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Senda Darwin Biological Station: Long-term ecological research at the interface between science and society

Estación Biológica Senda Darwin: Investigación ecológica de largo plazo en la interfase ciencia-sociedad

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ABSTRACT

Senda Darwin Biological Station (SDBS) is a field research center immersed in the rural landscape of northern Chiloé island (42° S), where remnant patches of the original evergreen forests coexist with open pastures, secondary successional shrublands, *Sphagnum* bogs, *Eucalyptus* plantations and other anthropogenic cover types, constituting an agricultural frontier similar to other regions in Chile and Latin America. Since 1994, we have conducted long-term research on selected species of plants (e.g., *Pilgerodendron uviferum*) and animals (e.g., *Aphrastura spinicauda, Dromiciops gliroides*) that are considered threatened, poorly known or important for their ecological functions in local ecosystems, and on ecosystems of regional and global relevance (e.g., *Sphagnum* bogs, North Patagonian and Valdivian rain forests). Research has assessed the responses of species and ecosystems to anthropogenic land-use change, climate change, and the impact of management. During this period, more than 100 scientific publications in national and international journals, and 30 theses (graduate and undergraduate) have been produced by scientists and students associated with SDBS. Because of our understanding of the key role that humans play in ecological processes at this agricultural frontier, since the establishment of SDBS we have been committed to creative research on the communication of science to society and ecological education. The integration of SDBS to the nascent Chilean network of long-term socio-ecological research will consolidate and strengthen basic and applied research to project our work into the next decade.

Key words: biodiversity, education, long-term socio-ecological research, private protected area, temperate rainforest.

RESUMEN

La Estación Biológica Senda Darwin (EBSD) constituye un centro de investigación inmerso en el paisaje rural del norte de la Isla de Chiloé (42° S), donde fragmentos del bosque siempreverde original coexisten con praderas de uso ganadero, turberas de *Sphagnum*, matorrales sucesionales, plantaciones de *Eucalyptus* y otras formaciones de origen antropogénico. Desde 1994 hemos realizado estudios de largo plazo centrados en algunas especies de plantas (e.g., *Pilgerodendron uviferum*) y animales (e.g., *Aphrastura spinicauda, Dromiciops gliroides*) catalogados como amenazados o escasamente conocidos y en ecosistemas nativos de importancia regional y global (e.g., turberas de *Sphagnum*, bosque Valdiviano y Nordpatagónico). Las investigaciones han considerado las respuestas de las especies y de los ecosistemas frente al cambio antropogénico del paisaje y cambio climático, así como los efectos de diferentes formas de manejo. Este escenario es semejante al de otras regiones de Chile y Latinoamérica lo que da generalidad a nuestros resultados y modelos. En este período, investigadores asociados a la EBSD han producido más de un centenar de publicaciones en revistas nacionales e internacionales y 30 tesis de pre y postgrado. Entendiendo el papel clave de los seres humanos en los procesos ecológicos de la zona rural, la EBSD ha desarrollado un programa de educación ecológica y vinculación del avance científico con la sociedad local y nacional. La integración de la EBSD a la naciente red de Sitios de Estudios Socio-Ecológicos de Largo Plazo en Chile consolidará y fortalecerá la investigación básica y aplicada que realizamos para proyectarla hacia la siguiente década.

Palabras clave: área protegida privada, biodiversidad, bosques templados, educación, investigación socio-ecológica de largo plazo.

INTRODUCTION

Temperate rain forests of southern South America, distributed from 35° to 55° S along the western margin of the continent, are characterized by their high degree of endemism, including relicts of ancient biotas largely lost or transformed by Pleistocene climate change (Armesto et al. 1996, Villagrán & Hinojosa 1997). The northern end of Chiloé Island, approximately at the midpoint of the latitudinal range of temperate, sub-Antarctic forests, is the location of Senda Darwin Biological Station (42°53' S, 73°40' W), SDBS hereafter.

This geographic region has at least three interesting features, from the point of view of ecological studies with a focus on ecosystem functioning: (1) Here, the glaciers reached their northwest limit during the last glacial period (Villagrán et al. 1995), which implies that present-day forests colonized the lowlands and mid-elevations only in the last 20 thousand years, following postglacial warming, displacing bogs and shrublands. Consequently, forests have maintained a degree of resilience against huge disturbances and past climatic changes during several glacial-interglacial cycles, which can inform us about its potential responses to future climate change. (2) Currently, the two most important native forest types that co-occur in the region have the highest biological diversity of all evergreen rainforests in southern South America. These are the Valdivian and the North Patagonian rainforests, both associated with emblematic plant and animal species for the region. Knowledge of the dynamics and sustainable management practices in these forests is still limited (Gutierrez et al. 2009). (3) It is an agricultural-forest frontier (Jaña-Prado et al. 2006), where land use change proceeds at a high pace (Echeverria et al. 2007), leading to fragmentation and conversion of native forests into other types of "anthropogenic" land cover, such as grazing pastures, eucalypt plantations, *Sphagnum* bogs (pomponales), and shrublands. Such changes, which also affect, lakes and seascapes, due to extended salmon farming, are producing major biological and cultural impacts that we are just beginning to understand.

SDBS is inserted in the mosaic of wild and anthropogenic communities that characterize this region (Fig. 1, Appendix), thus providing the opportunity to investigate ecosystem interactions within a rural landscape context, similar to other areas of southern Chile and South America (Armesto et al. 1998). From this place, we may also understand and model the biological and cultural changes that will shape the rural landscape in the future. For about 15 years, SDBS has supported scientific research on biodiversity and ecosystem processes conducted in this rural environment and in surrounding protected areas. During this period, with the sponsorship and/or support of SDBS, more than one hundred scientific publications in national and international journals, and 30 theses have been produced (Fig. 2). Research has been centered on a set of ecologically relevant species of plants and animals of the forest (e.g., threatened species, key mutualists, dominants, etc.) and on their ecosystem context. Several studies extend beyond three years, period that characterizes a regular funding cycle in Chile, and therefore can be defined as long-term studies (Armesto 1990). The goal of this article is to provide a synthesis of the advances and projections of the main research and education programs of SDBS, highlighting those driven by long-term questions. SDBS has now joined the nascent Chilean Long Term Socio-Ecological Research Network (LTSER), whose organization, objectives and agenda are presented in this Special Feature of the RCHN.

RESEARCH PROGRAM

Climatic characterization

The characterization of local climate, its seasonal and inter-annual fluctuations, and long term trends, represents an essential component of long-term studies of terrestrial ecosystems. SDBS maintains since 1997 a continuous record (with one-hour resolution) of wind speed and direction, solar radiation, air and soil temperatures, air relative humidity and precipitation. This is the only current instrumental climate record from northern Chiloé Island. The summary of monthly records of air temperature and precipitation (Fig. 3, Table 1) illustrates the seasonal patterns of climatic variability for this area. The inter-annual variability, estimated by the coefficient of variations (CV) of monthly precipitation between years are higher during the drier austral summer months (CV = 71, 74 and 64 %, for December, January and February, respectively) than during the wetter winter (CV = 31, 32 and 24 %, for June, July and August). Variance of air temperatures among years is much lower than for precipitation and higher in autumn and winter (CV = 27, 25 y 23 % for May, June and July). The annual averages of temperature and precipitation for the period monitored are 10° C and 2110 mm, respectively (Table 1). In the long-term such records can unravel trends that cannot be detected from short-term records. In particular, we are interested on the variability in the volume and frequency of the summer rains, for which a declining trend is expected in the next decades for south-central Chile (DGF & CONAMA 2006), and in comparing this trend with other longer-term climate records from this region (e.g., Puerto Montt). With the nascent Chilean LTSER Network we expect to maintain and compare records from a variety of ecosystems from semiarid and sub-Antarctic latitudes.

TABLE 1

Summary of climate record of EBSD, period 1997-2008 (excluding months with missing data due to instrumental failure).

Resumen del registro climático de la EBSD, período 1997-2008 (excluyendo meses con datos faltantes por falla instrumental).

Variable	Value
Mean annual temperature (°C)	9.6
Minimum-Maximum (°C)*	
General	4.0 – 19.1
Summer (Dec-Feb)	6.1 – 19.1
Autumn (Mar-May)	4.6 – 17.0
Winter (Jun-Aug)	4.0 – 11.0
Spring (Sep-Nov)	4.0 – 15.2
Mean annual precipitation (mm)	2109.9
Precipitation fraction	
Summer	13.2 %
Spring	20.2 %
Autumn	27.8 %

* Considering the monthly average of maximum and minimum temperature.

Permanent plots and forest dynamics

Long-term monitoring of forests is a valuable tool for detecting regeneration trends for long-lived species associated with regional and global changes in climate and/or disturbance regimes (Armesto et al. 1996, Garreaud & Battisti 1999, Gutiérrez et al. 2009). Forest monitoring is also useful for evaluating the effectiveness of protected areas and biodiversity conservation strategies, as well as the long-term consequences of forest management (Arroyo et al. 1999, Lindenmayer & Franklin 2002). However, monitoring of ecosystem state variables is a task not yet consolidated in Chile. In this context, the forest monitoring network led by SDBS is a pioneer initiative to explore the responses of native forests to future changes in climate and disturbance regimes.

Since 1998, SDBS has set up a network of permanent plots in primary and secondary forests, including sites first sampled in 1989 in Chiloé (Table 2, cf. Aravena et al. 2002). Nowadays, this network has 10 plots in Valdivian rain forests, 13 in North Patagonian forests, four in *Fitzroya cuppressoides* forests, and four in *Pilgerodendron uviferum* D. Don forests (Gutiérrez et al. 2004). SDBS also collaborates with other sites of Chilean LTSER, such as Fray Jorge (Gutiérrez et al. 2008a), other Parks and Reserves, such as Los Ruiles and Los Queules in central Chile, and subantarctic forests in Omora Etnobotanical Park (Table 2). In total, the permanent Plot network led by SDBS has 40 PP (Table 2), established with similar sampling protocols (Aravena et al. 2002) in private and public protected areas. In remnant old-growth forests in the rural landscape of northern Chiloé Island some 500-years old trees were recorded (Gutiérrez et al. 2004, 2009) (Table 2).

Recently, sampling of successional plots following anthropogenic fire in SDBS (SD1, Aravena et al. 2002) revealed patterns of recovery of forest structure. The size structure of trees in 1998 showed a concentration of trees in diameter classes < 10 cm (Fig. 4) along with some remnant snags and old trees from the original forest (*Weinmannia trichosperma* Cav. and *Nothofagus nitida* (Phil.) Krasser). Legacy trees facilitate the establishment of other tree species by increasing seed inputs by birds ("perch effect"). In the plot, the establishment of tree seedlings occurred mainly on logs and woody debris (Papic 2000). One decade later, trees with dap < 10 cm are still the most frequent, but the density of trees of intermediate diameter classes (10-35 cm) increased (Fig. 4). *Drimys winteri* J.R. et G. Foster and *Nothofagus nitida*, both fast-growing pioneer tree species, dominate in the first two decades of succession. Additionally, we recorded a higher number of tree species with stem diameter < 5 cm, and a higher proportion of shade-tolerant saplings (e.g., *Caldcluvia* paniculata (Cav.) D. Don, *Saxegothaea conspicua* Lindl. and *Podocarpus nubigena* Lindl.). Long-term monitoring

TABLE 2

Permanent plot network for periodical monitoring of native forests. The first 16 sites belong to Chiloé island. N = number of 50 x 20 m plots (* are 20 x 20 m) per site. Protected area considers different protection categories, private or public, n.a: is not considered a protected area by land owners. §: Plots represent a successional chronosequence with different ages from the last disturbance (Aravena et al. 2002). †: Plots represent old-growth forests along an altitudinal gradient with different disturbance regimes (Gutiérrez et al., unpublished data). ‡: Plots have been monitored regularly since their installation.

