript.

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