Red de parcelas de monitoreo periódico de bosques nativos. Las primeras 16 localidades pertenecen a la isla de Chiloé. N = número de parcelas de tamaño 50 x 20 m (* indica parcelas de 20 x 20 m). Área protegida se refiere a la categoría de protección, pública o privada, n.a.: no es considerada por los dueños como área protegida. §: Las parcelas representan una cronosecuencia sucesional con distintas edades desde la última perturbación (Aravena et al. 2002). †: Las parcelas representan bosques antiguos en un gradiente altitudinal con diferentes regimenes de perturbación (Gutiérrez et al., datos no publicados). ‡: Las parcelas han sido monitoreadas regularmente desde su instalación.

Site, or property name	Forest Type	*N*	Protected Area	Installation Date	Successional Stage	Disturbances
SDBS, Ancud	Ciprés de las Guaitecas	1	Private	1998	Early	Fire
SDBS, Ancud	Nordpatagonian	4	Private	1998‡	§	§
Fundo Rapoport, Ancud	Nordpatagonian	2	Private	1999	Early	Fire
Fundo Rapoport, Ancud	Ciprés de las Guaitecas	1	Private	1998	Early	Fire
Fundo Aguila Cárcamo, Ancud	Nordpatagonian	1	n.a.	1998	Mid	Selective cut
Koenig, Ancud	Nordpatagonian	1	n.a.	1999	Mid	Selective cut
Koenig, Ancud	Ciprés de las Guaitecas	1	n.a.	1998	Mid	Selective cut
Quemado Caulín, Ancud	Nordpatagonian	1	Private	1999	Initial	Fire
Guabún, Fundo Velázquez, Ancud	Valdivian	2	Private	2002	Late	None apparent
Ahuenco, Ancud	Valdivian	2	Private	2004	Late	None apparent
Fundo Cisnes, Ancud	Nordpatagonian	1	Private	2004	Mid	Selective cut
Melleico, Fundo Forestal Tantauco, Chonchi	Nordpatagonian	2	n.a.	2005	Mid	Selective cut
Melleico, Fundo Forestal Tantauco, Chonchi	Valdivian	4	n.a.	2002 and 2005	Late	None apparent
Abtao, Parque Nacional Chiloé	Alerce	1	Public	1989	Late	None apparent
Abtao, Parque Nacional Chiloé	Nordpatagonian	1	Public	1989‡	Late	None apparent
Colecole, Parque Nacional Chiloé	Valdivian	2*	Public	1990	Late	None apparent
Parque Nacional Fray Jorge, Ovalle	Coastal Olivillo	6	Public	2003	Late	None apparent
Reserva Nacional Los Queules, Cauquenes	Maulino	1	Public	-	Late	Fire
Reserva Nacional Los Ruiles, Cauquenes	Maulino	1	Public	-	Late	Fire
Parque Etnobotánico Omora, Puerto Williams, Isla Navarino	Subantartic deciduous and evergreen	5	Private	2004 and 2005	†	†

adds to experimental studies (Papic 2000, M. Bustamante, unpublished data) seeking to understand patterns and mechanisms of succession in Chiloé forests.

Studies of native forests of Chile have been conducted in secondary forests subjected to fire, woodcutting and cattle raising (Lara et al. 2000). Such studies are relevant to evaluate management practices and their effects, but it is also necessary to extend monitoring to old-growth forests, lacking direct human impacts (Gutiérrez et al. 2009), to evaluate predictions about effects of physical environment (e.g., disturbances and climatic regimes) and demography (e.g., mortality and recruitment).

PPs in forests can allow tests of hypothesis about the forest stability and resilience after disturbances (Hendrickson 2003). For example, we can investigate collateral effects of fragmentation on the persistence of plant-animal interactions and forest structure (Laurance et al. 1998, Gutiérrez et al. 2009); and evaluate the importance of old-growth forest structure for biodiversity conservation, regeneration dynamics and ecosystem functioning (Díaz et al. 2005, 2006, Jaña-Prado 2006, 2007, Carmona et al. 2002, Christie & Armesto 2003).

Studies of PP (Table 2) have documented changes in soil properties (e.g., C:N ratio) and biochemical

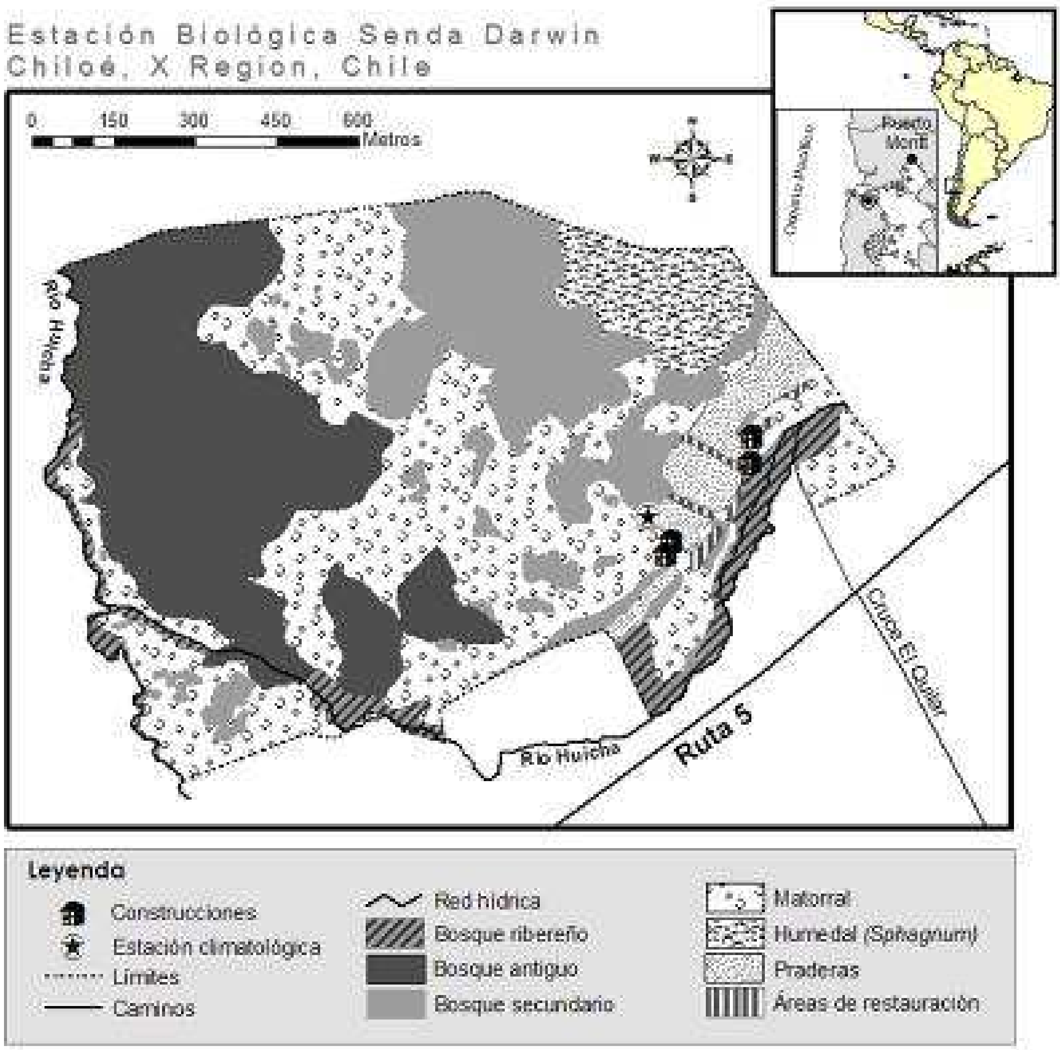

Fig. 1: Map of Senda Darwin Biological Station (EBSD), showing the main vegetation types of the rural landscape, and part of the station's facilities. Geographic coordinates (Weather station): 42°53' S, 73°39' W. Total surface: 115 ha.

Mapa de la Estación Biológica Senda Darwin (EBSD), distinguiendo los principales tipos de vegetación del paisaje rural, y parte de la infraestructura presente. Coordenadas geográficas (Estación climatológica): 42°53' S, 73°39' W. Superficie total: 115 ha.

processes (e.g., non-symbiotic nitrogen fixation and nitrogen mineralization) through a successional chronosequence in Chiloé forests (Aravena et al. 2002, Pérez et al. 2004, Carmona 2004). This work revealed the strong resilience of soil processes to anthropogenic fire disturbances of moderate intensity. Comparison of soil biogeochemical processes among primary and selectively logged forest stands indicated disruption of some basic soil functions (Pérez et al., 2009). Combining functional studies with tree demography will provide insights into the plant-soil interface and its effects on stand dynamics.

Peatland ecology and sustainable management of Sphagnum *moss*

Peatlands, dominated by mosses of the genus *Sphagnum*, are characterized by massive deposits of organic matter, with sparse or no tree cover. They are distributed in regions where precipitation exceeds 2000 mm, and are usually found in depressions with poorly drained soils, where water accumulates or flows very slowly. Peatlands play key ecological functions, because of their capacity to store rain water, preserve the quality of water that drains into the rivers and estuaries, and sequester large quantities of carbon in the form of

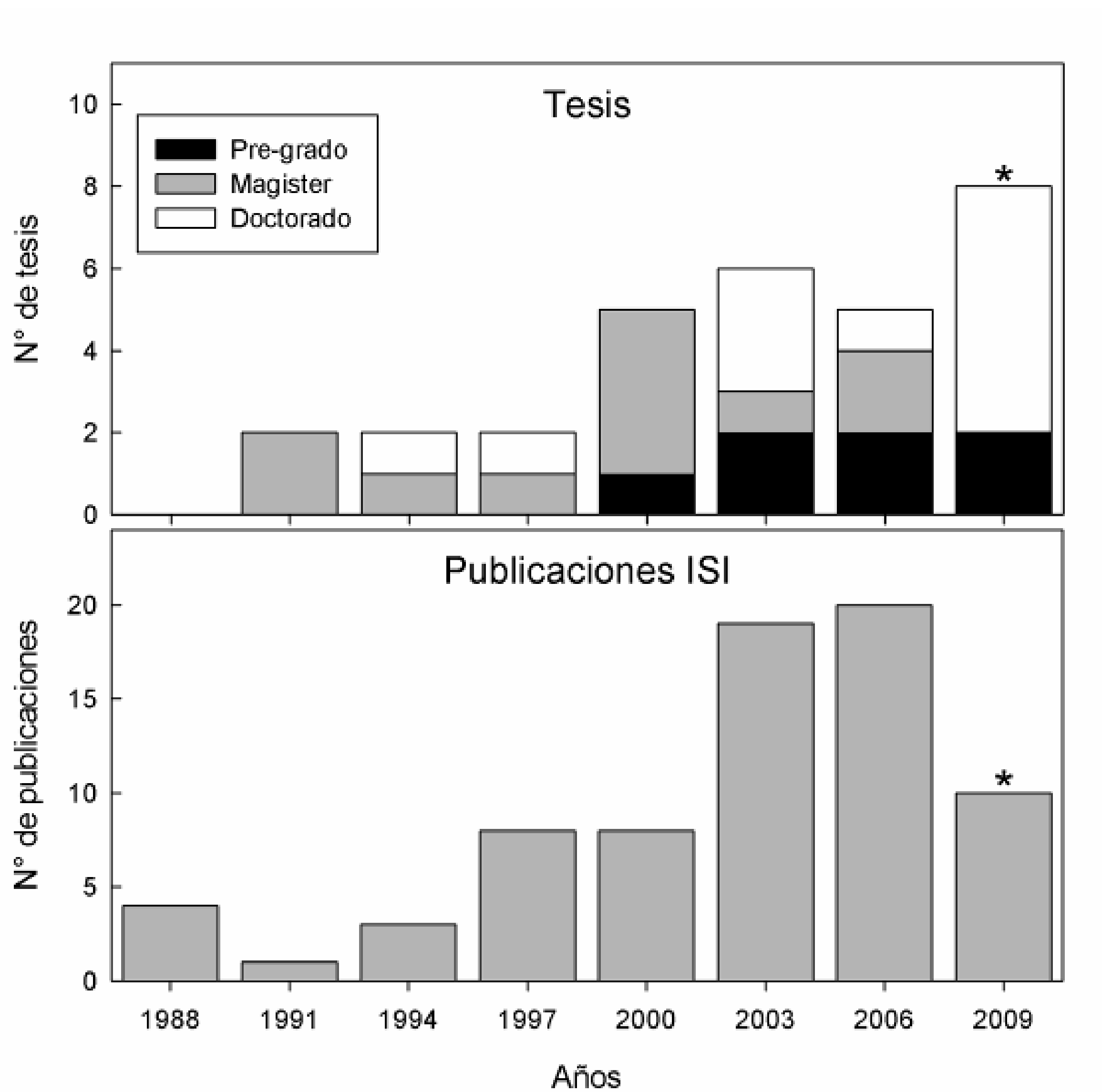

Fig. 2: Number of ISI publications and thesis (under and postgraduate) generated from studies within EBSD and its surroudings, or by associate researchers, counted by three years intervals, but the last one (*) including only year 2008 up to April 2009.

Número de publicaciones en revistas ISI y tesis (pre y postgrado) generadas a partir de trabajos en la EBSD y sus alrededores, o por investigadores vinculados a ella, en intervalos de tres años, salvo el último (*) que solo incluye el año 2008 y hasta abril del 2009.

organic matter (Clymo & Hayward 1982, Clymo et al. 1998, Gorham 1991, Moore et al. 1998).

In Chiloé, we find two types of peatlands: primary (natural) and secondary. Secondary or anthropogenic peatlands are generated by human action, and locally known as "pomponales" because of the common name for *Sphagnum* moss, "pompon" (Díaz et al. 2008). Natural or primary peatlands have accumulations of organic matter up to several meters and date back to the last glacial cycle (18 to 20 kyr BP), when moorland vegetation occupied most of Chiloé Island (Villagrán 2001). Anthropogenic peatlands present less accumulation of peat and are generated after fires or clearcutting of forest predominantly during the 20th century. Secondary peatlands are present in SDBS (Fig. 1).

For the past two decades, farmers of the Lake District have extracted peat moss (*Sphagnum magellanicum* Brid.) for commercial purposes. The moss is exported dehydrated and pressed, mainly to be used as substrate for horticulture. This extraction remains unregulated, as no government or private agency assumes responsibility over the management of the resource.

Starting in 2004 we have studied the ecology of peatlands. Fits, we assessed status of the moorland ecosystem and promoted the use of sustainable harvesting methods. Two documents are available in our web site (http://www.sendadarwin.cl), the first one addresses the ecological importance of peatlands and *Sphagnum* moss in Chiloé Island, and the second one is a field guide to the vascular flora of peatlands (primary

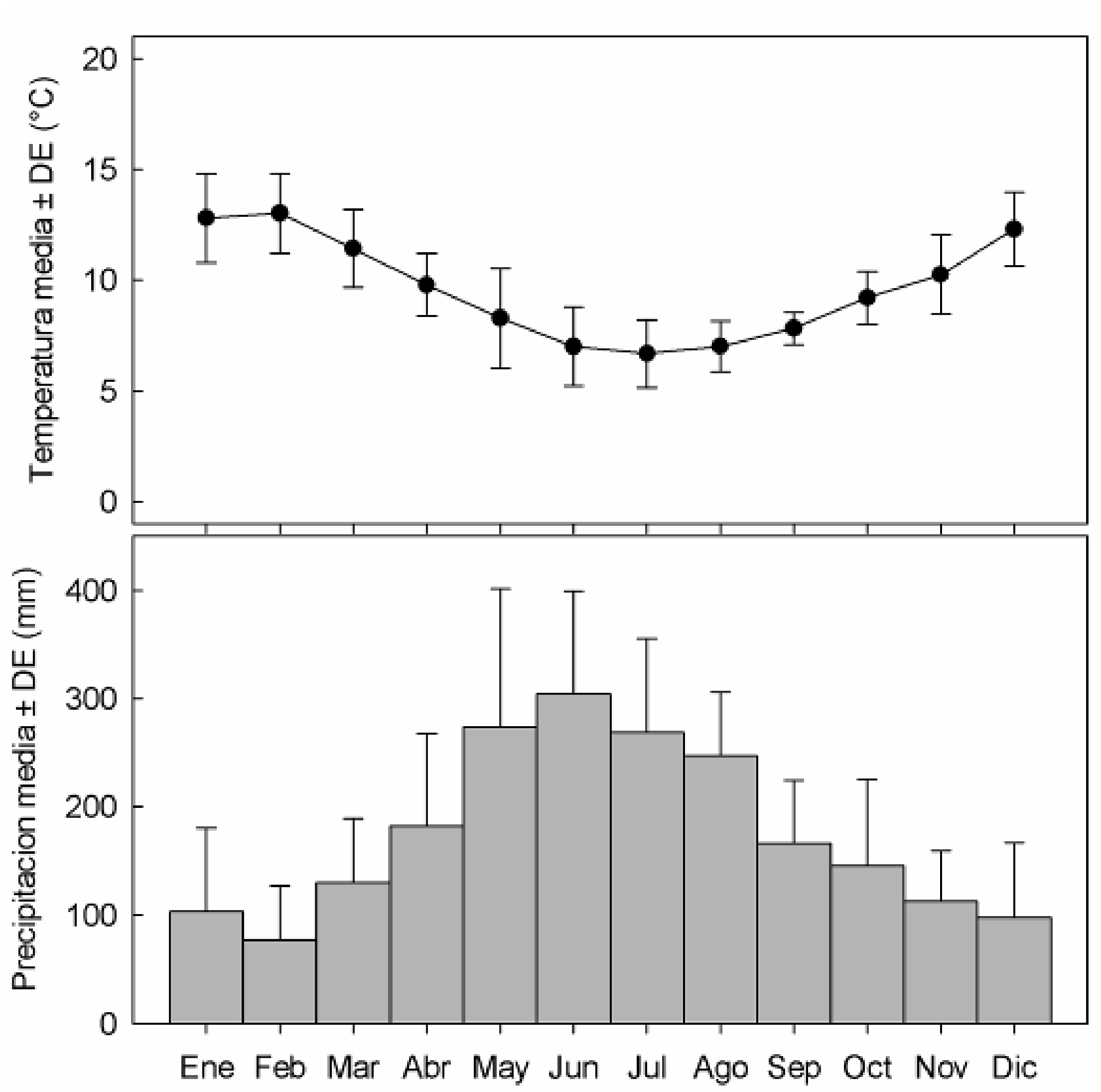

Fig. 3: Monthly averages and inter-annual variability of air temperature and precipitation from data of weather station of EBSD (1997-2008). Error bars: ± 1 SE (n = 8-13 years, upon data availability).
Promedios mensuales y variabilidad interanual de la temperatura del aire y precipitación según datos de la Estación Meteorológica de la Estación Biológica Senda Darwin (1997-2008). Barras de error: ± 1 DE (n = 8-13 años, según disponibilidad de datos).

and secondary). Training workshops have focused on the knowledge of moorland vegetation and the hydrology of peatlands. These have been addressed primarily to indigenous communities (Púlpito and Romazal) and to local farmers, but also to public agencies. A symposium was held in Puerto Montt to discuss the legal and environmental aspects of peatland sustainability.

On these bases, together with local private agencies and farmers' organizations, we implemented a productive and commercial model applied to local peatlands. Field experiments were conducted in farmers' plots to estimate the growth and productivity of the moss before and after harvesting (Díaz & Tapia, manuscript in preparation). In addition, technical advice was offered to farmers interested in the sustainable management of their peatland resources and for improving market options (Díaz 2008).

A second phase of this project, starting in November 2008 consists of evaluating the regeneration, growth and productivity of *Sphagnum* under different experimental conditions of light and humidity. Such experiments provide knowledge with social relevance, relates to the effects of future climate change, and lays the foundations for better management of this resource, which is currently neglected by government agencies.

Ecology of secondary shrublands

During the last decades, native forests of Chiloé Island have been increasingly replaced by successional shrublands with sparse tree regeneration (Díaz 2004, Echeverría et al. 2007). The dynamics of regeneration of degraded lands generated by anthropogenic activities has been a major focus of research at SDBS. Although shrublands are often surrounded by forest patches (< 300 m), providing propagule sources, tree colonization has not taken place for at least 50-60 years. The main pioneer tree species of Chiloé forests, *Drimys winteri* (Winteraceae) and *Nothofagus nitida* (Nothofagaceae), are frequently absent from these areas. We have investigated the biotic and abiotic factors that limit tree colonization of secondary shrublands.

Alteration of the hydrological cycle, due to shifts from forest to shrubland or pasture (Díaz et al. 2007), may be limiting tree colonization due to the seasonal flooding of the soils, suggesting that water table depth may act as an "environmental filter" (sensu Fattorini & Halle 2004). Water table levels are 15 to 50 cm higher in shrublands than in neighboring forest, even during the drier summer months (Díaz et al. 2007). Tree seedlings established on woody debris survived longer than on soil, suggesting that elevation above the soil level may be required for tree seedlings to become established (Papic 2000).

Seeds of most the woody species in Chiloé are actively dispersed by frugivores and do not present dormancy (Armesto & Rozzi 1989, Willson et al. 1996). Seed rain could also be a limiting factor for tree colonization of anthropogenic shrublands and pastures (Jaña-Prado 2007). Woody vegetation that survives the disturbance or becomes established immediately following the disturbance could facilitate propagule arrival. Secondary vegetation dominated by the shrub *Baccharis patagonica* H. et A. receives much lower seed rain density than vegetation dominated by shrubs of *Berberis* (Bustamante-Sánchez & Armesto, ms in

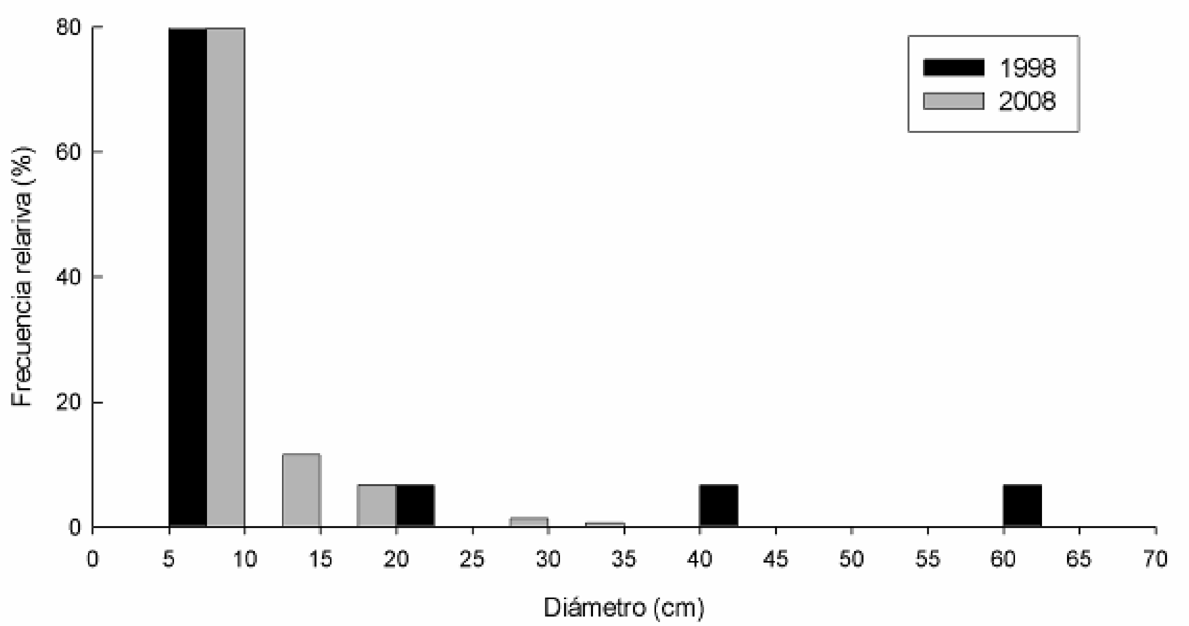

Fig. 4: Changes of diameter structure of a secondary forest of EBSD after 10 years of post-fire succession.
Cambios en la estructura de diámetros de un bosque secundario de la EBSD después de 10 años de sucesión postincendio.

preparation). Such difference may be related to the behavior of seed-disseminating, fruit-eating birds, which preferably visit the fleshy-fruited shrubs of *Berberis* spp., rather than dry-fruited *Baccharis* (Armesto et al. 2001, Jaña-Prado 2007). During the post-dispersal phase, seed predation by birds and rodents, and facilitation by established vegetation are relevant modulators of tree recruitment in secondary shrublands. Dispersed seeds are subjected to higher predation in shrublands dominated by *B. patagonica* than in pastures (Table 3). The pioneer tree species *Embothrium coccineum* J.R. et G. Foster germinates and can become established in open areas covered by the moss *Sphagnum magellanicum* (Díaz & Armesto 2007), while seed germination and/or survival of *Amomyrtus luma* Mol. and *Eucryphia cordifolia* Cav. can only occur under the cover of shrubs (Bustamante-Sánchez et al., MS in preparation). To date we have identified mechanisms that delay or facilitate tree regeneration in tree-less successional areas, based on studies have lasted one or two seasons (e.g., Díaz & Armesto 2007, Armesto et al. 2001, Jaña-Prado 2007, Bustamante-Sánchez et al., ms. in preparation). However, it is necessary to extend these studies to temporal scales more congruent with the dynamics of successional processes, integrating the effects of climate variability and fluctuations in tree fecundity (Clark et al. 1999). The nascent Chilean LTSER Network will enable the implementation of studies at decadal scales in accordance with population dynamics and longevities of pioneer and late successional species.

Experimental studies of climate change

Both climate change models and instrumental data for the temperate region of southern South America, predict a decline and irregularity of summer rainfall for the next decades (DGF & CONAMA, 2006). For this reason, during the year 2007 we started a long-term experiment that simulates a reduction of 20-30 % of summer precipitation in two 60-80 years old, secondary forests (canopy of 15-20 m), dominated by *Nothofagus nitida, Drimys winteri*, and *Caldcluvia paniculata*. Our experimental setup excludes a fraction of rain through the canopy (throughfall) within two 20 x 20 m plots, which are compared with two control plots (without rain exclusion) of the same dimensions. This long-term study follows a protocol similar to those used in similar throughfall exclusion experiments, focusing on one hectare of seasonal tropical forest in Brazil (Nepstad et al. 2002). The throughfall exclusion treatment has been applied during two consecutive summers in one of the plots, and radial growth of trees, fern cover, litterfall, soil respiration, and litter decomposition responses have been monitored continuously. Records of soil moisture and air temperature have been maintained during the whole year, in both control and treated plots. The goal of this experiment is to assess the resilience of population and ecosystem processes in temperate forests in the face expected climate change trends, especially considering that summer drought can be a limiting factor for the arboreal recruitment (Papic 2000).

Chucaos: Population biology and conservation

Chucao tapaculos (*Scelorchilus rubecula* [Kittlitz]) (Fig. 5A) are emblematic birds of the southern rainforest in Chile and westernmost Argentina. They are narrowly endemic to the rainforest zone, occupying a very limited geographic range, and requiring dense vegetative cover (Willson 2006). They nest in cavities, occupying holes in alive or dead trees, fallen logs, soil monticules, and eventually litter and epiphyte accumulations (DeSanto et al. 2002). Because this species is highly sensible to habitat loss and fragmentation (Sieving et al. 2000), it can serve as referent for the conservation of other species restrained to forest. We studied populations of chucaos in SDBS and forest fragments in the surrounding rural landscape for 15 years, documenting unknown aspects of their biology and natural history, as well as the effects of forest fragmentation and forest cover loss on nest success and dispersal through the landscape (e.g., Willson et al. 1994, Willson 2006).

Chucaos are nonmigratory, understory (first vertical 2 m of forests) birds that seldom fly very far. They forage for invertebrates on the forest floor, sometimes also consuming small frogs and fallen fruits (Willson 2006). They are strongly territorial and each mate defends an average territory of 1 ha in size. Territorial conflict sometimes involves physical combat near a territory border, especially early in the nesting season.

TABLE 3

Mean percentage of seed predation, principally by rodents and granivorous birds, of eight woody species in a shrubland of *Baccharis patagonica* and a pastures. Seed predation stations were installed (one petri dish per species with 10 seeds each one) during the summer and fall of 2005. The number of seeds left was counted after five nights of exposure to the granivores. Between parentheses is shown the standard error.

Porcentaje medio de remoción o depredación de semillas de ocho especies leñosas principalmente por roedores y aves granívoras en un matorral de *Baccharis patagonica* y en una pradera. Se instalaron estaciones (una placa petri por cada especie, con 10 semillas cada una) durante el verano y otoño de 2005. El número de semillas remanentes se contó después de cinco noches de exposición a los granívoros. En paréntesis se muestra el error estándar.

	Summer	Autumn
Shrubland	29.2 (4.1) N = 92	87.3 (2.7) N = 105
Pasture	5.3 (1.9) N = 93	66.8 (4.1) N = 105
Kruskal-Wallis test	$H_{(1.185)}$ =28.39; P < 0.001	$H_{(1. 210)}$=11.14; P < 0.001

Chucaos mature one year after hatching, they are socially monogamous, and both parents care for the chicks. Annual survival of banded adults was 44 % from age one to age two years, and 72 % from age 2 to age 7 years (Willson & Pendleton 2008). The longest-lived individuals so far recorded reached age 7, but the average lifespan is much shorter.

Their predators include diurnal and nocturne raptors birds. Chucaos often show great alarm if they see a chuncho (*Glaucidium nanum* [King]) and hide their chicks if they detect a peuquito (*Accipiter chilensis* [Vieillot]) or a concon (*Strix rufipes* King) nearby. Domestic dogs and cats that roam in the forest are another serious threat. Main nest predators are probably rodents and the marsupial monito del monte (*Dromiciops gliroides* [Thomas]) (Willson 2006). Nest success is greater in nests protected by long entrance tunnels than in less well-protected sites. A pair can raise two, or occasionally three broods each year in remnant forest fragments of rural landscape of northern Chiloé Island. Nest success of chucaos was c. 72 % in continuous forest (in Chiloé National Park) and 63 % in fragmented forests, compared to 20-30 % in open-cup nesters in the same region (DeSanto et al. 2002, Willson et al. 2005). Logging is a significant threat to Chucaos in forest fragments, because by removing large trees, it removes safe nest sites. Logging, together with grazing and trampling by cattle, also destroys good understory cover and so increases exposure to predators and reduces the production of leaf litter, where chucaos find most of their food.

In the rural landscape, some forest fragments are completely surrounded by pastures, isolated from other forest patches. Because pastures are barriers to movement of Chucaos (and other forest-understory birds), isolation increases the inbreeding potential and reduce its reproductive success (Castellón & Sieving 2006a, 2006b, Willson 2004). Banded juvenile Chucaos were more likely to remain in isolated natal fragments than in forest patches that were connected to other fragments. About 21 % of juveniles in isolated fragments stayed there when they matured, compared to only 3 %

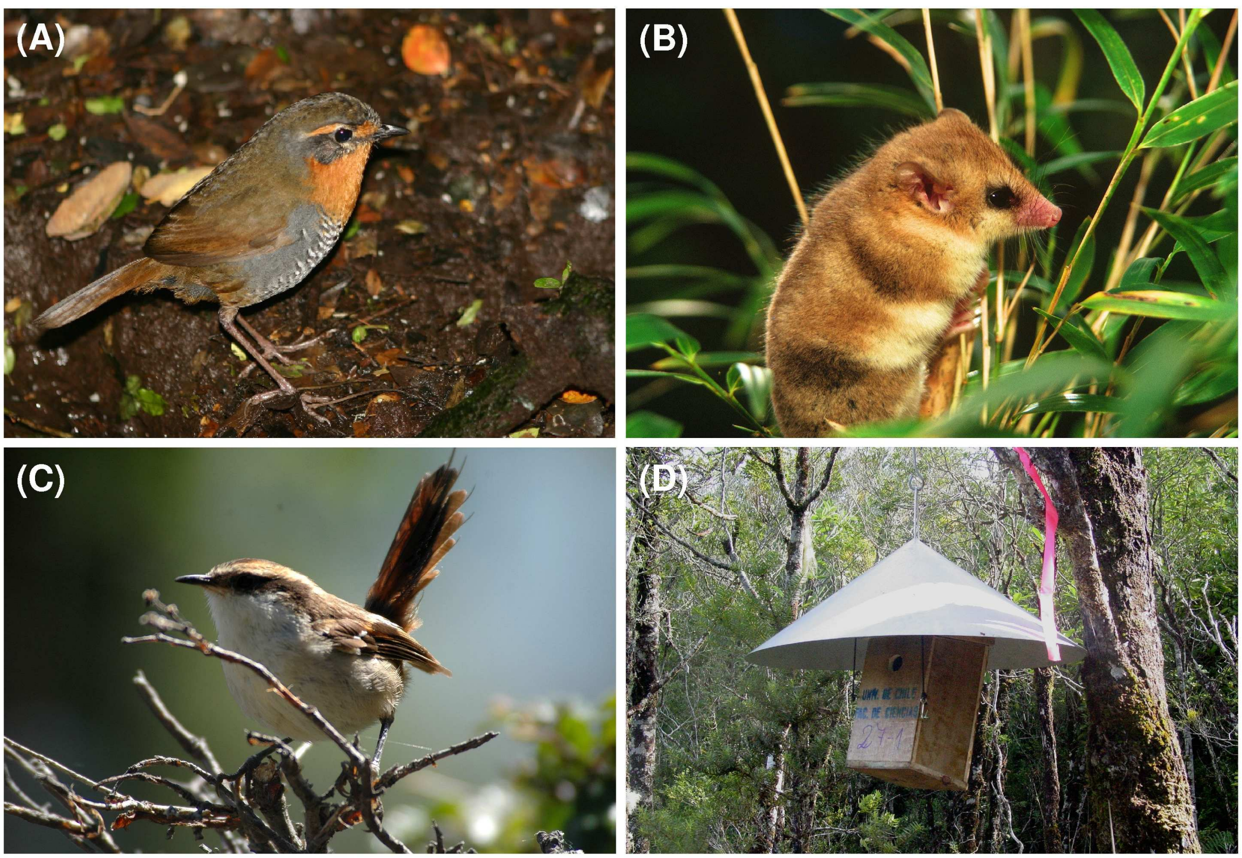

Fig. 5: Bird and mammal species most intensively studied in EBSD and the LTSER network: A: chucao (*Scelorchilus rubecula*). Photography: Juan Luis Celis. B: monito del monte (*Dromiciops gliroides*). Photography: Andrés Charrier. C: rayadito (*Aphrastura spinicauda*). Photography: Juan José Sanz. D: nesting box for rayadito studies and other temperate forest birds, with protection against monito del monte, an egg and chick predator.

Especies de aves y mamíferos más intensamente estudiadas en la EBSD y la red ESELP. A: chucao (*Scelorchilus rubecula*; fotografía: Juan Luis Celis). B: monito del monte (*Dromiciops gliroides*; fotografía: Andrés Charrier). C: rayadito (*Aphrastura spinicauda*; fotografía: Juan José Sanz). D: caja anidera para estudios en rayadito y otras aves de los bosques templados, con protección metálica para evitar el ingreso del monito del monte, un depredador de aves y polluelos.

in well-connected fragments. In addition, males in isolated fragments failed to obtain mates (18 %) more often than in connected fragments (1 %). Chucaos use corridors of dense vegetation to move from one fragment to another (Sieving et al. 2000). These travel corridors can be just a few meters wide (3-5 m), at least when the necessary dispersal distances are on a scale of 10-100 m. However, zones with huge open areas and scarce forest fragments have low probability of dispersion and the risk of chucao populations (and other birds of forest understory) is higher (Castellón & Sieving 2007).

Long-term studies of this endemic species have allowed understanding of the main threats to its persistence and proposing landscape designs that facilitate the persistence of viable populations within rural environments (Willson & Armesto 2003). The implementation of such designs requires the participation of social and political actors, especially the rural landowners.

Demography and conservation of the rare marsupial Dromiciops gliroides

The arboreal marsupial monito del monte (*Dromiciops gliroides*) (Fig. 5B), is endemic to South American temperate rainforests (Hershkowitz 1999) and is rather poorly known among Chilean mammals (Celis-Diez 2010). Its distribution extends along the Chilean Pacific rim from Talca (ca. 35°30' S) (Lobos et al. 2005) to Chiloé Island (ca. 44°00' S) and adjacent forested habitats of Neuquén and Río Negro provinces in southwestern Argentina (Hershkowitz 1999). It is considered a living fossil or relict in the South American mammal fauna since it constitutes the only extant member of the order Microbiotheria, with strong phylogenetic links with Australasian marsupials (Palma & Spotorno 1999).

Currently, habitat loss within its limited geographical range leads to the inclusion of *D. gliroides* in the IUCN red list, as near threatened. At SDBS we studied for four years, biological and ecological features of this species, that includes behavior, phylogeographical connection between Chiloe and mainland populations, and estimations of population density in remnant old-growth and selectively-logged forest fragments. Studies have documented that populations from Chiloé island, mainland of the Lake District, and from Bariloche (Argentina) are derived from ancestral populations that persisted further north (Himes et al. 2008) during the glacial history of temperate rain forests (Villagrán 2001).

D. gliroides is the only SouthAmerican mammal that hibernates under cold-temperate winter conditions and/or during food shortages (Bozinovic et al. 2004, Celis-Diez 2010). During winter *D. gliroides* nests in tree hollows or in snags, or inside the dense bamboo understory, where it builds ball-shaped nests using ferns, mosses and bamboo leaves (Jiménez & Rageot 1979; Celis-Diez 2010).

Since November 2005, we maintain an annual census of *Dromiciops gliroides* in remnant forest fragments in the rural landscape of northern Chiloe Island, in and around SDBS, in order to estimate long-term demographic patterns and population densities. We recorded similar densities of *D. gliroides* in old growth (OG) and selective logged (SL) forest patches; however, they were only occasionally present in shrublands (Celis-Diez 2010). In both OG and SL forests population growth rates were positive, and populations increased in summer with respect to the previous winter.

Survival probabilities of *D. gliroides* did not differ between OG and SL forests over four years (2005-2009), despite a reduction in the number of large trees, a proxy for tree hollow abundance, in SL patches. Increased native bamboo cover in SL forest, as a consequence of canopy opening, could mitigate the reduction in tree hollow densities, and at the same time offer protection against predators.

With respect to *D. gliroides* parasites, we recorded three species of ectoparasites. Two flea species (*Chiliopsylla allophyla* (Rothschild) and *Plocopsylla diana* Beaucournu et al.), previously known on rodents, and the first Chilean record of a specific-parasite, the tick *Ixodes neuquenensis* Ringuelet, found only on *D. gliroides* (Marín-Vial et al., 2007). We also recorded the nematode *Pterygodermatites* sp. (Rictulariidae), a digestive parasite, and an *Hepatozoon* sp., a new species of hemoparasite that could have co-evolved with *Dromicios* gliroides (Merino et al. 2009). New genetic evidence suggests that the potential vector of *Hepatozoon* could be the tick *Ixodes neuquenensis* (Merino et al. 2009).

Darwin's fox, an emblematic carnivore of Chiloé Island, currently endangered

Among the three Chilean fox species, Darwin's fox (*Lycalopex fulvipes* Martin) is the smallest and only endemic species to Chile. This rare fox, due to its low population numbers, its almost exclusive insular population and the loss of its habitat, is considered in critical danger of extinction (Jiménez et al. 2004). Among Chilean mammals, and among canids worldwide, it is one of the species with a highest priority for conservation (Cofré & Marquet 1998, Macdonald et al. 2004). Until only a few years ago, when a small population was found in the Cordillera de Nahuelbuta, 600 km north of Chiloé Island (Medel et al. 1990), it was considered a subspecies of the chilla fox (*Pseudalopex griseus* [Gray]), present only in Chiloé Island (Osgood 1943, Miller et al. 1983). . Currently, it is considered a genetically different species and ancestral to all South American canids, having a broader distribution in the past (Yahnke et al. 1996). At the same time, it is the largest terrestrial carnivore of the island, with an important role in the ecological food web of the forests and the rural landscape of Chiloé.

Since the mid 1970s, we studied its distribution, feeding habits, habitat preferences, use of space, social structure, and its relation to human impact on the landscape of Chiloé. Even though it was first described from a specimen collected by Charles Darwin in 1834, knowledge about its ecology and natural history remained poor until very recently (Osgood 1943, Medel et al. 1990). At present, the fox is detected in the rural landscape of Chiloé Island that contains fragments of native forest, from sea level to the top of the coastal range or Cordillera de Piuchué (650 m), and from the surrounding areas of SDBS in the north to the forest of Iñío in the southern end of the island (Jiménez et al. 2005[1]). Although this species was thought to depend on the cover of old-growth native forests (Miller et al. 1983), studies with radio telemetry in at least six localities and in 35 different individuals show that today the fox inhabits the mosaic of old-growth and secondary forests, mixed with shrubland and open areas that dominate the landscape of Chiloé. It can also be seen today in coastal sand dunes and beaches, where it finds food, independenly of the level of habitat disturbance (Jiménez et al., unpublished data). Its diet is varied and opportunistic, including pudu deer, small mammals, birds, insects, coastal invertebrates, seaweed, shellfish and fleshy fruits depending on the place and season of the year (Jiménez & Rau 1999[2], Jiménez 2007). During autumn it consumes large quantities of fruits and disperses the seeds of *Myrceugenia planipes*, and two bromeliads that grow on rocks near the coast (*Fascicularia bicolor* (R. et P.) Mez and *Greigia sphacelata* (R. et P.) Regel), to distances > 700 m from the parent (Jiménez 2007). It also disperses the hairy seeds of *Uncinia* sp. that stick to its skin.

Darwin's fox is active all day, it has a low sexual dimorphism and its color and corporal morphology are typical of mammals of humid forests (Jiménez & McMahon 2004, Jiménez 2007). In contrast to most canids, it does not defend exclusive territories and home ranges present broad overlaps among males and females of different ages (Killian 2005, Jiménez 2007). Human impact on native forest does not seem to affect its presence when the level of forest fragmentation is low. At present, the highest obstacle for the conservation of this fox is direct persecution by man and its pets (Jiménez & McMahon 2004). People from Chiloé know almost nothing about its biology and have negative perceptions towards the fox (Díaz 2005). Frequently, today, Darwin's foxes are hunted by humans or killed by their dogs. In addition, we have found ecto- (González-Acuña et al. 2007) and endoparasites (Jiménez et al., unpublished data) shared with domestic dogs, which can transmit viral diseases, such as canine distemper (Jiménez et al., unpublished data). The conservation and viability of this threatened species in Chiloé Island will strongly depend on the management of the rural landscape and the responsible ownership of dogs in the rural communities.

*Long-term study of the thorn-tailed rayadito (*Aphrastura spinicauda*)*

Since 2002, we conducted long-term studies of one of the most common birds in native Chilean forests (Rozzi et al. 1996, Cornelius et al. 2000), the thorn-tailed rayadito or yiqui-yiqui (*Aphrastura spinicauda* Gmelin; Furnariidae) (Fig. 5C). These studies began in SDBS, but in subsequent years they extended to other sites from the nascent LTSER network (Parque Etnobotánico Omora and Parque Nacional Fray Jorge). The purpose of such studies was to learn about phenotypic, genetic and historical variability of this widely distributed species in a geographic context. This bird is endemic to the austral temperate forests of South America and ranges from Fray Jorge National Park (30° S) to Cape Horn (56° S) (Johnson & Goodall 1967, Remsen 2003, Rozzi 2003). It is a primarily insectivorous, small bird (11-13 g), secondary occupant of tree hollows to nest; it lives in conspicuous groups during the non-reproductive season (Vuilleumier 1967, Grigera 1982, Ippi & Trejo 2003, Moreno et al. 2005, Cornelius 2008). Along its latitudinal range of 2800 km, populations of this species experience contrasting environments and selective pressures, and its study can contribute to understanding the causes of microevolutionary change and processes of speciation and subspeciation (e.g., Foster 1999, Quispe et al. 2009). To investigate life history traits of the thorn-tailed rayadito, we installed wooden nest boxes (Fig. 5D) in remnant forests of SDBS and Los Cisnes farm, in rural northern Chiloé Island. Boxes are monitored yearly during the reproductive season. In this period, adults and chicks use the nest box; enabling us to mark them for subsequent identification and follow-up. We recorded the size and timing of egg lay (Moreno et al. 2005), sexual roles in parental care, morphological differences (Moreno et al. 2007), parasitological data (Merino et al. 2008) and behavioral traits (Moreno et al. 2007; Ippi et al., unpublished data, Vásquez et al., unpublished data).

Until present (2008), in rural areas of Chiloé Island, the thorn-tailed rayadito is a species with a high parental investment, four (modal value) large eggs in relation to its body size, and a long dependency period of chicks. These characters are more similar to species of tropical birds than to birds inhabiting high-latitude forests in the northern hemisphere (Moreno et al. 2005). Both parents have low sexual dimorphism and participate equally in the incubation and feeding of the chicks (Moreno et al. 2007), and the defense of the nest (Ippi et al., unpublished data).

Given that the thorn-tailed rayadito belongs to one of the most diverse families worldwide (c. 200 species)

[1] JIMÉNEZ JE, P RUTHERFORD, C BRICEÑO, E LEEGWATER & SM FUNK (2005) The critically endangered Darwin's fox (*Pseudalopex fulvipes*), where and how many are left? Combining field data and GIS modelling, XIX Congreso anual de la Society for Conservation Biology, Brasilia, Brazil.

[2] JIMÉNEZ JE & JR RAU (1999) Dieta del zorro de Darwin en Chiloé: Variabilidad espacial y temporal. Resumen, II Taller de Carnívoros, organizado por el Servicio Agrícola y Ganadero, Coihaique.

and to the suborder Suboscine, one of the least known (Irestedt et al. 2001, Jaramillo 2003, Remsen 2003), information on its ecology and evolutionary biology could disclose new ways in which organisms meet the challenges of environmental change in time and space. This work offers a novel theoretical base applicable to the study of many South American species. Moreover, long-term studies of species that depend on forests, such as the thorn-tailed rayadito, can provide general models or indicators for developing conservation or management strategies applicable to less known, phylogenetically-related, cavity nesting species (Vásquez & Simonetti 1999).

Unraveling the linkages between species diversity and forest structure

Many tropical and temperate rainforests in the world have a structure determined by the spatial and vertical distribution of physical and biological components, such as large emergent trees, snags, and dense vegetation in the understory (e.g., Aravena et al. 2002, Carmona et al. 2002, Van Pelt 2007, Gutiérrez et al. 2009). Such structures provide habitat and resources to many plant and animal species in these ecosystems (Franklin et al. 1981). Temperate rainforests of southern South America are characterized by a multi-layered canopy (Gutiérrez et al. 2009), dominated by broad-leaved evergreen trees, with trunks and branches lushly covered by a rich assemblage of vascular and non-vascular epiphytes and vines, and a ground layer covered by 2-3 m tall native bamboo, especially under canopy gaps (Gutiérrez et al. 2008b). Forest structural elements are very important for native birds. Reid et al. (2004) showed that birds that dwell in the forest understory tend to be more abundant under the dense cover of native bamboos (*Chusquea* spp.), where they find food and protection against local predators. Two understory bird species, Des Murs' Wiretail (*Sylviorthorhynchus desmursii* Des Murs, Furnariidae) and the ochre-flanked tapaculo (*Eugralla paradoxa* (Kittlitz), Rhinocryptidae), spend their life cycle in the dense bamboo patches (McPherson 1999, Díaz et al. 2006). Three other understory birds, chucao tapaculo (*Scelorchilus rubecula*), Magellanic tapaculo (*Scytalopus magellanicus* [Gmelin]) and huet-huet (*Pteroptochos tarnii* Kittlitz), all belonging to the family Rhinocryptidae, protect themselves under the bamboo cover and nest in cavities in logs and hollows close to the ground (DeSanto et al. 2002, Willson et al. 2005). Other structures of old-growth forests (>200 years old) are the large, canopy emergent trees (generally long-lived pioneers) and snags. Old trees and snags are critical for the persistence of cavity nesting birds such as the Magellanic Woodpecker (*Campephilus magellanicus* [King]), the Slender-billed Parakeet (*Enicognathus leptorhynchus* [King]) and the Spiny-tailed Rayadito (*Aphrastura spinicauda*, Willson et al. 1996, Cornelius 2006). In 30-80 years-old secondary forests, with similar tree composition, but lacking large trees and the dense understory under tree-fall gaps, bird species richness drops from 16 to 9 and bird abundance is 60 % lower (Díaz et al. 2005).

The forest canopy, sometimes reaching over 30 m, is still a knowledge frontier in forests . We lack information about many biological and chemical processes occurring at the interface between forests and atmosphere, such as carbon assimilation, cloud and fog interception, or nutrient capture. Moreover, the forest canopy supports rich but poorly known assemblages of small organisms, including invertebrates, mosses and lichens (Ozzane et al. 2003, Benzing 2004, Erwin 2004). Díaz et al. (2010) investigated the canopy of emergent trees (25-30 m tall) from coastal old-growth Valdivian forests, with minimal human disturbance (e.g., Gutiérrez et al. 2008b), where just three tall emergent trees held 33 % of all vascular epiphytes described for the entire Valdivian ecoregion, and the 50 % of the known species of Chilean filmy ferns (Hymenophyllaceae). In other words, each large tree is an extraordinary reserve of forest biodiversity. Epiphytic biomass was positively correlated with the tree size, and one hectare of forest can hold about 10 tons of epiphytes, based on just one tree species (Díaz et al. 2010). These new data open up many questions, such as: How do epiphytes colonize the trees where they occur? What is the relation between epiphyte and invertebrate species composition and the species and age of trees? What are the ecological functions of this large array and biomass of epiphytes in the forest canopy? (Díaz 2009). A large biomass of epiphytes strongly enhances the diversity of invertebrates and birds in the forest canopy (Ellwood & Foster 2004, Cruz-Angón & Greenberg 2005, Díaz 2009). A long-term will help understand the linkages among the different components of the forest biodiversity and their ecological functions. This understanding is necessary to make compatible biodiversity conservation with forest management, especially under future land use and climatic scenarios.

Pollinator assemblages in Chiloé forests

For nearly a decade, we have studied the assemblage of pollinators in the rural landscape mosaic of forests and pastures surrounding SDBS. Most temperate forest species here have biotic pollinators (Smith-Ramírez & Armesto 1994, Smith-Ramírez 1993, Riveros 1991). The plant-pollinator interaction network of remnant forests in northern Chiloé includes 128 pollinator species and 26 woody plant species (11 shrubs, 9 trees and 5 vines), with a total of 316 mutualistic interactions (Smith-Ramírez et al. 2005). The pollinators identified included 21 species of hymenopterans, 52 dipterans, 47 coleopterans and four bird species. *Embothrium coccineum* (Proteaceae) was the only woody plant pollinated by a passerine, *Elaenia albiceps*, in addition to the only hummingbird species in the forest, *Sephanoides sephaniodes* (Molina) (Smith-Ramírez & Armesto 2003).

The plant-pollinator interaction network of forest remnants was highly asymmetric, as few plant species monopolize many pollinator species, and a small number of pollinators visits the majority of plant species

(Ramos-Jiliberto et al. 2009). Moreover, the network has a nested structure, whereby interactions of the less connected species are a subset of those more connected.

Simulations of species loss from the plant-pollinators network (Ramos-Jiliberto et al. 2009), which may occur in the future due to habitat loss or forest exploitation, showed that if trees (or forest patches) were removed from the rural landscape that could result in a massive local extinction. This would not be the case if shrubs were removed, with the exception of one key species, *Tepualia stipularis* (H. et A.) (visited by 47 pollinator species). If this species is lost that would cause a decrease of the network nesting. Loss of Hymenopterans, even though they are not the most diverse pollinator group, would produce a cascade extinction of pollinators and plants from the system. Hymenopterans are the most generalist insect group, because one species (*Bombus dahlbomii* Guérin) accounted for 50 % of the visits to all flowers. Extinction of this species would change the entire interaction network.

Pollinator studies are often conducted during one or two flowering seasons. However, long-term work (3-9 years) in SDBS, quantifying flower visitors to *Embothrium coccineum*, *Amomyrtus meli*, *Myrceugenia planipes* (H. et A.) and *M. ovata* (H. et A.) Berg. var. *ovata* (C. Smith, unpublished data), present in forest fragments or isolated trees in the rural landscape, shows that pollinator species richness and frequency of visits varied greatly between years (Smith-Ramirez et al. 2007). In the case of *E. cordifolia* and Myrtaceae species, an inverse pattern in the frequency of visits by *Apis mellifera* Linnaeus (introduced from Europe) and native bumblebee *B. dalhbomii*, in alternate years. Thus, in years with high frequency of *Apis* (c. 40 % of visits), *Bombus* is rare (6 % of visits), and these patterns revert during the next season. Among possible explanations of this phenomenon long-term studies of specific parasites of these hymenopterans are being investigated.

Restoration ecology assays

Restoration ecology seeks to imitate natural succession and accelerate the recovery of degraded ecosystems to restore structure, biodiversity and/or environmental services. Interventions can include species introduction, management of altered processes or threatened species, or the setback or ending of degradation processes. Restoration experiments implemented at SDBS are actions that are expected to restore locally declining species and ecological processes.

Immersed within rural landscape of northern Chiloé Island are small remant populations of *Pilgerodendron uviferum* (D. Don) Florín, the southernmost conifer of the world, endemic to southern Chile and adjacent Argentina (39°-55° S). In the northern limit of its geographic distribution, populations of this long-lived conifer have been strongly reduced and degraded by forest burning, timber extraction, and land cover change. Populations of *Pilgerodendron* that still persist within the rural landscape have low genetic diversity (Allnutt et al. 2003) and are restrained to poorly drained soils (Armesto et al. 1995). We decided to run experiments to identify effective restoration strategies that could promote the recovery of this valuable tree species in the rural landscape. Since 2002 we monitored the establishment of nursery-propagated *Pilgerodendron* trees in successional shrublands, particularly evaluating the effects of substrate (*Sphagnum* moss cover) and vegetation shade on the growth and survival of this threatened species. Plants were generated from cuttings (vegetative propagation) from trees in five local remnant populations in northern Chiloé Island. Cuttings were rooted and grown during two years in the greenhouse of SDBS and then transplanted into eight 7 x 7 m plots. Individuals from each source population were randomly distributed within plots. Four plots were located in an area with high *Sphagnum* moss cover (> 60 %) and the other four in a site with low *Sphagnum* cover (< 10 %). Sites also differ in soil water saturation, with more humid soils at high *Sphagnum* cover. Within plots, plants were regularly planted at 1 m intervals, in microhabitats with or without dense shrub cover. After four years, tree growth has been lower in open areas, as growth was favored under dense shrub and fern shade, and high *Sphagnum* cover also resulted in lower tree growth (Fig. 6). *Pilgerodendron* survival was higher in plots with low *Sphagnum* cover and in shaded microsites, regardless of the source of plants.

The higher growth of *P. uviferum* under shade, despite its characterization as a pioneer species after disturbance, points to the fact that shrubs and ferns have an important "nurse" effect on this species, by facilitating its survival and growth. In contrast, high *Sphagnum* cover, known as indicator of water-logged soils, inhibits *P. uviferum* growth. These results suggest that restoration of this threatened conifer is favored under dense shrub cover and in well-drained soils. In spite of its slow growth, its durable, fine and aromatic wood, used for making high-quality doors and windows, make this species a valuable resource to be included in restoration programs in this rural area. A long-term challenge is to assess the effects of tree planting on water table levels and to compare these effects with those of *Eucalyptus* plantations that have been massively introduced in disturbed areas of native forests.

Single-species restoration can be fruitless if these efforts are not accompanied with manipulations to maintain or repair damaged ecological processes. Experimental studies of succession in shrublands of northern Chiloé Island have shown that low seed inputs can be a limiting factor for tree regeneration, and that tree establishment on piles of woody detritus is higher than on naked soil (Papic 2000). Based on this context, in July 2004 we started a field experiment whose goal was to assess facilitation of tree regeneration in an abandoned pasture, through the use of artificial perches to attract seed dispersing birds and the installation of coarse woody debris under perches (comparing woody detritus, logs and soil as substrates). Results after five years have shown that artificial perches increase the seed rain of bird-dispersed trees several times over that of open areas (Fig. 7).

However, despite the increased propagule rain, the establishment of native woody species has been null on any of the three substrate types, despite the proximity of surrounding native forests (< 500 m). Consequently, other edaphic or environmental factors must limit tree establishment in the abandoned pasture. Possibly, it will be necessary to consider the use of "nurse plants" and natural or artificial structures that improve the protection of seedlings from solar radiation and enhance the arrival of seeds.

Biological corridors

In rural landscapes, forest patches surrounded by pastures are frequently inter-connected by riparian vegetation and zones of dense shrubs. Such structures may become "biological corridors" (Argent & Zwier 2007), that is, potential routes for plant and animal dispersal (Johansson et al. 1996, Tewksbury et al. 2002, Haddad et al. 2003). Biological corridors may enhance the movement of the forest-dwelling organisms through the landscape. However, their effectiveness as facilitators of animal movement in the anthropogenic landscape needs to be tested in real situations.

Understory birds (Rhinocryptidae and Furnariidae) use corridors of dense vegetation that are more than 25 m wide to migrate in the landscape (Sieving et al 2000). The reproductive biology of Des Mur's wiretail, *Sylviorthorhynchus desmursii* (Díaz et al. 2006), *Eugralla paradoxa* (Sieving et al 2000) and Chucao Tapaculo (see above) are positively affected by the presence of riparian vegetation. A wild cat, the guiña (*Leopardus guigna* [Molina]), uses ravines covered by dense native forest to move through the rural landscape (Sanderson et al 2002).

Interactions may change in biological corridors

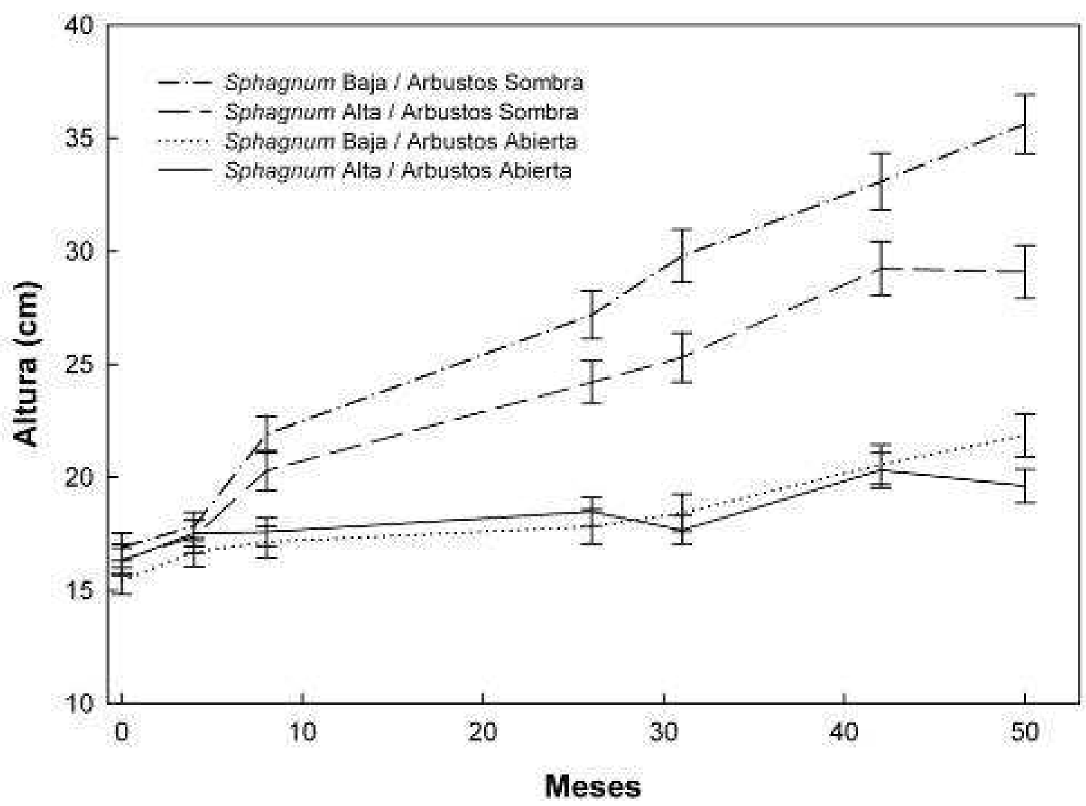

Fig. 6: Height growth of juvenile individuals of *Pilgerodendron uviferum* planted at two secondary shrubland sites of EBSD under two substrate conditions, high and low *Sphagnum* cover, and two shrub cover conditions, open area and under shrub shadow. The plants were produced within the greenhouse of EBSD from five different remaining natural populations. The curves correspond to polynomial trend fit. Mean values ± 1 SE are shown.

Crecimiento en altura de individuos juveniles de *Pilgerodendron uviferum* plantados en dos sitios de matorral secundario en la EBSD bajo dos condiciones de sustrato, cobertura alta o baja de *Sphagnum*, y dos condiciones de cobertura de arbustos, en espacios abiertos o bajo sombra. Las plantas fueron producidas en el vivero de la EBSD a partir de esquejes de cipreses de cinco poblaciones diferentes. Las curvas corresponden al ajuste de una línea de tendencia polinomial. Se muestran los valores medios ± 1 EE.

when compared to continuous forests. A study of nest predation using artificial nests (Willson et al. 2001) showed that predation was higher in narrower (< 10 m wide) than in wider corridors (> 50 m wide). Recent studies of the ecological function of riparian corridors in the landscape found that the seed rain of avian-dispersed fleshy-fruited species (Jaña-Prado 2007) and seed predation by rodents differed from upland forests, situated away from rivers (50-100 m). Seed traps placed in riparian forests in a rural landscape of northern Chiloé captured a higher number of seeds by one order of magnitude than seed traps in upland forests (Fig. 8). Finally, seed predation in the same riparian habitats was lower than in upland forests.

The higher seed rain in the riparian corridors suggests that the frugivorous birds are using these habitats more intensely, or that they are consuming more fruits from trees in this type of forest. Consequently, riparian forests are critical to maintain the connectivity among remnant forest patches in the rural landscapes of Chiloé. Trees in riparian forest receive more light than trees in the forest interior, which may result in larger crops that could attract more birds and propagules in the rural landscape.

ECOLOGICAL EDUCATION IN THE RURAL CONTEXT

Knowledge generated by the scientific research conducted in or around SDBS has been disseminated directly to the local and regional community, without "intermediaries" and almost immediately. This is a major advantage of long-term ecological research sites.

The learning method, known as the "first hand inquiry cycle" (Rozzi et al. 2000, Papic & Armesto 2003, Feinsinger 2003), is channeled through hands-on workshops: Teaching Ecology in the Schoolyards (EEPE), held in rural schools of Chiloé Island since 1997, with participation of SDBS scientists. This methodology is based on the direct training of schoolteachers, students, park guards and landowners to answer questions about they surroundings, using a simple version of the scientific method. Questions are

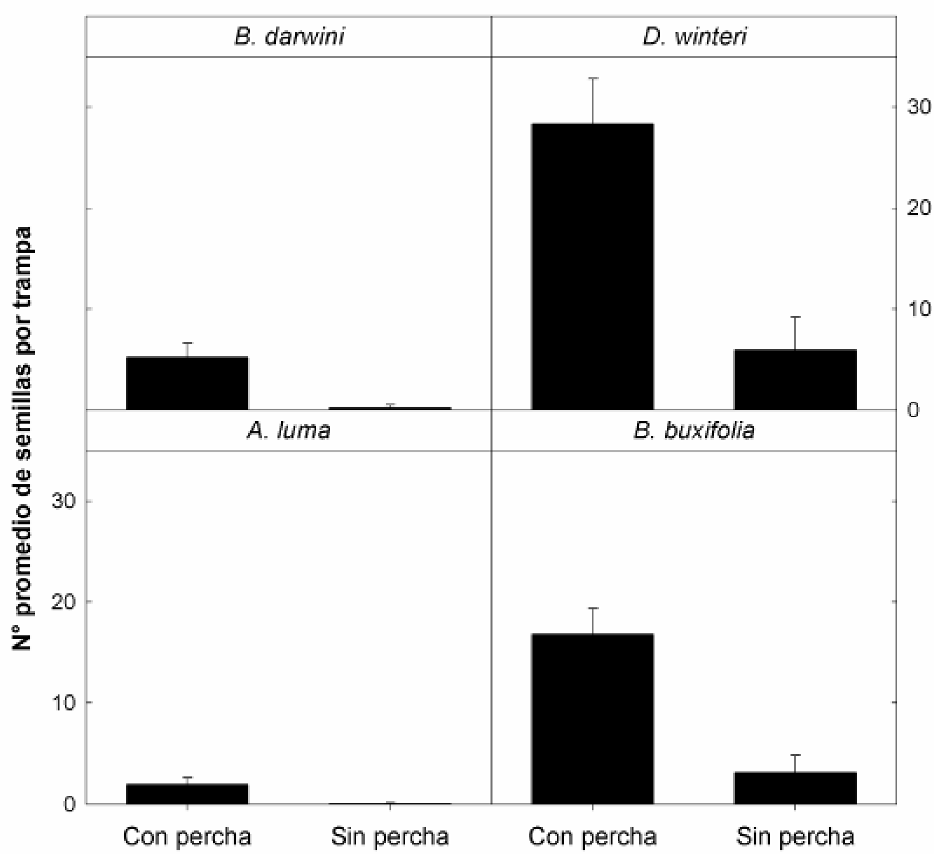

Fig. 7: Average number of seeds per trap of four woody species recorded during the sampling period (Spring-Summer) of year 2005 within traps under artificial perches (n = 15) and traps without perches (n = 15) installed in a abandoned pasture of EBSD. Error bars: ±1 SE.

Número promedio de semillas por trampa de cuatro especies leñosas (*Drimys winteri, Amomyrtus luma, Berberis buxifolia, Berberis darwini*) registradas durante la temporada de muestreo (primavera-verano) del año 2005 en trampas de semillas bajo perchas artificiales (n = 15) y trampas sin perchas (n = 15) instaladas en una pradera de la EBSD. Barras de error: ± 1 EE.

formulated by workshops participants and simple observations and experiments are designed collectively to answer these questions. Later, results, conclusions and reflections are presented to and discussed with the entire group. Starting in 2000, we have run workshops for more than 500 school children and 60 teachers in Chiloé and other locations (Puerto Montt, Valdivia, Santiago, La Serena). In turn, workshop participants have replicated the inquiry cycle with their students, contributing to a multiplicative effect.

The inquiry cycle is also a tool for supporting conservation and ecological research in parks and protected areas by working with park guards. CONAF (Chilean Forest Service) personnel have customarily participated in workshops specifically aimed at designing biodiversity studies and education trails for visitors. Workshops also promote the dialog among scientists and teachers, students and the local community, fostering collaboration, and the long-term analysis of problems of local or regional interest.

The minimal cost of these workshops, the efficient use of local resources, avoiding the introduction of sophisticated tools, lacking in schools or parks, added to the public communication of results and reflections derived from each inquiry, makes this methodology an ideal method to stimulate the generation of local knowledge in a community that can be critical about its social and natural setting.

The EEPE methodology is also applied to spreading the principles of ecosystem ecology. Working with 60 students from three rural schools from Chiloe, we investigated the process of organic matter (OM) decomposition, to gain basic understanding of biogeochemical processes that link OM degradation with plant growth. Decomposition assays were set up at each school yard (litter bag method), using fresh leaves from two native woody species (*Aristotelia chilensis* Mol. “maqui” y *Nothofagus nitida* “coigüe de Chiloé”) and two organic substrates of anthropogenic origin (paper and pine wood). Organic substrates showed different decomposition rates during the six months duration of the assay. Leaves of native species lost more mass on average than other materials (Fig. 9). Results indirectly documented the action of different kinds of decomposer

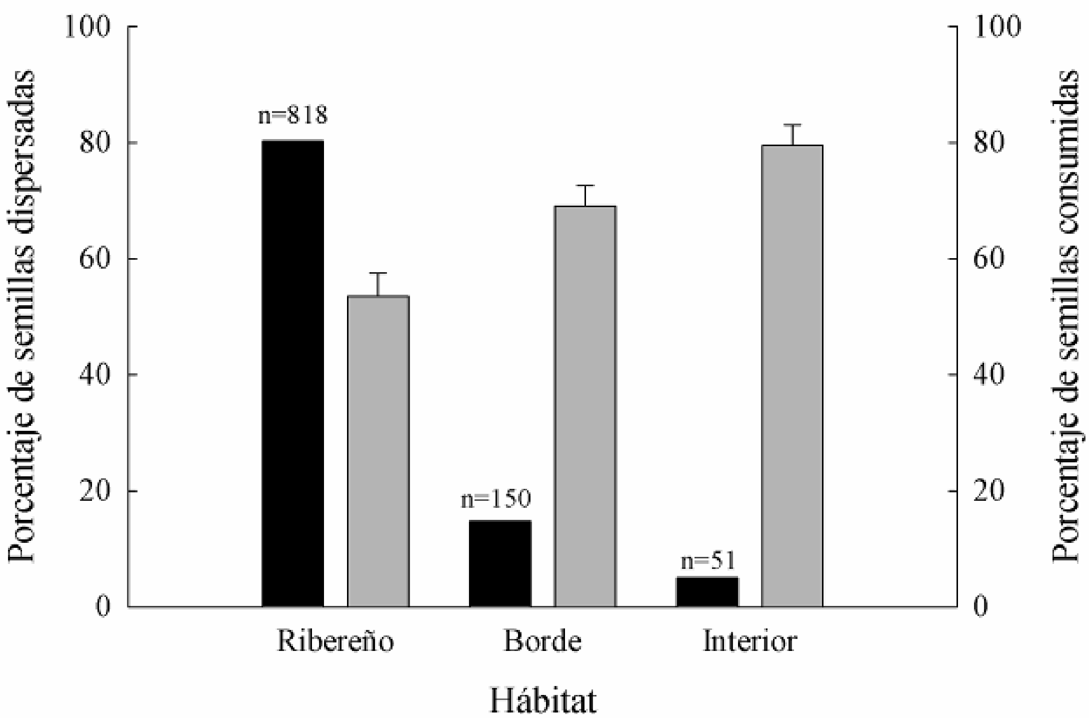

Fig. 8: Percentage of dispersed seeds within riparian and non-riparian habitats (border and interior of forest), in relation to the total number of fallen seeds in the traps (left axis, black bars). Differences between habitats: $\chi 2$ = 1,025, df = 2, $P < 0.001$. Mean percentage of seed removal by predators of *Embothrium coccineum* and *Aristotelia chilensis* (right axis, grey bars) within each habitat is also shown. Differences between means: $t_{\text{interior-riparian}} = 4.89$; $P < 0.001$, $t_{\text{edge-riparian}} = 2.91$; $P < 0.05$, $t_{\text{interior-edge}} = 2.12$; $P < 0.05$ (after Bonferroni correction).

Porcentaje de semillas dispersadas en hábitats ribereños y no ribereños (borde e interior), en relación al total de semillas caídas en trampas (eje izquierdo, barras negras). Diferencia entre hábitats: χ^2 = 1,025, df = 2, $P < 0.001$. También se presenta el porcentaje promedio de remoción de semillas por depredadores de *Embothrium coccineum* y *Aristotelia chilensis* (eje derecho, barras grises) en los diferentes hábitats. Diferencia entre medias: $t_{\text{interior-ribereño}} = 4.89$; $P < 0.001$, $t_{\text{borde-ribereño}} = 2.91$; $P < 0.05$, $t_{\text{interior-borde}} = 2.12$; $P < 0.05$ (después de corrección por Bonferroni).

organisms and were formally presented at a Scientists Fair held at SDBS.

Parallel to EEPE workshops, we have focused on charismatic animal species (threatened or poorly known) from Chiloe, as central subjects of workshops and education materials directed to inform the local and regional community. For instance, the rare arboreal marsupial *Dromiciops gliroides* has been portrayed in local and national TV and press reports. Additional information is given through internet, books, posters and lectures for schools, local organizations and government. The education program of SDBS has also communicated results of studies on Darwin's fox (*L. fulvipes*) and pudú deer (*Pudu pudu* [Molina]), under a collaborative program with local animal protection organizations that call for sterilization of cats and dogs in rural zones.

Links with the local community

One of the goals of SDBS is to establish effective mechanisms for communication between ecologists and other professionals and the local community. Facilities of SDBS, built for that goal are the "Beagle" Ecological Education Center and the education trail "Pichihuillilemu" (little forest of the south). The "Beagle" provides classrooms for workshops and courses with local people and visitors. Its accommodations and location near a riparian forest (Fig. 1) stimulate creative thinking and the exploration of the surroundings. In a similar way, "Pichihuillilemu" trail is visited by over 100 school students, teachers, and numerous tourists every year, who can learn about the flora, fauna and ecology of the Chiloe forest. Some workshops on specific subjects have attracted much audience. Subjects include the application of scientific knowledge to native plant propagation (using the "Luis Cavieres" greenhouse facility), forms of forest management friendly to biodiversity, and uses of native plants.

Other forms of communication of knowledge generated in SDBS to non-scientists are local press articles (newspapers, La Estrella de Chiloé and El Insular), the EEPE Bulletin (Audubon Society), and local TV. For the Darwin's fox conservation project, 16 micro-documentaries were filmed, in collaboration with a Chilean TV producer. Additionally SDBS is regularly present in traditional annual fairs in Chiloe Island, where biodiversity knowledge blends with local culture

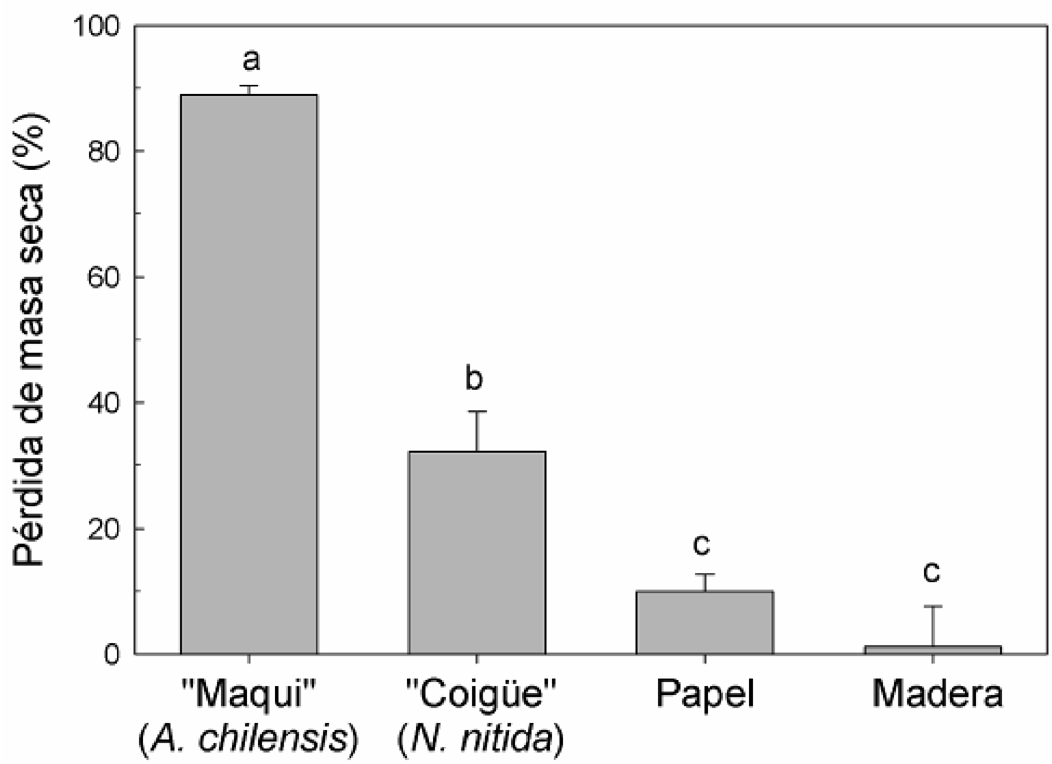

Fig. 9: Degradation (mass loss) of leaves of two native trees (*Aristotelia chilensis* y *Nothofagus nitida*), paper and pine wood during six months in rural schoolyards of Ancud district (N = 3). Different letters shows significant differences ($P < 0.05$) between decomposing organic materials according to ANOVA.

Degradación (pérdida de masa) de hojas de dos árboles nativos (*Aristotelia chilensis* y *Nothofagus nitida*), papel y madera de pino durante seis meses en los patios de escuelas rurales de la comuna de Ancud (N = 3). Las letras distintas indican diferencias significativas ($P < 0.05$) entre los distintos tipos de material orgánico en descomposición de acuerdo a un ANDEVA.

and traditions. Such work with the community has allowed the transfer of first-hand knowledge to landowners and rural inhabitants (Table 3). The ineffective transfer of scientific knowledge to decision makers or managers is one of the major causes of underdevelopment and loss of natural capital. To contribute to correct this problem, SDBS maintains a permanent education program, led by scientists or their students (undergraduate and graduate), in coordination with other long-term sites supported by the Institute of Ecology and Biodiversity (IEB).

Agricultural program

Since it was founded, one of the main goals of SDBS was to develop an agricultural program in harmony with traditional practices of local farmers in northern Chiloé Island. Since 2008, we started a new agro-ecological program aimed at making SDBS a model of sustainable agriculture and forestry production, compatible with the conservation of local biodiversity. This approach is based on the development of innovative subsistence activities, accessible to small landowners, requiring low investments, and that can be replicated in other rural areas of southern Chile.

An essential component of this approach is promoting local capacity building, through workshops and technical training for landowners that seek to improve management tools and expand the potential for production of goods and services in natural and rural areas.

Current agricultural production of SDBS is based on sheep raising (for meat and wool), crops of native potatoes, garlic, and harvesting local varieties of apples for vinegar and homemade cider. In addition, we keep a nursery for the propagation of native plants. Part of this agricultural production is for domestic consumption and part is sold in local markets.

We hope to progressively diversify and enhance our agricultural crops within the land previously designated for this purpose in the Station's management plan, not affecting conservation areas. Among the new ideas, we began developing an "experimental silvicultural garden" using a specific combination of native tree species to maximize the production of timber and non-timber forest products, including species with known economic value, such as *Gevuina avellana* Mol., and other less often cultivated, such as *Amomyrtus luma* and *Embothrium coccineum*. All species are grown in our nursery from local seed.

In collaboration with the Universidad Católica de Chile, we are conducting a study of the potential for growing plant fibers traditionally used by indigenous or local communities in Chiloé. These studies are complementary to the research developed within the Long-Term Socio-Ecological Research Network of IEB, and will foster the application of scientific knowledge by local communities to enhance their local economy, improving social well being.

CONCLUSION AND PROJECTIONS

The rural landscape of northern Chiloé Island, where SDBS is emplaced, offer ample opportunities to integrate biological knowledge and its application, through a complex rural landscape gradient, from old-growth forests with 300-yr old trees, and minimal anthropogenic disturbance, to increasingly human-dependent ecosystems, such as pastures, farmlands and tree plantations. Within this seminatural matrix distinct land uses coexist, including native forest patches, anthropogenic grasslands, shrublands representing different successional stages, in a space shared between humans and native plants and animals. Moreover, SDBS is part of this rural environment, where the traditional way of life of the Chilote inhabitant coexists with the fast and changing globalized world. In this context, long-term ecological research is extremely relevant for understanding how do the changes in terrestrial ecosystems, determined by the resource demand of global markets, the spread of introduced species and new crops (e.g., salmon farming) and industrial management practices, will affect biodiversity and other ecological functions of regional and global importance.

Two examples of ecosystem services, relevant to society, whose drivers and pace of change we are currently investigating are: (1) primary productivity (including carbon fixation and retention) in old-growth and successional forests, and (2) sustainability of the hydrologic cycle within rural zones, where it is directly affected by logging, wetland exploitation and drainage, and massive plantations of *Eucalyptus*. Such studies require an ecosystem approach, clever experimentation, and ecological long-term research. Information on these ecological services is essential for regulating sustainable management practices and land use. Global changes, including climate change, will affect local cultures, through loss of biodiversity and introduction of exotic ones, landscape homogenization and loss of traditional harvest practices. Long-term socio-ecological studies allow us to think of and test integrated strategies for maintaining a sustained flux of ecosystem goods and services. For instance, conservation of forests to enhance clean water production for human consumption has an obvious economic benefit to society (The Economist, January 2005). The subject of recovering the capacity of native ecosystems (or resilience) after natural catastrophes, such as fires or droughts, is relevant in the face of climate change scenarios that predict a decline of precipitation in south-central Chile. Long-term studies allow us to obtain experimental data on the effects of such changes. An added value of doing research in temperate and subantartic forests is their character of "frontier", considering the pattern of human colonization of the planet (Mittermeier et al. 2003), and especially because of the absence of atmospheric pollution levels that dominates temperate ecosystems in the northern hemisphere. Chilean forests (and their associated fluvial systems) are models of the pre-industrial condition of nutrient cycles (Hedin et al. 1995, Perakis & Hedin 2002, Armesto et al. 2009). Long-term studies will allow us to anticipate the changes of biogeochemical processes derived from the advance of agriculture and industrialization.

An innovative contribution of the Chilean LTSER is keeping phenological and reproductive records of numerous species of native plants and animals that inhabit rural environments. These simple and low cost records are relevant to detect, prevent or mitigate the effects of accelerated land cover change, and anticipate the expected effects of climate change in the region. In this regard, systematic research, periodical censuses and demographic models, such as those developed for rayadito, chucao and/or monito del monte, can provide valuable data about the persistence of biodiversity within rural landscapes, under different real or simulated management and socio-ecological scenarios. Learning about ecosystems in the rural landscape of Chiloé Island can teach us how to face the uncertainties of the future.

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APPENDIX

The Senda Darwin Biological Station

Currently, SDBS is under the administration of Senda Darwin Foundation –ex Institute of Ecological Research Chiloé-, nonprofit institution dedicated to the integration of the scientific research with the education, the knowledge application in decision making on conservation and management of temperate rainforests (Rozzi & Armesto 1996, Rozzi et al. 2000). The properties that at present comprising the SDBS has been sequentially acquired thanks to support from several people committed with the conservation of native forest (see acknowledgments). In 2003 SDBS was recognized by the National Forest Service (CONAF) as Private Wild Protected Area, consolidating this conservation, research and education initiative led by ecologists.

Why the name "Senda Darwin" ("Darwin's trail")

The name of SDBS was chosen for evocate the visit and travel of the English naturalist Charles Darwin to the northern zone of Chiloé island, in 1834 (Willson & Armesto 1996). Darwin is also an inspiration source for researchers and studious of Natural History, who was the precursor of many central ideas of ecological sciences, and collected some emblematic species of plants and animals that inhabit the zone, as for instance the Darwin´s toad (*Rhinoderma darwini*), Darwin's fox (*Lycalopex fulvipes*) and the "calafate" (*Berberis darwini*).